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SITE-SPECIFIC PEST MANAGEMENT IN NEBRASKA CORN AND SOYBEAN PRODUCTION SYSTEMS

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by

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Site-specific management (SSM) is widely used by farm producers to fertilize their fields. However, whole field management is currently practiced in integrated pest management (IPM). Site-specific management and agricultural technology can improve IPM especially when precision application of inputs can reduce selection pressure on pest populations, benefit the environment, or save costs of inputs. There is potential for site-specific pest management (SSPM) where pests, or environments vary spatially, and recommended management practices can be applied with precision. Three case studies are evaluated for SSPM to be applied in Nebraska corn and soybean production systems including corn rootworm, preemergence herbicides, and soybean cyst nematode. Additional research will be needed for SSPM to reach its potential in future agricultural production systems.

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CHAPTER 1

FRAMEWORK AND CONCEPTS OF INTEGRATED PEST MANAGEMENT AND SITE-SPECIFIC MANAGEMENT

Introduction

The term integrated pest management (IPM) was first used during the second half of the 20th century. Integrated pest management has since developed into a holistic approach for pest management in agricultural systems, and varying levels of IPM are implemented on farms across the world to manage insect, disease, and weed pests. Many definitions of IPM have been put forward over the years. Kogan (1998) proposed the definition:

> “IPM is a decision support system for the selection and use of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost/benefit analyses that take into account the interests of and impacts on producers, society, and the environment.”

Integrated pest management practices have been employed to manage insect (Wright et al. 1987), disease (Nutter 2007), and weed (Swanton and Weise 1991) pests in a range of crops by tailoring management strategies to the biology and ecology of specific pest species and to the agricultural production system. Goals for IPM programs include economic management of pests, reducing risk of crop loss, reducing selection pressure on pest populations, and maintaining environmental quality (Norris et al. 2003). Pest management strategies are integrated into the cropping system with these goals in mind (Figure 1.1).

Site-specific management (SSM) is the practice of treating distinct areas within agricultural fields as separate management zones instead of applying the same

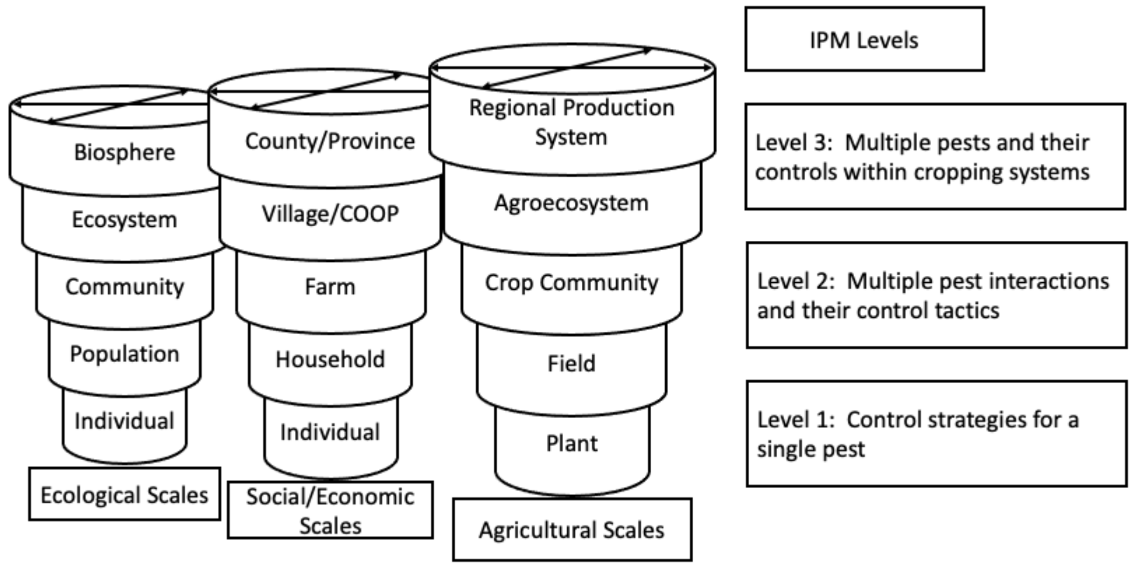

Figure 1.1. Visual description of the integration of pest management strategies within ecological, social/economic, and agricultural contexts. Adapted from (Kogan 1998).

management evenly across an entire field. Field boundaries are often established by roads, fences, and legal descriptions. In contrast, factors such as soil characteristics, landscape position and drainage may vary within field boundaries. Site-specific management applies the right crop management tools in the right place by dividing large field areas into smaller sized management zones.

> "A management zone is a sub-region of a field that expresses a relatively homogeneous combination of yield-limiting factors for which a single rate of a specific crop input is appropriate (Doerge 2019)."

Goals of SSM include outcomes with increased economic returns and reduced environmental impact. In practice, SSM requires a site or perimeter of a management zone with a known position or boundaries, information collected about that site or zone, and an action based on this information. Agricultural technology tools including global positioning system (GPS), geographic information system (GIS), remote sensing, and variable rate controllers enable the application of SSM across large areas (Shannon et al. 2018). Common applications for SSM include varying fertilizer rates, soil lime rates, seeding rates, crop varieties, irrigation applications, and pesticide applications within crop fields (Doerge 2019).

Site-specific management and IPM share common goals and in many cases are compatible in practice. This document serves as a blueprint for evaluating SSM practices and their suitability for implementation within IPM programs in Nebraska corn and soybean production systems. To provide a framework, this chapter will review the concepts and practices important to the practice of IPM and SSM.

Integrated Pest Management

Arthropod Management. Integrated pest management is a knowledge intensive process that considers pest ecology, economic factors, and the crop production system. Pest life cycles, alternate hosts, spatial patterns, and mobility are considered when developing IPM programs. Pest populations can be suppressed below levels causing economic injury using preventative tactics. Preventative tactics are often cultural methods such as tillage, crop rotation, host plant resistance, or adjusting planting date. Pest monitoring is used to estimate the crop yield loss associated with pest population levels. When an economic threshold is reached, chemical or biological insecticides, or early harvest of the crop are applied to avoid economic crop damage.

Knowledge of pest biology is key to developing and implementing effective preventative tactics. Reproduction of mites in corn is favored by hot canopy temperatures and water stressed host plants. Raun et al. (2000) reported adjustments in irrigation practices reduced mite populations to below threshold levels in corn where acaricides had previously been applied annually as a stand-alone tactic to control mites. In water limited environments, twospotted spider mite (*Tetranychus urticae*) and Banks grass mite (*Oligonychus pratensis*) populations are suppressed on drought tolerant corn hybrids compared to non-drought tolerant hybrids (Ruckert et al. 2021).

Corn rootworms, *Diabrotica virgifera*, (CRW) have a narrow host range, and the mobile adults prefer corn for feeding and lay eggs in these fields. Thus, crop rotation effectively prevents larval damage from western and northern CRW. Landscape level studies conducted in the Midwest USA concluded that rotation out of continuous corn and rotation of corn Bt traits reduced the frequency of corn rootworm problem fields across large areas (Carrière et al. 2020).

After preventative or suppressive tactics are integrated into crop management to reduce pest population equilibriums below the economic injury level (EIL), then ongoing monitoring programs and treatment thresholds are implemented to support treatment decision making. Sampling and thresholds are decision tools used to estimate the level of yield loss that will occur due to pests if no actions are taken. Soybean aphid, *Aphis glycines*, is native to Asia and since its detection in Midwest USA in the year 2000, has become the most significant insect pest on soybeans in this region. Sampling plans were developed based on knowledge of soybean aphid densities, spatial patterns, economic costs of sampling, and desired precision levels for decision making (Hodgson et al. 2004). Based on their sequential sampling plan that tallies the number of plants with 40 or more aphids, treatment decisions for soybean aphid can be made by sampling between

11 and 19 plants under most soybean aphid densities. Treatment thresholds for aphids can be further improved if crop growth stage and cumulative stress over time are considered in determining potential risk for crop loss. Catangui et al. (2009) developed stage specific cumulative soybean aphid day economic injury levels (ADEIL). Using this method, the EIL is calculated with additional information including the time when soybean aphid was first detected in the field and the current soybean growth stage.

Actions recommended for managing insect pests when thresholds are reached include insecticide applications and early harvest. When selecting tactics, important considerations include resistance management, economics, environment, and compatibility with other crop production practices. Timely insecticide applications protect plants from economic insect damage before EILs are reached. Pyrethroid insecticides are commonly used for management of western bean cutworm, *Stiacosta albicosta*, in Nebraska cornfields (Archibald et al. 2018). The adults oviposit eggs in masses on the upper corn leaves and larvae feed on pollen, silks, and developing ears (Michel et al. 2010). Detection of egg masses and estimation of potential yield loss is important for timing insecticide applications for western bean cutworm since the larvae are protected from insecticide applications once feeding on the ear beneath the husk.

Larvae of the Dectes stem borer, *Dectes texanus*, tunnel inside the pith of the soybean stem, girdle the inside of the stem near the soil level, and overwinter in the base of the stem directly below the girdle (Hatchett et al. 1975). The girdled stems are predisposed to late season lodging which causes losses at harvest. It is recommended to plant later maturing soybean varieties to allow a timely harvest of Dectes stem borer infested soybean fields to decrease losses from lodged plants (Wright and Hunt 2011).

Disease Management. Biotic plant diseases are infections caused by pathogens including fungi, bacteria, virus, and nematode pests. Disease only occurs when a susceptible host, a pathogen, and a favorable environment are all present. These three factors together are known as the disease triangle. Disease cycles are used to describe the primary inoculum, dispersal of inoculum, infection courts, colonization, secondary inoculum, and survival of plant pathogens as they relate to the epidemiology of a disease. Management tactics are selected based on an understanding of disease cycles and fall into four categories: avoidance, exclusion, eradication, and protection (Schuman and D'Arcy 2010).

Disease avoidance management strategies are focused on avoiding environmental conditions that favor disease development. Damping off is a seedling disease favored by slow seedling emergence that is common in cold, compacted, or poorly drained soils. Planting soybean when soil temperatures favor seedling emergence is a strategy to avoid the environment that favors seedling diseases such as Pythium seed rot (Rothrock et al. 2015).

Disease management that excludes pathogens focuses on the pathogen part of the disease triangle. Disease exclusion involves practices such as seed certification standards or quarantines at ports of entry. Exclusion is an important management tactic for diseases affecting seedlings. Seedborne pathogens in corn that cause ear rot and also cause damping off in seedlings include *Fusarium* spp., *Penicillium* sp., *Aspergillus* spp., *Rhizopus* spp., *Rhizoctonia* spp., *Bipolaris* spp., *Alternaria* spp., *Nigrospora* spp., and others (Dodd and White 2016). Selecting seed that is low in disease incidence can reduce primary inoculum of damping-off pathogens through exclusion.

Soybean cyst nematode, *Heterodera glycines*, (SCN) is native to Asia and as United States soybean acreage increased in the 1900's, it became important to exclude this pest from the region's expanding soybean production. From 1957 to 1972, the movement of infested soil and plant material was regulated by a federal quarantine for SCN. The quarantine was unsuccessful possibly due to infested soil and plant material being moved to new areas prior to the quarantine. Today, SCN can be detected in most soybean growing regions in the United States despite the quarantine (Davis and Tylka 2021).

Eradication measures are used as a management strategy to reduce levels of inoculum by cultural practices, chemical control, or biological control. Goss's bacterial wilt of corn is caused by *Clavibacter nebraskensis*. Historically, Goss's wilt outbreaks occurred most often in the western Corn Belt in parts of Colorado, Kansas, Nebraska, and Wyoming (Schuster et al. 1972, Jackson et al. 2007). Since the mid 2000s, the disease increased in prevalence and now is found further east throughout the Corn Belt (Langemeier et al. 2017). Chemical control options targeting Goss's wilt are not effective and available management options include planting resistant hybrids, and reducing primary inoculum through residue burial, crop rotation, and alternate hosts removal. Goss's wilt alternate hosts include johnsongrass (*Sorghum halepense*), large crabgrass (*Digitaria sanguinalis*), annual ryegrass (*Lolium multiflorum*), green foxtail (*Setaria viridis*), yellow foxtail (*Setaria pumila*), and giant foxtail (*Setaria faberi*) (Ikley et al. 2015). Herbicides and tillage targeting the alternate hosts can reduce the level of primary inoculum in the field.

Eradicant chemical controls are effective for management of fungal diseases. Chemical fungicides that fall into the eradication category have systemic action and are taken up by plant tissues and translocated throughout the plant. These fungicides are effective at reducing disease severity even after initial infection occurs.

Disease protection practices work to guard plants from infection even if the pathogen inoculum is present. Gray leaf spot (GLS) is caused by the fungal pathogen, *Cercospora zea-maydis*. Gray leaf spot management strategies include corn residue management, hybrid tolerance, and fungicide application (Rees and Jackson 2008). Hybrid tolerance and fungicide application strategies protect the corn crop when gray leaf spot inoculum is present and favorable environmental conditions are forecasted. While no hybrid is completely immune to GLS, hybrids vary significantly in their tolerance to the disease and selecting tolerant hybrids is an important strategy when planting corn in fields with a history of GLS (Carson 2016). Fungicides are effective at managing the disease. The economics of fungicide application for GLS vary by the price of corn, corn growth stage, hybrid susceptibility, disease severity, and environmental factors (Munkvold et al. 2001). Protectant fungicides cover plant tissues with a protective layer that is impermeable to fungal infection. Since they are not translocated within the plant, coverage and timing are important for fungicide application efficacy.

Weed Management. Weeds cause economic yield loss to growing crops through competition for resources including water, nutrients, and sunlight. The impact of weed competition on crop yield varies by crop species, crop growth stage, row spacing, tillage system, and relative emergence date (Cousens et al. 1987, Halford et al. 2001, Knezevic et al. 2003). Integrated weed management (IWM) is the application of multiple weed control measures including cultural, genetic, mechanical, biological, and chemical means (Swanton and Weise 1991).

Herbicides and herbicide tolerant crops play an important role in modern weed management systems as the adoption of reduced tillage crop production systems increases due to concerns about soil erosion and crop production efficiency (Givens et al. 2009). Economic thresholds that are common in insect pest management are not used for herbicide application decisions. Instead, there is an emphasis on the long term management of a low weed seedbank in the soil since any weeds that survive will produce seeds and increase the weed population size in future growing seasons (Beckie et al. 2019). Post-emergence herbicides are best used in combination with pre-emergence soil applied herbicides that prevent weed emergence. Crop varieties that tolerate post applied herbicides such as glyphosate (Roundup Ready), 2,4-D (Enlist), imazamox (Clearfield), and others have been developed to improve weed management systems. While herbicide tolerant crops provide an efficient and simplified weed management system, the use of multiple tactics and herbicide MOAs is still recommended as part of a diversified integrated weed management plan that prevents over reliance on a single strategy and the development of herbicide resistance in weed populations (Knezevic 2002).

Tillage systems, knowledge of the critical period of weed interference, enhancement of crop competitiveness, modeling of the crop-weed interference, crop rotation, and seedbank dynamics are all considered when developing IWM systems (Swanton and Weise 1991). Crop rotation impacts weed populations since different crops vary in their ability to compete with weeds, tolerate different herbicide modes of action, and allow different application windows for herbicides and tillage. Winter annual crops compete effectively with weeds that emerge later in the spring (Knezevic et al. 2021). Integrating winter wheat into a corn-soybean rotation may allow tillage and/or non-selective herbicide applications during July, August, and September.

Adjustments in row spacing can favor crops as part of an IWM plan and affect the competitive interaction between crops and weeds. Row spacing and the time of weed emergence relative to crop emergence have a significant effect on soybean yield loss due to competition and total weed biomass (Hock et al. 2006). Soybeans planted in narrow 19 cm rows tolerate competition from weeds early in the growing season better than soybeans planted in 76 cm rows (Knezevic et al. 2003).

Resistance Management. Resistance management reduces selection pressure applied to a pest population for a heritable trait that confers resistance to a pest management strategy. While pests can adapt to overcome any one management strategy, strategies that are used across large areas as a stand-alone tactic are most likely to cause pest population shifts (Coble and Schroeder 2016). Pest management tools such as chemical pesticides, herbicide tolerant crops, and genetic pest resistance are often the most efficient and at times the only practical way to manage a particular pest. Using a combination of management tactics, including preventative ones, reduces selection pressure and delays the development of resistance in pest populations (Beckie 2006). Available tools for managing pests are limited and few additional chemical pesticides and genetic resistance traits are in development (Duke 2012). Conserving our available tools is important for sustainable management of pests into the future. Roundup Ready (RR) and Bt crops have provided growers with several years of efficient management of weeds and insect pests. In some cases, pest resistance to these strategies has reduced their utility in recent years. Using a combination of multiple strategies as part of an IPM plan is recommended to help preserve their utility.

Roundup Ready crop varieties have transgenic tolerance to the non-selective post herbicide glyphosate. Roundup Ready soybeans were launched initially in 1996 and were adopted by farmers due to their simplicity, compatibility with trending farm practices, and economic benefits (Figure 1.2) (Carpenter and Gianessi 1999). Transitioning toward post emergence herbicide applications, no-till practices, and narrow row soybeans are made easier and less expensive by the roundup ready system. In 1998, using Roundup Ready soybeans and applying a single post application of glyphosate cost \$16.45 per acre. A single pre-plant herbicide

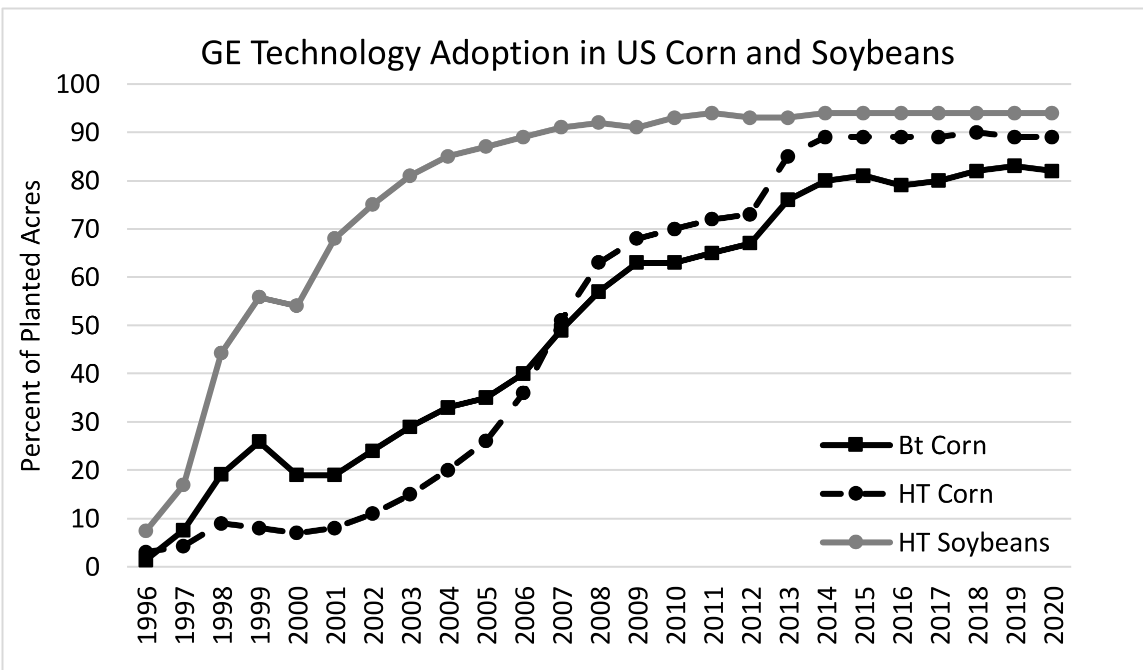

Figure 1.2. Percent adoption of Bt corn, herbicide tolerant corn, and herbicide tolerant soybeans in the United States from 1996 to 2020 (USDA ERS 2021).

application of a conventional herbicide cost $13.50 per acre, and multiple herbicide mixes cost about $25.00 per acre (Carpenter and Gianessi 1999).

The RR weed control system used as a stand-alone weed management strategy across a large acreage of corn, soybean, and other crops led to the eventual problem of glyphosate resistant weeds. Glyphosate resistance was slow to develop in weed populations initially due to its unique MOA and lack of soil residual activity (Bradshaw et al. 1997). In 2006, glyphosate resistant horseweed (*Conyza canadensis*) populations were detected in Nebraska soybean fields ten years after the release of RR soybeans (Heap 2021). Since 2006, several glyphosate resistant weeds have become difficult to control for Nebraska farmers including waterhemp (*Amaranthus tuberculatus*) and Palmer amaranth (*Amaranthus palmeri*). Additional herbicide tolerance traits such as Enlist E3 and Roundup Ready 2 Yield Xtend technologies have been released to provide farmers with new strategies to manage glyphosate resistant weeds in soybeans. Similar herbicide tolerance traits have been released in corn as well. Integrating these strategies into an IPM program will help to extend their utility for the future. A proactive and diversified approach is recommended for herbicide resistance management include using multiple effective herbicide MOAs, applying full labeled herbicide rates, and using a combination of preventative or suppressive strategies (Norsworthy et al. 2012).

Transgenic Bt corn expresses insecticidal proteins from the bacterium *Bacillus thuringiensis* targeting CRW, European corn borer, *Ostrinia nubilalis*, (ECB) and other pests. Bt corn hybrids resistant to ECB were first commercially available in 1996 and hybrids resistant to CRW became available to corn producers in 2003. These technologies were adopted rapidly and benefited growers by reducing the need for insecticide applications. The number of farmers who reduced insecticide applications targeting ECB between 1996 and 1998 increased from 13.2% to 26%. Producers also perceived the Bt technology to provide a yield advantage over non-Bt hybrids (Pilcher et al. 2002). A study published in 2010 showed that benefits from controlling ECB with Bt corn extended to corn fields planted to non Bt hybrids (Hutchison et al. 2010).

The high dose refuge strategy is used to preserve the benefits of Bt corn hybrids. This strategy ensures that target pest insects that feed on Bt corn plants are exposed to a high dose of the Bt toxin that is lethal to nearly all individuals in the population. A refuge of non-Bt corn is planted alongside Bt corn plantings. The refuge produces susceptible individuals that will have a high probability of mating with any potential resistant individuals surviving on Bt corn plants. This is intended to dilute resistance genes in the pest population and delay resistance to Bt toxins expressed in corn (Siegfried and Hellmich 2012). Despite a strong selection pressure from season long expression of Bt toxins in corn plants and from widespread usage of the Bt corn hybrids, ECB has been effectively controlled by Bt corn hybrids since the initial commercialization of the technology in the mid 1990s.

In contrast to the success of the high dose refuge strategy for ECB, some WCR populations have been selected for resistance to Bt proteins targeting this pest since the introduction of these hybrids in 2003. One reason for this is that WCR populations are initially less susceptible to Bt corn plants (Meihls et al. 2008). The refuge strategy is therefore less effective at delaying resistance development in the case of WCR. WCR has a history of evolving resistance and adapting to a wide range of management strategies including insecticides (Souza et al. 2021), traits (Gassmann et al. 2011), and rotation to non-host crops (Levine et al. 2002). An IPM program that combines multiple strategies and reduces selection pressure is recommended to extend the effectiveness of these management tactics.

Site-Specific Management

Crop management inputs commonly applied to corn and soybean fields in Nebraska include fertilizers, seeds, pesticides, and irrigation water. Optimum applications of these inputs may vary within fields due to differences in soil texture, soil organic matter, soil pH, elevation, topography, and land use history. Site-specific management manages this variability by delineating management zones, selecting appropriate management recommendations within each of these zones, and differential application of inputs in the various zones (Pierce et al. 1994). In contrast, standard or conventional management treats the whole field as a single management zone and applies management equally across variable field conditions.

Management zones are delineated using spatial data and different methods of spatial mapping are used for different applications. Yield mapping can be used for delineating management zones, among other uses (Fulton et al. 2018). Yield data does not identify what is affecting yield but can be overlayed with multiple data layers representing several years' yield data, soil sampling data, or maps of applied inputs. Multiple sets of georeferenced data are layered together for analysis and mapping in GIS software, such as ArcGIS (Fulton et al. 2018).

Aerial imagery is another spatial data layer that can be used to guide variable crop management within fields. The ability to efficiently collect spatial data at multiple times in the growing season is a key advantage for aerial imagery for use in site-specific management. A range of sensors can be mounted to airborne platforms for mapping agricultural fields. Canopy temperature, NDVI, elevation, plant population, and canopy height can be mapped using remote sensing and used to guide crop management. Resolution requirements are important considerations when collecting spatial data. For aerial imagery applications, spatial resolution is simply the size of an image pixel on the target (Campbell and Wynne 2011). Imagery collected from satellite, manned aircraft and UAVs for agriculture typically has spatial resolution of 30 m, 1.5 m and 2-25 cm, respectively. Spatial resolution is an important consideration when delineating management zones from imagery as well as other layers such as yield maps and grid soil sampling.

Temporal resolution is the revisit time for satellites or how often the manned aircraft or UAV flights collect imagery of the field. Multiple visits to a field during the growing season can potentially help explain what factors are limiting yield in different areas of the field. For example, the plant diseases Cercospora leaf blight and Asian soybean rust have been differentiated using their unique, pathogen specific spatial and temporal signatures through remote sensing (Nutter et al. 2010). A pathogen's dispersal and infection mechanisms can produce distinct gradients, shapes, and expansion rates of disease affected areas within crop fields and across large areas (Nutter et al. 2010).

Soil properties can be mapped using grid soil sampling or on-the-go soil mapping. On-the-go soil sensing from Veris Technologies Inc and others maps soil properties at a high resolution by using sensors mounted on a mobile platform and taking continuous measurements while moving across a field (Figure 1.3). Soil electrical conductivity (EC) is measured with on-the-go soil mapping and effectively measures soil texture since the smaller clay particles in the soil conduct more electrical current than larger sand particles (Kweon et al. 2012). Soil cation exchange capacity and water holding capacity is largely determined by the soil texture, clay minerals present, and organic matter content. These soil properties and others can be mapped at a high resolution with on-the-go soil mapping to delineate areas of relatively homogenous crop productivity or management zones (Adamchuk 2006).

Figure 1.3. Examples of on-the-go soil mapping platforms from Veris Technologies Inc. (Veris Tech 2021).

Crop management inputs commonly applied in a site-specific manner include fertilizer rates, soil lime rates, seeding rates, crop varieties, irrigation applications, and pesticide applications (Doerge 2019). Soil pH and lime recommendations can vary across a field. Site specific management applies lime variably to areas of the field that vary in liming recommendations due to soil pH or texture. In this way SSM identifies problem areas of the field and applies lime to increase their productivity.

Another approach to SSM is to identify low, medium, and high productivity field areas and manage these areas according to their yield potential. Nitrogen fertilizer may be variably applied according to yield potential of field areas. Managing field variability can increase yields and profits by redistributing inputs to management zones according to their need (Shannon et al. 2018). Variable rate precision equipment can be outfitted with multispectral sensors. This allows the application equipment to detect crop nitrogen deficiency and respond in real-time while applying nitrogen to the field (*Project SENSE** 2021).

Soil applied herbicides are used to control weeds pre-emergence. Herbicides adsorb to soil particles and the availability of the herbicide in the soil depends on soil organic matter and texture, two properties that can vary across a field. Variable rate soil applied herbicide applications have the potential to improve the efficacy of herbicides in fields with varying soils (Gundy et al. 2017).

Precision agriculture technologies such as GPS guidance, variable rate application equipment, and others improve efficiency of SSM. Although they require additional investment and knowledge, some precision agriculture technologies are becoming widely adopted. Much of the equipment required for SSM is already available or widely used. A 2020 survey showed that 86% of US agriculture retailors provided their customers with GIS field mapping and 89% offered variable rate fertilizer application (Erickson and Lowenberg-DeBoer 2020). Perceived expense, time, and complexity of new technologies are possible barriers for SSM (Lambert et al. 2015).

Conclusion

Integrated pest management and SSM are both crop management strategies that share the goals of positive economic, social, and environmental outcomes. A limitation to these complex strategies is the higher requisite knowledge and skill level needed to successfully implement IPM and SSM practices. However, SSM and agricultural technology can improve IPM especially when precision application of inputs can reduce selection pressure on pest populations, benefit the environment, improve efficacy, or save costs of inputs. Site-specific pest management may be appropriate in cases where pests, or environments vary spatially, and recommended management practices can be applied with precision. This doctoral document evaluates opportunities for site-specific pest management to be applied in Nebraska corn and soybean production systems.

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CHAPTER 2

SITE-SPECIFIC PEST MANAGEMENT

Introduction

Site-specific management (SSM) is the practice of applying inputs variably within fields according to needs. This contrasts with whole field management, which applies one application rate across the whole field. Site-specific management divides fields into multiple management zones that are managed as distinct areas with the goals of increased economic and environmental benefits. Integrated pest management (IPM) is a system for selecting pest management tactics that considers economic, environmental, and social factors and integrating this strategy into the crop production system. Goals for IPM include economic management of pests, reducing risk of crop loss, reducing selection pressure on pest populations, and maintaining environmental quality (Norris et al. 2003).

Site-specific management and IPM share common goals and are compatible in practice. SSM may enhance IPM strategies because pest populations and agricultural environments vary spatially. Advantages to a site-specific approach to IPM include economic and environmental benefits, and resistance management for some IPM tactics. Applying pesticides only when and where needed saves input costs and decreases the impact on the environment. Applying preemergence pesticides variably as soil types change in a field provides economic and environmental benefits by applying less while maintaining acceptable pest control. Untreated areas of a field act as refuges for susceptible populations of pests, enhancing resistance management. Potential drawbacks to site-specific pest management (SSPM) include the cost of sampling and technology required to accurately map pest populations in a field and apply inputs with precision.

Growers' risk perception of leaving areas of a field untreated can also be a limiting factor in adoption of SSPM.

Pest Spatial Distributions

For site-specific pest management, pest populations need to be aggregated at the field scale (Park et al. 2007). Many significant pests of corn and soybeans in Nebraska have a spatial distribution that is aggregated at the field scale. Table 2.1 lists several of these pests, their field scale spatial distribution, and management recommendations. For some of these pests, field studies have found relationships between known field characteristics and pest "hot spots" in the fields (Avendaño et al. 2004). Other studies have used scouting or remote sensing to map pest distributions in a field (Mfuka et al. 2020). Aggregated pests are more easily managed by SSPM if they are stable over time and predictable. Therefore, understanding the movement of pests is critical for implementing SSPM. Insects in the egg and larvae stages, soil borne pathogens, and weeds often occur in predictable patches in fields.

Profitability

The profitability of a SSM strategy depends on the value of the crop and the cost of the input being applied variably (Table 2.2). Applying more expensive inputs in a site-specific manner are more likely to provide economic benefits than less expensive ones. Higher value crops are more likely to profit from SSM than lower value ones because yield gains in high value crops such as sugarbeet result in a higher net return than yield gains in lower value crops such as wheat (Swinton and Lowenberg-DeBoer 1998). More recently SSM for fertilizer application has seen widespread adoption. Profitability of variable rate pesticide application is estimated to be lower than variable rate fertilizer. It

Table 2.1. Spatial distribution and management of pests of corn and soybeans.

Pest	**Spatially aggregated at field scale?**	**Notes**	**Recommended Management Practices**
		Arthropods	
Corn Rootworm	Yes	Corn Phenology (Park and Tollefson 2005), mortality factors of eggs and larvae (Macdonald and Ellis 1990, Ellsbury et al. 1998, Ellsbury and Lee Jr 2004) correspond to larval damage.	Crop rotation, host plant resistance, insecticides for root protection, insecticides for control of adults (Drees et al. 1999, Hodgson and Gassmann 2015)
Western Bean Cutworm	No	Egg masses are randomly dispersed in corn fields (Moraes 2012).	Host plant resistance, insecticides targeting larvae (Peterson et al. 2018)
Bean Leaf Beetle	Yes	Overwintering populations are randomly distributed, and 1st and 2nd generations are aggregated (Park and Krell 2005).	Insecticides targeting adults (Hodgson et al. 2017)
		Diseases	
Soybean Cyst Nematode	Yes	SCN eggs have an aggregated distribution in soybean fields (Avendano et al. 2003). Correlated to soil texture in fields with high soil variability (Avendaño et al. 2004).	Host plant resistance, crop rotation, soil applied nematicide, seed treatments (Davis and Tylka 2021)
Sudden Death Syndrome	Yes	SDS is positively related to soil pH, bulk density and moisture content at field capacity, inversely related to available K and macro-porosity in soybean fields (Chong et al. 2005)	Host plant resistance, seed treatments, avoid planting into wet, compacted soil (Adee et al. 2020)
White Mold	Yes	Soybean yield loss due to white mold is correlated to NDVI and is not randomly distributed in fields (Mfuka et al. 2020)	Host plant resistance, cultural practices, fungicides (Mueller et al. 2015)
		Weeds	
Common Ragweed	Yes	60% of sampling points lacked Common ragweed (Clay et al. 1999)	Herbicides, tillage, cultural practices (Knezevic et al. 2021)
Canada Thistle	Yes	80% of sampling areas lacked Canada thistle (Clay et al. 1999)	Herbicides, tillage, cultural practices (Knezevic et al. 2021)
Redroot Pigweed	Yes	Found in less than 10% of sampling areas (Clay et al. 1999)	Herbicides, tillage, cultural practices (Knezevic et al. 2021)
Setaria spp.	Yes	About 70% of grid points lacked Setaria spp. (Clay et al. 1999)	Herbicides, tillage, cultural practices (Knezevic et al. 2021)

is estimated that 71% of variable rate fertilizer applications are profitable, while 18% of variable rate pesticide applications are estimated to make a profit (Erickson and Lowenberg-DeBoer 2020).

Table 2.2. Profitability summary for site-specific nutrient management studies from Swinton and Lowenberg-DeBoer (1998).

Study	**Crop**	**Inputs Managed**	**Grid Cell Area (acres)**	**Proportion of site years where SSM more profitable than whole field**	**Treatment of annual sampling (S) and VRA costs**
(Anonymous 1996)	Sugarbeet	N	2.75	100% (2/2)	S and VRA cost of $22/acre included
(Carr et al. 1991)	Wheat, Barley	NPK	3	20% (1/5)	S and VRA cost of $4/acre added
(Fiez et al. 1994)	Wheat	N	3	0% (0/4)	S and VRA cost of $4/acre added
(Lowenberg-Deboer and Aghib 1997, unpublished)	Corn	PK	3	42% (5/12)	S, VRA and data mgmt cost of $9.85/acre included
(Schnitkey et al. 1996)	Corn, Soybean	PK	2.5	83% (15/18)	S and VRA cost of $4/acre included
(Snyder et al. 1996)	Corn (irrigated)	N	0.75	50% (2/4)	S, VRA and data mgmt cost of $17.31/acre included
(Wibawa et al. 1993)	Wheat, Barley	NP	3	0% (0/2)	VRA cost of $3/acre substitutes for $1/acre
(Wollenhaupt and Buchholz 1993)	Corn	PK	2.5	50% (1/2)	S and VRA cost of $3.30/acre included
(Wollenhaupt and Wolkowski, 1994, unpublished)	Corn	PK	2.1	100% (5/5)	VRA cost of $3/acre substitutes for $1.44/acre

Cost of sampling is a major factor in the profitability of SSPM programs. Information obtained from sampling has value only when it affects decisions that are made (Swinton and Lowenberg-DeBoer 1998). The cost of some types of information (e.g., yield maps and soil characteristics) may be allocated across several years. In contrast, other information (e.g., insect counts) may be most useful for short term decision making. Therefore, identifying information about field attributes that is useful for multiple years and correlates to pest distribution can reduce sampling costs for SSPM (Park et al. 2007).

An important impediment to implementation of SSPM is the perception of risk among farmers transitioning from whole field pest management to SSPM. The level of real risk needs to be acceptable for crop production, but perceived risk can be reduced by improvements in technology and information. Sampling strategies need to have the accuracy to identify all areas of the field with pest populations that can cause economic damage. An alternative strategy to evaluate the potential of SSPM programs and minimize risk is to apply one management tactic across an entire field and apply another tactic in a site-specific manner. Evans et al. (2002) suggests this method be used to manage potato cyst nematode (PCN) because a 20 m grid sampling plan failed to detect smaller sized PCN problem areas in the field. In this way, no field areas are left completely untreated, but large pest “hot spots” are treated with a second input.

Arthropod Management. Some arthropod pests require multiple applications of pesticide each season, increasing the input costs for management. Colorado potato beetle, *Leptinotarsa decemlineata*, (CPB) is a major pest in potato crops. Potato growers in the northeast USA make up to 11 applications of insecticides to control this pest

(Wright et al. 1987). Weisz et al. (1996) compared whole field IPM to site-specific IPM for CPB and other insect pests and found a potential insecticide savings of 30% to 40% using site-specific IPM. The study used weekly scouting and thresholds for CPB adults, larvae, and egg masses to delineate management zones within fields and applied insecticides to only areas above threshold levels.

Strategies that make sampling more efficient and less expensive than direct insect counts are likely to increase the profitability of SSPM for arthropods. Corn rootworm, *Diabrotica virgifera*, (CRW) damages corn plants through larval feeding on roots and adult beetles feeding on corn silks. Corn rootworm is distributed variably within fields, and the spatial distribution of CRW eggs and adults corresponds to soil characteristics, root injury, and crop phenology (Ellsbury et al. 1999) (Table 2.1). A sampling program for use in SSPM of CRW that relies on information about soil characteristics would be less costly than direct counts of insects, due to time required for direct counts and because information about soil characteristics can be used for multiple years.

Disease Management. The value of variably applied inputs is an important driver of SSM profitability. Nematicides for control of potato cyst nematode, *Globodera pallida*, (PCN) are an expensive input with potential for variable rate application in potato crops in the UK. Evans et al.(2002) found that although input cost savings provided by SSPM of PCN more than paid for grid sampling at a density of 20 m, sampling at this density left occasional patches of untreated nematode affected areas that presented a challenge to the long-term management of PCN. Therefore, it was proposed that more expensive fumigant nematicides be applied in a site-specific application and a granular nematicide be applied to the entire field at planting time.

In some cases, remote sensing can be used for efficient sampling and mapping of plant disease issues. Mfuka et al. (2020) used Landsat 8 and MODIS satellite images to map estimated soybean yield loss due to white mold (table 2.1). Using readily available satellite imagery can take the place of more expensive sampling techniques to make SSPM more profitable.

Weed Management. Some management recommendations e.g., herbicide label rates, may vary based on field conditions like weed size, soil organic matter content, or soil texture. Of these, soil organic matter and texture are relatively stable over years. A study in Kansas grain sorghum fields by Gundy and Dille (2021) used the Veris MSP3 soil mapping system that measures soil EC, organic matter and pH to build variable rate soil applied herbicide prescription maps. The maps were based on soil texture estimated from EC, and soil organic matter. Since these properties are relatively stable over time, the maps are useful for multiple years, reducing cost of sampling. This study and others (Koller and Lanini 2005, Mohammadzamani et al. 2009) show SSPM for preemergence herbicide can save between 10% and 39% of herbicide use while maintaining acceptable weed control.

Environmental benefits

Site-specific pest mangement may be a partial solution to the need to produce high yielding crops while protecting the environment. Pesticides can contaminate surface water and groundwater and affect non target organisms. Without the use of chemical pesticides however, crop production worldwide would be drastically reduced due to lower yields (Avery 1995). Site-specific pest management avoids the use of pesticides where not necessary to protect the environment from pesticide pollution while maintaining high yields.

Arthropod Management. Biological control is an important management strategy for mites in corn. Spider mite populations in corn are regularly held in check below thresholds by natural enemies such as predatory mites, green lacewing larvae, minute pirate bugs, thrips, and lady beetles (Peairs 2014). Insecticides applied to control pests are a cause of mite outbreaks because of the insecticides' effect on the natural enemies that hold mite populations in check. Reducing insecticide treated area in fields by using SSPM has potential to conserve these beneficial species and reduce the need to treat fields with miticides.

Disease Management. The difficulty of controlling the potato cyst nematode (PCN) in potato crops has led to an increase in the use of nematicides. The difficulty in controlling PCN combined with low economic thresholds has led to applications of two types of nematicides, fumigant and granular for control of this pest. Evans et al. (2002) found that the cost of grid sampling for nematodes would be recovered if sampling led to decisions to not treat 42% of the field with a granular, 27% with a fumigant, or 16% with both granular and fumigant nematicides. The economic reasons for adopting SSPM for PCN are also supported by the environmental benefits from reductions in pesticide use for potato production.

Southern root knot nematode, *Meloidogyne incognita*, is a major pest in cotton in the USA. Fumigant nematicides provide the most consistent yield response to application. However, they are highly toxic to non-target organisms and cause environmental harm. Overstreet et al. (2014) used soil EC readings to delineate nematode management zones in cotton fields. Using zone management in cotton fields in Arkansas, they reduced 1,3-dichloropropene nematicide application by 36% to 42% when compared to whole field management.

Weed Management. Applying residual herbicides variably according to soil characteristics may provide environmental benefits. Soil applied herbicides provide residual weed control after application because of their persistence in soils. For this reason, they pose a risk of environmental contamination or herbicide carryover to following non-tolerant rotational crops. Soil characteristics and weather conditions play a role in determining herbicide persistence in soils and contamination of ground and surface water (Helling 2005). Applying variable rates of residual herbicides as soil characteristics change in a field can lessen these risks.

Resistance Management

Insect Management. Resistance management strategies that reduce selection pressure on a population through reduced pesticide use and conserving susceptible pest populations are more likely than pesticide mixtures to be successful in delaying the development of resistance (Tabashnik 1989). Site-specific pest management has the potential to conserve susceptible populations of pests in areas of a field where pest population levels have not reached economic thresholds.

A study by Fleischer et al. (1997) compared the susceptibility of CPB populations in fields managed by whole field IPM with those managed by site-specific IPM approaches. Beetle populations collected at the season end from fields that received whole field treatments of esfenvalerate insecticide had increased resistance to esfenvalerate than beetles collected prior to insecticide application. In site-specific IPM fields, beetles collected from field areas that received higher numbers of insecticide applications were more resistant than beetles collected from areas with fewer applications. Resistance to esfenvalerate did not increase in areas with fewer applications (Fleischer et al. 1997). With some movement between populations in the same field, there is potential for site-specific IPM to delay resistance development through acting as a refuge for susceptible pests.

Disease Management. Fungicides are often applied to healthy plants as a preventative tactic prior to disease development. Site-specific pest management may have less value as a resistance management strategy for some pathogens because of the preventative use pattern of many fungicides and nematicides. This contrasts with insecticides and post applied herbicides which are applied to crops when insects and weeds are already present (Damicone 2014). Site-specific pest management may be useful for management of fungal diseases that occur predictably in patches within a field, but not for many fungal diseases that occur in uniform, random, or in aggregated patterns that are not stable over time. Soil borne diseases such as soybean white mold and soybean cyst nematode occur in stable aggregations and are better suited to SSPM.

Weed Management. Although many weed species are spatially aggregated at the field scale, SSPM for post emergence control may not be a reliable resistance management strategy for some weed species. Palmer amaranth, *Amaranthus palmeri*, is a weed pest that has developed resistance to multiple herbicides (Heap 2021). A study conducted in cotton fields determined the consequences of a single uncontrolled glyphosate resistant Palmer amaranth plant (Norsworthy et al. 2014). Within three years Palmer amaranth infested 95 to 100% of all fields in the study resulting in complete crop loss. Consequently, the authors recommended a zero threshold strategy for managing the spread of glyphosate resistant Palmer amaranth. Therefore, in some fields, leaving areas untreated without post emergence herbicide is not recommended for resistance management as a single plant left untreated can have a devastating effect on crop yields years later.

Variable rate soil-applied preemergence herbicides may be used as a resistance management strategy for fields with variable soils. Using less than the recommended rate of herbicides reduces efficacy and contributes to the development of resistant weed populations by exposing weeds to less than lethal rates (Beckie 2006). Soil applied herbicide activity is affected by soil organic matter, soil texture, soil pH, and soil water content, properties that may vary across fields (Blackshaw et al. 2011). In fields with variable soils, applying preemergence herbicides variably according to soil characteristics ensures that the recommended rate for each soil type is applied.

Conclusion

Site-specific management may enhance IPM when in-field spatial distributions of pests are aggregated and stable over time. Reasons for adopting SSPM include economic benefits, environmental benefits, and resistance management for some pests. The profitability of SSPM likely varies for each field or location, and it depends on the value of the crop, value of the variably applied input, the cost of sampling, and the cost of variable rate application. Site-specific pest management is well suited for pests that vary spatially in predictable patches that are stable over time. Site-specific pest management may benefit the environment through applying less pesticides and at the same time maintain high yields through applying pesticides only where and when necessary. Site-specific pest management shows the most potential for resistance management of arthropod pests, and additional study is needed to determine the value of SSPM as a resistance management strategy for disease and weed pests.

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CHAPTER 3

POTENTIAL FOR SITE-SPECIFIC PEST MANAGEMENT IN NEBRASKA CORN AND SOYBEAN SYSTEMS

Introduction

Site-specific management (SSM) is the practice of applying inputs variably within fields according to needs. This contrasts with whole field management, which applies one application rate to the whole field. Site-specific management divides fields into multiple management zones that are treated as distinct areas with the goals of increased economic and environmental benefits.

Integrated pest management (IPM) is a system for selecting pest management tactics that considers economic, environmental, and social factors and integrating this strategy into the crop production system. Goals for IPM include economic management of pests, reducing risk of crop loss, reducing selection pressure on pest populations, and maintaining environmental quality (Norris et al. 2003).

Reasons for adopting SSPM include economic benefits, environmental benefits, and resistance management for some pests. The profitability of SSPM is site-specific, and depends on the value of the crop, value of the variably applied input, the cost of sampling, and the cost of variable rate application. Site-specific pest management may benefit the environment through applying less pesticides, and at the same time, maintain high yields through applying pesticides only where and when necessary.

Currently, SSPM practices are being adopted less than other SSM practices such as variable rate fertilizer application. In 2020, 89% of agriculture retailers offered variable rate fertilizer services to farm producers. Only 27% of agriculture retailers offered variable rate pesticide applications (Erickson and Lowenberg-DeBoer 2020).

SSM may enhance IPM when the spatial distribution of pests is aggregated and stable over time. Corn rootworm (CRW) and soybean cyst nematode (SCN) have aggregated spatial distributions and cause significant damage to crops in Nebraska (Ellsbury et al. 1999, Avendano et al. 2003). In fields with variable soils, preemergence herbicide rates vary based on soil characteristics (Gundy and Dille 2021). This chapter examines three case studies to determine their potential for using SSPM in Nebraska corn and soybean production systems.

Corn and Soybean Production

In 2021, crop producers in the USA planted 93.4 million acres and harvested 85.4 million acres of corn. The average corn yield in 2021 was 177 bu/acre (Figure 3.1). In Nebraska, crop producers planted 9.9 million acres of corn and had an average yield of 194 bushels per acre in 2021. Farmers planted 87.2 million acres of soybeans in the USA and 5.6 million acres in Nebraska in 2021. Yields averaged 52.1 bu/acre and 63 bu/acre in the US and Nebraska, respectively in 2021 (USDA 2022).

Annual rainfall in Nebraska ranges from less than 16 inches per year in the western part of the state to 34 inches per year in the southeast. Corn and Soybeans are grown under either irrigated or non-irrigated field environments. Typical crop rotations for the area include continuous corn, corn-corn-soybean, and corn-soybean.

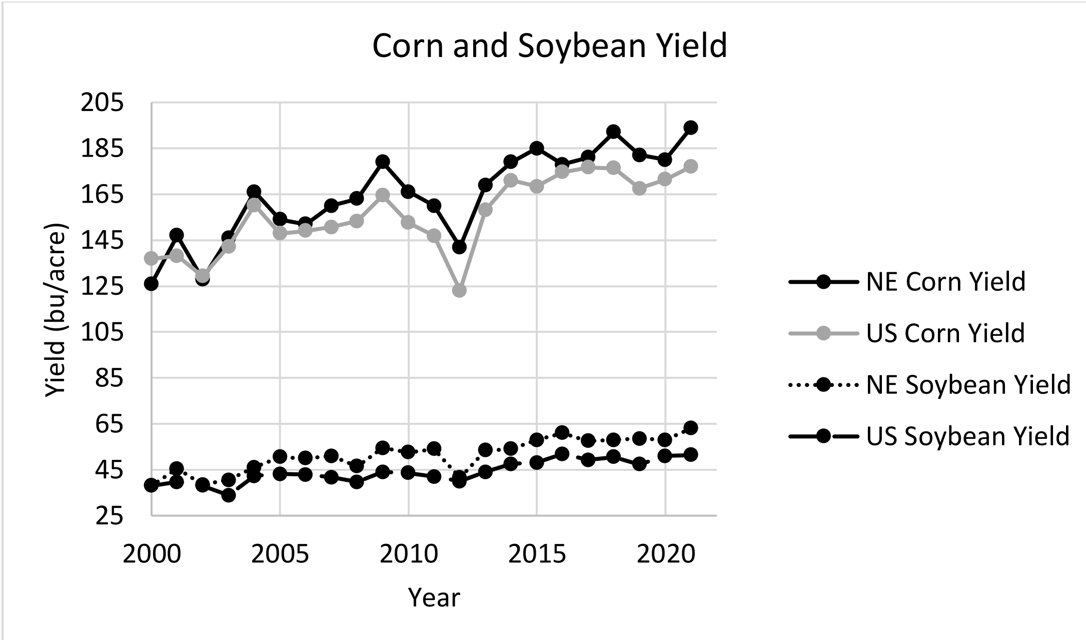

Figure 3.1. Corn and soybean yield for the US and Nebraska 2000 through 2021.

Corn Rootworm Case Study

Western corn rootworm, *Diabrotica virgifera virgifera*, is one of the most economically significant insect pest of corn in the USA (Drees et al. 1999). Western corn rootworm is closely associated with corn as both a larval and adult host plant; therefore it is primarily a pest in continuous corn fields.

Damage. Larvae cause damage to corn by feeding on roots. Larval feeding affects corn plants' ability to take up water and nutrients from the soil and may impact grain yield. If damage is severe, three root nodes may be completely pruned from the stalk, predisposing the corn plant to lodging in high winds. Adult WCR cause damage to corn plants through feeding on silks, interfering with pollination (Drees et al. 1999).

Life Cycle. Western corn rootworm is a univoltine pest. Eggs are oviposited in the soil of cornfields in July, August, and September. Western corn rootworm overwinters in the egg stage and egg eclosion occurs in late May and early June. Larval development rates are dependent on temperature (Meinke et al. 2009). Adults emerge from the soil in late June and July when they feed, mate, and oviposit eggs in corn fields.

Management. Management tactics for WCR include crop rotation, host plant resistance, insecticides for root protection, and insecticides for adult control. Although some grassy weed species are alternate hosts, both WCR larvae and adults are closely associated with corn as a host plant. When a field is planted to a non-host crop such as soybean, larvae starve without a host plant to feed on (Drees et al. 1999).

Transgenic corn hybrids expressing the *Bacillus thuringiensis* toxin for CRW have been developed and available to growers since 2003 (Difonzo 2021). Since that time, CRW populations have developed resistance to some Bt events incorporated into corn hybrids in some locations. Strategies to delay the development of resistance include rotating out of corn at least every four to five years, planting Bt hybrids pyramided with multiple traits targeting corn rootworm, and rotating between Bt hybrids and non-Bt hybrids with soil insecticides (Hodgson and Gassmann 2015).

Soil insecticides are applied in a band over the row or directly into the furrow at planting time and provide a zone of protection surrounding the main roots of the plant. Corn rootworm larvae can feed on and complete development on roots outside the insecticide treated zone and up to 50% of CRW populations in fields treated with a soil insecticide may survive and emerge as adults (Drees et al. 1999). Insecticides for controlling adult WCR beetles are applied to prevent egg laying and subsequent problems the following season, or to prevent silk feeding during the pollination period.

Evaluation. Although SSPM for CRW is not commonly practiced, CRW larvae vary spatially across fields. Ellsbury et al. (1999) found correspondence of spatial distributions of CRW egg and adults with measured soil characteristics, root injury, and crop phenology. The field in their study had 16 m of topographic relief and soils that varied from fine silty, fine loamy, and fine montmorillonitic soil types. While CRW larvae spatial distributions can vary from one year to the next, this study demonstrates the potential to produce CRW prediction maps for management. Further research is needed to compare the crop injury and profitability of whole field management with SSPM for CRW. Technology is currently available to prescriptively apply soil insecticide with an electronic metering system ("SmartBox" 2022). Multiple hybrid planters that switch between two corn hybrids as the planter moves across a field are also available ("vSet Select" 2022).

Resistance management for CRW can be improved by SSPM. In areas of the field with fewer CRW larvae where inputs are not applied, the larvae that are present will not be exposed to soil insecticide or Bt toxins. In this way, SSPM has the potential to conserve CRW populations that are susceptible to pest management tactics. Corn rootworm refuges are required when planting Bt corn hybrids and SSPM can further enhance this resistance management strategy.

The economics of applying soil insecticides or planting a Bt hybrid vary widely. In 2020, a grower could expect to pay an estimated $12.00 to $49.00 per acre for granular soil insecticide to manage CRW, depending on the product selected (Wright et al. 2021). Estimated price for transgenic rootworm protection with multiple Bt toxins that target CRW range from $25.00 to $45.00 per bag of seed. At a planting population of 34,000 seeds per acre costs of transgenic rootworm protection is estimated at $10 to $20 per acre. The profitability of SSPM depends on what proportion of the field is left untreated as well as the total cost of inputs to be applied variably (Figure 3.2). One strategy would be to plant a Bt hybrid to the whole field and variably apply soil insecticide. This would prevent field areas that did not receive any treatment. Another strategy is to variably apply both Bt hybrid and soil insecticide together to maximize any saving from untreated areas.

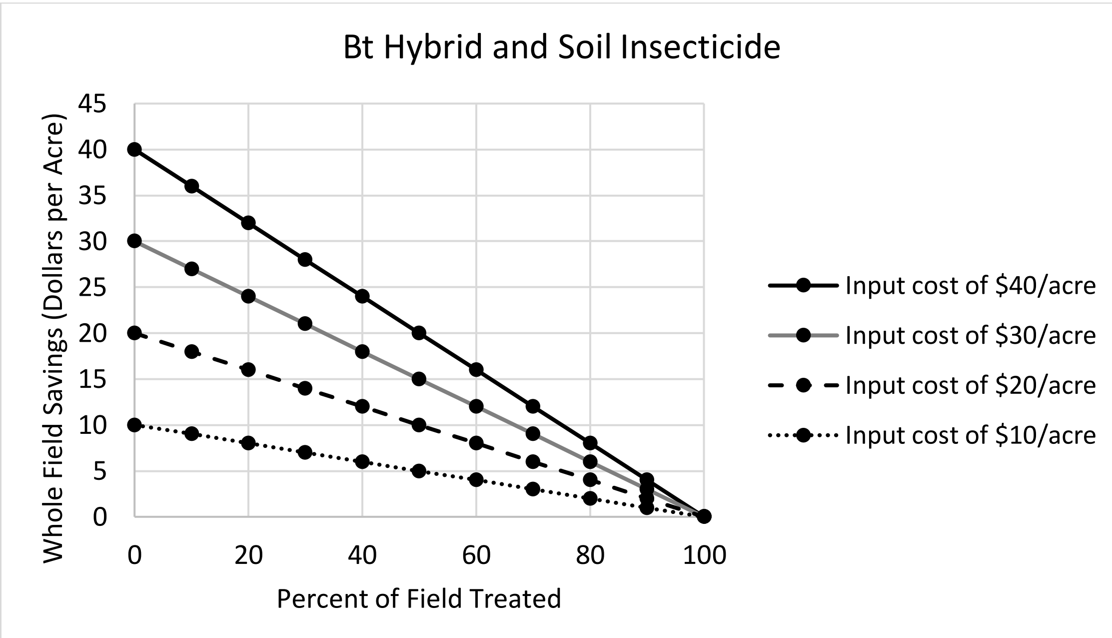

Figure 3.2. Savings from using SSPM for CRW depends on the cost of input and the percent area of the field to be treated.

In conclusion, SSPM is not commonly practiced for management of CRW likely because spatial patterns may vary each year. However, there is potential for CRW larvae populations to be mapped using soil and crop canopy characteristics. Research is needed that compares whole field management with SSPM of CRW. The expense of planting a Bt hybrid and applying a soil insecticide together shows potential economic benefits for

SSPM over whole field management. Given that equipment required to prescriptively apply these inputs is readily available and the potential for improved resistance management, more study should be directed toward SSPM for CRW.

Soil Applied Herbicide Case Study

Preemergence herbicides are applied to the soil prior to weed emergence and provide residual control of weeds before they emerge. Normally, these herbicides are used as a whole field management tactic where the same rate is applied across the field. However, the rate of preemergence herbicides depends on soil characteristics that may vary within a single field.

Environment. Soil-applied herbicide activity is affected by soil organic matter, soil texture, soil pH, and soil water content (Blackshaw et al. 2011). Soil applied herbicides provide residual weed control after application because of their persistence in soils. For this reason, they pose a risk of environmental contamination or herbicide carryover to the following non-tolerant rotational crops. Soil characteristics and weather conditions play a role in determining herbicide persistence in soils and contamination of ground and surface water (Helling 2005). Applying variable rates of residual herbicides as soil characteristics change in a field can lessen these risks.

Resistance Management. Variable rate soil-applied preemergence herbicides may benefit resistance management in fields with variable soils. Using less than the recommended rate of herbicide reduces efficacy and contributes to the development of resistant weed populations by exposing weeds to less than lethal rates (Beckie 2006). In fields with variable soil texture and soil organic matter, applying preemergence herbicides variably according to soil characteristics ensures that the recommended rate is applied for each soil type.

Evaluation. Soil-applied herbicide label rates vary based on field conditions like soil organic matter content, or soil texture (Table 3.1, Table 3.2). A study in Kansas grain sorghum fields (Gundy and Dille 2021) used a Veris MSP3 soil mapping system that measures soil EC, organic matter and pH to build variable rate soil-applied herbicide prescription maps. The maps were based on soil texture estimated from soil EC, and soil organic matter content. Field locations in the study varied by more than 1.5% in soil organic matter and had multiple soil texture classes. They showed that in these fields with variable soils, variable rate application saved between 10% and 30% of herbicide applied while maintaining acceptable weed control. Another study by (Mohammadzamani et al. 2009) determined that variable rate application can decrease the amount of preemergence herbicide applied by up to 13% compared to a uniform rate. They employed soil sampling to obtain information about the variability of soil organic matter and soil texture in the field. Koller and Lanini (2005) used weed maps from previous years to guide variable rate preemergence herbicide applications and reduced herbicide use by 24% to 39% while maintaining acceptable weed control. These studies show SSPM for preemergence herbicide can save between 10% and 39% of herbicide use while maintaining acceptable weed control.

Rate control equipment for variable rate herbicide applications is readily available. Injection metering systems, pulse width modulation control, and variable orifice nozzles provide the capability to apply herbicides at variable rates by spray boom sections or by each individual spray nozzle. Sökefeld (2010) provides a brief review of variable rate sprayer technologies.

Table 3.1. Application rates and cost estimates for select herbicides (Knezevic et al. 2021).

Herbicide	Crop	Low Rate	High Rate	Units	% Change	Varies By SOM or Texture?	Cost Estimate ($/acre)
Acuron	Corn	2.5	3	qt/acre	16.67%	SOM	$40-$45
Resicore	Corn	2.25	3	qt/acre	25.00%	SOM/Tex	$18-$25
Zidua	Corn/Soybean	1.5	2.5	oz/acre	40.00%	Texture	$12.75-$34
Authority XL	Soybean	5	9.6	oz/acre	47.92%	SOM/Tex	$15-$32

Table 3.2. Application rate table from Authority XL label.

Soil Texture	Organic Matter	
	0.5 - 2%	2 - 4%
	Ounces Product Per Acre	
Coarse: Loamy Sand, Sandy Loam	5.0 - 6.0	6.0 - 7.0
Medium: Loam, Silt Loam, Sandy Clay Loam	6.5 - 7.5	7.0 - 8.0
Fine: Silty Clay Loam, Clay Loam, Clay	7.0 - 8.0	8.0 - 9.6

In conclusion, soil-applied herbicides are well suited for variable rate application. Maps of soil texture and soil organic matter content can be used for several years' variable rate applications. In fields with variable soils, variably applying preemergence herbicides ensures that the proper rate is applied as soils change in the field. This is a worthwhile pest management strategy because of environmental impacts, resistance management, and economic savings.

Soybean Cyst Nematode Case Study

Soybean cyst nematode (SCN), *Heterodera glycines*, causes more damage to soybean yields than any other soybean pathogen. Since its introduction into the USA in

1954, SCN has become widespread throughout soybean growing regions (Niblack and Riggs 2015).

Damage. Soybean cyst nematode feeding on soybean roots causes patches of low yielding, stunted, and dead plants. Soybean cyst nematode can cause yield losses of 10%-30% in fields without visible above ground symptoms. Therefore, SCN damage often goes unnoticed or is misdiagnosed as abiotic stress.

Life Cycle. Soybean cyst nematode has six life stages including eggs, four juvenile stages, and the adult stage. The first juvenile stage molts inside the egg and the second juvenile stage emerges from the egg. The mobile second juvenile stage nematode then penetrates and enters the root to form a feeding site. After feeding begins, the nematode is no longer mobile and undergoes three more molts to reach the adult stage. As adults, the female nematodes produce 200 to 500 eggs that are able to stay viable for 10 years. The life cycle takes as little as three to four weeks under optimum conditions (Davis and Tylka 2021).

Management. Management tactics for SCN include host plant resistance, crop rotation, cultural practices, soil nematicides, and seed treatment nematicides. Management of SCN should focus on improving soybean yields, reducing infestation levels, and preserving the yield potential of resistant varieties.

Planting SCN resistant varieties is an important management strategy for SCN. Nematode reproduction on resistant varieties is less than 10% compared to SCN susceptible varieties (Davis and Tylka 2021). While there are seven soybean lines resistance to SCN, the most common source of resistance in soybean varieties today is PI

88788. A greater emphasis on rotating sources of SCN resistance is needed to preserve the utility of resistant varieties into the future.

Crop rotation to a non-host crop is the most effective management strategy because SCN is not able to reproduce in the absence of living host plants. SCN can also cause yield loss to some alternate hosts in the genus *Phaseolus*. While rotation to non-host crops can avoid the buildup of SCN populations, it is difficult to completely eradicate SCN since SCN eggs can remain viable in a dormant state for up to 10 years (Davis and Tylka 2021). A good strategy is to incorporate SCN resistant varieties into a crop rotation of several years.

Soil nematicides are applied at planting time and provide long enough protection to show yield increases. This tactic will not eradicate SCN from the soil and is not a long-term population management strategy. They are expensive, highly toxic to off-target organisms, and have labeling issues depending on the location (Niblack and Riggs 2015).

There are many commercially available chemical or biological seed treatments for management of SCN (Bartels et al. 2021). Although they do not provide season long protection, seed treatments for SCN provide protection long enough after planting to result in a yield increase at harvest.

Evaluation. Although SSPM is not commonly used for management of SCN, mapping field areas that are at high risk for SCN based on soil texture is a potential option for SSPM. Soybean cyst nematode reproduction is related to many factors including soil texture, soil moisture content, and host plant factors. Avendaño et al. (2004) proposed that SCN can only sustain high populations levels in soils with more than 60% sand, less than 20% silt, and less than 20% clay. Therefore, soil texture must have a regulating effect on SCN populations in soybean fields. Visible, above ground symptoms should not be used to delineate management zones for SCN because significant yield loss from SCN may occur even if no above ground symptoms are visible (Tylka et al. 1998).

Technology to prescriptively apply seed treatments and soil nematicides is commercially available to soybean producers. Soil applied nematicides can be applied variably in the furrow at planting ("SIMPAS" 2022). A multi-variety planter can be used to switch between nematicide treated seed and non-treated seed as the planter moves through the field ("mSet" 2022).

The potential profitability of SSPM for SCN is modest due to the relatively low cost of nematicide seed treatments when compared to costs of other inputs. Soybean farmers can expect to pay around $6 to $15 per bag of seed for nematicide seed treatments. A bag of soybean seed contains about 140,000 seeds. If planting at 120,000 seeds per acre, the cost of nematicide seed treatments range from $5 to $13 per acre.

In conclusion, there is potential for mapping SCN risk in fields by soil texture for use in SSPM. While SCN causes significant yield loss, inputs such as seed treatments are relatively modest in price, offering little potential for savings using SSPM. The best management strategy for SCN avoids buildup of SCN populations by rotation to non-host crops and planting SCN resistant varieties. Site specific pest management for SCN may be appropriate when incorporated into an IPM strategy that uses crop rotation and resistant varieties.

Conclusion

Site-specific pest management offers the most potential profit when input costs are higher, and sampling is efficient and inexpensive. Soil-applied herbicides are among the more expensive inputs considered here and their rate may vary more than 40% across different soil characteristics. Several studies have demonstrated herbicide savings between 10% and 39% in variable fields using variable rate herbicide applications. Input costs for management of CRW vary widely but can be expensive when planting a Bt hybrid and applying a soil insecticide together. Field areas at high risk for CRW will need to be mapped each year since this pest varies spatially each year. While SCN causes significant yield loss to soybeans each year, management strategies such as nematicide seed treatments and resistant varieties are relatively inexpensive and there is potential only for modest savings from using SSPM for SCN. Since the best management strategies for SCN involve crop rotation and SCN resistant varieties, SSPM for SCN should be incorporated into an IPM plan that includes these strategies.

Site-specific pest management is adopted at a lower rate than other SSM practices, such as variable rate fertilizer. Here we evaluate the potential of SSPM in Nebraska corn and soybean production systems using case studies where pests or environments vary spatially within fields. For SSPM to reach its potential, more research is needed that maps pest populations, prescriptively applies inputs, and compares the profitability and crop injury of SSPM with whole field management.

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