Hindawi
International Journal of Agronomy
Volume 2019, Article ID 9390501, 11 pages
https://doi.org/10.1155/2019/9390501

Review Article

Rewarding Best Pest Management Practices via Reduced Crop Insurance Premiums

Hugh J. Beckie[1] **Stuart J. Smyth,**[2] **Micheal D. K. Owen**[3] **and Savannah Gleim**[2]

[1]*Australian Herbicide Resistance Initiative, School of Agriculture and Environment, University of Western Australia, Crawley, WA 6009, Australia*
[2]*Department of Agricultural and Resource Economics, University of Saskatchewan, Saskatoon, SK S7N 0X2, Canada*
[3]*Department of Agronomy, Iowa State University, Ames, IA 50010, USA*

Correspondence should be addressed to Hugh J. Beckie; hugh.beckie@uwa.edu.au

Received 27 July 2018; Accepted 4 December 2018; Published 2 January 2019

Academic Editor: Patrick J. Tranel

Despite decades of research, development, and extension on the mitigation and management of pesticide resistance, the global agricultural situation is becoming increasingly dire. Pest populations with evolved resistance to multiple pesticide sites of action are becoming the norm, with fewer remaining effective xenobiotics for control. We argue that financial incentives and not regulations are needed to encourage farmers or land managers to use best management practices recommended by academia. Although some incentives are offered by pesticide manufacturers or distributors, there is a paucity of incentives by other industry sectors and all levels of government (federal or state/provincial). Crop insurance can be important to facilitate and reward best pest management practices and address other important agricultural policy objectives. Herein, we describe possible changes to crop insurance programs in the United States and Canada through premium rate changes to incentivise clients to adopt best management practices.

1. Incentivising a Change in Behaviour

Incentives have long been used to encourage markets to shift existing practices or to encourage the development of new activities. The standard example is how patents are granted to individuals, companies, and universities engaged in research and development. In return for investing in research and development activities, patent acts in most countries provide the patent holder with up to 20 years of protection on their invention. In agriculture, investment incentives markedly changed in the 1980s when it became possible to patent plants and the processes used to create plants. This change was most noticeable in Canada for canola (*Brassica napus* L.) research and development. In the period from 1950 to 1984, the private sector did not develop and release a single canola variety, yet this figure jumped to 12 from 1985 to 1989, 39 from 1990 to 1994, and 76 from 1995 to 1998 [1]. United States (U.S.) releases of plant cultivars, notably those with traits for pest protection introduced by genetic engineering, have also markedly increased [2].

Farmers commonly adopt new technologies upon witnessing the benefits. Field trials and tours are one way that farmers are able to observe the various agronomic traits or practices that they deem desirable, such as higher yield, less seed pod shattering (canola), drought resistance, or resistance against lodging. When it comes to information on crop choices, farmers rely on personal experience 80% of the time [3]. Personal experience works well when the technologies deliver clearly improved benefits over existing ones. As examples, the adoption of high-clearance sprayers allowed farmers the opportunity to desiccate taller field crops in the fall; transgenic crops allowed farmers to obtain improved weed control [4]. What options exist to incentivise farmers to adopt technologies or practices when the evidence of benefits may be less obvious?

One example is the midge-tolerant wheat (*Triticum aestivum* L.) stewardship program in Western Canada. Infestations of wheat midge (*Sitodiplosis mosellana*) reduce spring wheat yields by an average of 30% at a cost of $30 million annually [5]. Midge-tolerant wheat was commercialized in

2010, coupled with an aggressive outreach program educating farmers about proper use of the technology, principally the recommended rotation interval. It was stressed that there was no alternative option for midge control should the pest evolve resistance. Five years after introduction, midge-tolerant varietal blends had reached 18% of wheat area in Western Canada and one-third in the province of Saskatchewan [6]. Adoption of this technology resulted in a reduced need for scouting and insecticide applications and higher yields, as insecticides were not completely effective against the pest. These tangible benefits provided the incentive for farmers to comply with the stewardship program to mitigate the evolution of pesticide resistance. However, when it comes to ensuring that farmers are adhering to best management practices to mitigate the evolution of chemical resistance in pests such as weeds, what incentives exist?

To better understand how to incentivise a change in behaviour, there is increasing attention focused on the human dimension of the evolution and management of pesticide resistance, specifically the economic and social drivers affecting farmer decisions [7]. Presentations by weed scientists, crop consultants, economists, and rural sociologists addressed interdisciplinary aspects of the herbicide resistance problem and explored different management approaches at the Second Summit on Herbicide Resistance in 2014 in Washington, DC [8]. There was broad consensus that short-term economics is a key driver in the decision-making process of farmers or land managers. The role of government regulations vs. financial incentives in spurring adoption of recommended herbicide resistance mitigation or management practices was an important topic discussed at the summit. As stated by a number of presenters, herbicide resistance management falls within the broader context of integrated weed management, with the goal of using a diverse mix of herbicide, cultural, and mechanical practices to reduce weed population abundance. One idea proposed was a regulatory incentive to enable herbicide registrants to receive an extended data exclusivity period in exchange for not developing one new herbicide in multiple crops grown together in rotation, or for implementing practices such as robust herbicide mixtures or limitations on herbicide application frequency; this proposed incentive would theoretically provide a mechanism to register herbicides in ways that promote their longevity [9]. Approaches based only on product market incentives have unfortunately contributed to and exacerbated the current situation of widespread multiple herbicide resistance in key weeds due to a singular focus on herbicides [9]. Herbicide resistance (integrated weed) management is much more than just herbicide diversity.

If financial incentives by the private sector are not sufficient for effective herbicide resistance management, what about financial incentives by the public sector, e.g., federal or state/provincial government agencies? Government agencies, whether in the U.S. or Canada, have not formulated or implemented policies to address herbicide resistance mitigation or management during the past 50 years, in contrast to insecticide resistance management (e.g., *Bacillus thuringiensis* refuge requirement). Ultimately, all stakeholders—farmers, retailers, agronomists, crop consultants or advisors, government agencies, farm organizations and crop commodity groups, professional societies, scientific community, and the media—must play a role in herbicide resistance management [10].

In this review, we explore public policy options to address pesticide resistance, specifically, how crop insurance could be an important vehicle to reward the adoption of best management practices. Following an overview of the economics of best management practices in crop production, with a focus on crop rotation, we outline the state of herbicide resistance, recommended best management practices, and crop insurance programs in the U.S. and Canada, using case studies from the State of Iowa and Province of Saskatchewan, respectively. Lastly, we propose an adaptation or expansion to an existing actuarial model for premium rate discounts in crop insurance to include the degree of adoption of best pest management practices.

2. The Economics of Best Management Practices

2.1. Focus on Crop Rotation. Crop rotation or crop diversity is widely considered a foundational or primary best management practice. Crop rotations can be a constructive management tool for farmers, but can also be deleterious if the rotations become too short. Crop rotation should sustain profitable crop production. While rotations are intended to provide long-term benefits such as yield stability and soil health, short-term economics can alter a farmer's crop rotation plan and negatively impact their land and future production. In the early 1990s, economic factors such as high interest rates, low commodity prices, and concerns of environmental degradation shifted land and crop production practices. Concomitant advances in technology and machinery, improved seed varieties and agrochemicals, and a growing global market with a broad pallet of agricultural commodity demands led to a reduction in fallow and tillage intensity and increased production of canola, pulse crops such as field pea (*Pisum sativum* L.) and lentil (*Lens culinaris* Medic.), and formerly niche crops in the Northern Great Plains of North America [11].

Farmers have good intentions to follow a sustainable crop rotation plan, yet short-term factors can hinder such plans. Such factors that influence a farmer to diverge from their planned rotation are a result of market conditions (i.e., crop prices), environmental factors (e.g., adverse weather), and capital constraints (i.e., equipment). The most substantial challenge for incentivising rotations is profitability. Presently, canola has generally been the most consistently profitable crop for farmers in Western Canada. It is recommended that canola not be grown more frequently than every third year for agronomic reasons (chiefly disease mitigation) [12], yet there is considerable financial incentive to shorten this rotation. An agronomic incentive would be to increase the yields of cereals and pulses so that they are as profitable as canola; however, this goal is a long-term solution that is well over a decade away.

Within crop insurance, there are currently limits to encourage best management practices. While these practices may have environmental and long-term benefits in dealing with pest management, the short-term nature of crop insurance, being an annual expense, does not typically directly incentivise best management practices. Providing incentives towards best management practices for crop insurance is a means to potentially reduce the occurrence of economic gains swaying agronomic practices that are not optimal in the long run.

2.2. Best Management Practice as a Form of Cross Compliance. Best pest management practices are not a component of crop insurance programs in North America. Nor are they a component in Europe's system as a result of multiple insurance schematics across European Union countries. Instead, the U.S. and Europe both have their own payment for subsets of best management practices as a public good known as Cross Compliance. Cross Compliance was included within the 1985 U.S. Farm Bill as an environmental provision to incentivise farmers to reduce the cultivation of highly erodible land and the draining of wetlands [13]. If they employ these practices, they forfeit eligibility for a number of income support programs. Approximately 40 million ha of U.S. crop land meet the requirements of Cross Compliance and receive direct payments for agrienvironmental practices.

Similarly, Cross Compliance was introduced in the European Union in 2003 under the Common Agricultural Policy as an agrienvironmental payment [14]. Within that policy, Cross Compliance became a mechanism of direct payment for farmer compliance to meet standards regarding the environment, food safety, and health of plants and animals. Under Cross Compliance, farmers have statutory management requirements (hereafter Requirements) and good agricultural and environmental conditions (hereafter Conditions), in which Requirements are more rooted in food safety and animal welfare practices, while Conditions cover the areas of environment, climate change, and land conditions. Each European Union country is required to implement Cross Compliance within the policy; however, each interprets Requirements differently based on their own agricultural industries and establish their own minimums for Condition levels. When standards are met, payments are made to farmers; however, violations in a given year can reduce direct payments from 5 to 15%. In cases of conscious negligence, the subsidised principle can be reduced from 20–100% and be carried over multiple years. The countries are required to conduct their own spot inspections and are incentivised to do so, as each country retains 25% of the enforced negligence reductions from their farmers' direct payments.

The Cross Compliance of the U.S. and EU are enforceable based on their nation's interpretations of farmer's rights and public goods. In Canada, farmers have the right to proceed in whatever practices they wish to conduct on their privately owned land. However, government has the right to introduce or change current rights of land ownership and production to have farmers implement or not exercise particular practices as a result of public funding [13]. Given that the Canadian federal-provincial crop insurance program is subsidised through public funding, the governing agencies have the opportunity to offer greater incentives for those who act in the public good through implementation of best management practices. If the provincial and federal governments were to incentivise the crop insurance program, farmers participating in the program could essentially be releasing some of their production rights in return for adopting best management practices, paying reduced insurance premiums commensurate with the degree of adoption.

3. Crop Insurance Programs in the United States and Canada: Case Studies from Two Jurisdictions

Availability of crop insurance programs and grower participation rate varies widely among developed countries. For example, fewer than 1% of Australian growers have multiperil crop insurance due to a number of reasons, including the cost of premiums [15]. In contrast, the majority of growers in the U.S. and Canada are enrolled in crop insurance programs. Because crop insurance differs significantly between the U.S. and Canada, we examine two respective scenarios from jurisdictions in both countries: State of Iowa and Province of Saskatchewan. Each jurisdiction represents a significant proportion of agricultural land in their respective countries.

3.1. Iowa, United States: Overview. The U.S. Environmental Protection Agency has recently mandated more rigorous herbicide resistance reporting and mitigation protocols for crop protection companies, in response to the introduction of auxinic-resistant crops and associated herbicides. Another federal agency, the United States Department of Agriculture Risk Management Agency, has the ability and capability to help manage the risk of herbicide resistance in U.S. agriculture through programs such as crop insurance that might be used to provide incentives to farmers [10, 16]. The Federal Crop Insurance Corporation, a part of this agency, is the source of crop insurance for U.S. farmers and ranchers [17, 18]. Insurance companies in the private sector sell and service the crop insurance policies (Approved Insurance Providers), which contain references describing good or sustainable farming practices [19]. This agency helps develop and approve crop insurance premium rates. In that role, they could incentivise herbicide resistance management as a good agronomic practice to avoid losses in crop yield or quality; policy premiums could be lower for those following best management practices [16]. Support for this initiative may not be high, however, as fewer than 40% of Iowa farmers who participated in a 2017 survey favoured private company- or government-incentivised best management practices for herbicide resistance management [20].

3.1.1. Iowa Is Representative of the Midwest Corn Belt. Iowa is located close to the geographic center of the U.S. The state is representative of agriculture in the U.S. Corn Belt and has an area of approximately 14.5 million ha, of which 86% is crop land [21]. Corn (maize) (*Zea mays* L.) production and soybean (*Glycine max* L. Merr.) production in the state represent 19 and 17% of U.S. totals, respectively. In 2017, Iowa had 86,900 farms, continuing the trend over the past 50 years of fewer, larger farms [21, 22].

Herbicide-resistant weed issues in Iowa are also representative of the Midwest Corn Belt. The most important herbicide-resistant weeds are waterhemp (*Amaranthus tuberculatus* L.), horseweed (*Conyza canadensis* L. Cronq.) and giant ragweed (*Ambrosia trifida* L.), although waterhemp is ubiquitous in Iowa fields. Resistance in waterhemp populations has evolved to acetolactate synthase (ALS) inhibitors, photosystem-II inhibitors, glyphosate, protoporphyrinogen oxidase (PPO) inhibitors, and hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors in 100, 97, 98, 17, and 28% of the fields, respectively, based on a survey of about 900 Iowa populations [23]. Multiple herbicide resistance within waterhemp is the norm, with 69% of the populations with evolved resistance to three of the above herbicide sites of action. The most common multiple-resistance pattern is ALS inhibitor plus photosystem-II inhibitor plus glyphosate. Resistance to four and five herbicide sites of action is estimated to occur in 15 and 5% of the populations, respectively.

Management of herbicide-resistant weeds in Iowa is also representative of the Midwest Corn Belt. A survey conducted in 2014 found that more than 90% of respondents reported they found weed management to be a never-ending technology treadmill, and 82% suggested that weeds would evolve resistance to any new herbicide technology [24]. Sixty-four percent also suggested that the evolution of new resistances in weed populations was a major concern despite new technologies, and 69% blamed a "few" farmers and poor management for the evolution of herbicide-resistant weeds. More than 89% of survey respondents reported the same or increased use of herbicides, while 54% indicated that they had not changed scouting practices. Respondents reported they used cover crops (21%), but 50% had no plans to include cover crops. Extended and more complex crop rotations and converting crop land to perennial crops represented 15 and 14% of respondents, respectively. Seventy-one percent reported that they purchased crop insurance. Only 8% of farmers who participated in the 2017 survey suggested that crop insurance discouraged them from using alternative practices that might help herbicide resistance management [20].

3.1.2. Best Management Practices That Could Qualify for Insurance Premium Discounts. Good farming practices are defined by the United States Department of Agriculture Risk Management Agency as "the production methods utilized to produce the insured crop and allow it to make normal progress toward maturity and produce at least the yield used to determine the production guarantee or amount of insurance, including any adjustments for late planted area, which are (1) for conventional or sustainable farming practices, those generally recognized by agricultural experts for the area or (2) for organic farming practices, those generally recognized by the organic agricultural industry for the area or contained in the organic plan" [25]. The Approved Insurance Provider can contact the Federal Crop Insurance Corporation to determine whether or not a specific production method is considered to be Good Farming Practice [19]. Unfortunately, this definition is ambiguous, open to multiple interpretations, and could apply to almost any production practice a farmer chooses to adopt. Agricultural experts, as designated by the agency, who can determine if a practice meets the Good Farming Practice criteria include the Cooperative Extension Service, United States Department of Agriculture, agricultural departments of universities, certified crop advisers, and certified professional agronomists. While pests and diseases are mentioned, there is no discussion about weeds and specifically, no mention of herbicide-resistant weeds.

Weed scientists have dedicated considerable effort to developing best herbicide resistance management practices [26]. Most farmers feel they already are using best management practices and thus managing herbicide-resistant weeds effectively [24, 27, 28]. However, many of the practices farmers adopt are those that require the least effort and are the least effective at addressing herbicide resistance management [22]. Many of the best management practices that farmers adopt focus on herbicides; however, it is not possible to manage herbicide-resistant weeds simply by spraying herbicides. Practices that farmers are less likely to adopt are those not easily integrated into their current production system or require time or labour to implement. Unfortunately, given the current demographics of agriculture, time or labour needed for the most effective herbicide resistance management practices (e.g., cover crops) is limited or deemed insufficient [22, 29, 30].

Effective best management practices must impact the biology and ecology of herbicide-resistant weeds, and these are the practices that could be incentivised by discounted cost of crop insurance. Ecologically based weed management must include a diverse suite of tactics to provide acceptable weed suppression [31]. The tactics, such as crop residue cover or crop planting density, should enhance weed seed bank losses, inhibit weed seedling establishment, and minimise weed seed production [32].

It is also critically important that the best management practices are easily assessed and documented by the Federal Crop Insurance Corporation or agency that accepts the responsibility of documentation. Incentivised yet voluntary approaches are more likely to be effective if there are persuasive reasons to participate, clearly defined behavioural standards, and an ability to monitor outcomes with consequences due to noncompliance [33]. Thus, a number of recommended best management practices would not be eligible for crop insurance discounts. While as many practices as possible should be implemented for best herbicide resistance management, a number of them (e.g., preventing weed seed production [26]) are general in nature and do not suggest a specific procedure or action that could be efficiently documented. Some best management practices are relatively specific but do not impact weed population dynamics, such as scouting, equipment sanitation, use of multiple herbicide sites of action, or applying the recommended herbicide rate at the recommended application timing relative to weed development. Such practices are difficult to document and therefore may be considered ineligible for a crop insurance incentive. However, documentation of some of these best management practices may be achieved by farmer receipts for services rendered (e.g., scouting and pesticide application) or products purchased (e.g., agrochemicals). Best management practices that do impact weed biology and ecology are diverse crop rotations, cover crops, and tillage. These practices, outlined below, would be highly effective for herbicide resistance management and are easily documented.

(1) Crop Rotation as a Tactic to Qualify for Insurance Premium Discounts. Iowa farmers perceive the benefits of extended crop rotations for herbicide resistance management [20]. For example, reduced herbicide use was recognized by 64% of the farmers who participated in a 2017 survey. However, only 27% agreed that crop rotations other than corn/soybean could be as profitable. Fifty percent of the farmers suggested that the culture of Iowa agriculture was not supportive of alternative crop rotations and indicated that the lack of viable markets (70%) and lack of input support by agribusiness companies (58%) were important barriers to diverse crop rotations [20]. Therefore, the respondents' attitudes and actions are not the same. Research has shown that rotating cool- and warm-season crops effectively decreases weed population density [34, 35]. Diverse crop rotations also allow for the reduction of herbicides without a loss of potential crop yield [36]. More diverse crop systems (inclusion of small-grain cereals or perennials) had lower production costs and greater economic return to land and management regardless of subsidies [37]. The inclusion of a perennial forage provided the greatest economic return, the lowest production costs, and the greatest impact on the weed seed bank. However, the more diverse crop production systems had greater labour requirements than a conventional 2-year corn/soybean rotation.

(2) Cover Crops as a Tactic to Qualify for Insurance Premium Discounts. Sixty-one percent of Iowa farmers who participated in a 2017 survey rated themselves as poor or very poor with regard to using cover crops [20]. However, the documented benefits of cover crops are well established and include weed suppression and improved soil and water quality, nutrient cycling, and depending on the choice of cover crops, cash productivity [38]. The extent of these benefits may be offset by the cost of establishing the cover crop, loss of income if the cover crop interferes with other crops, and other production expenses. Depending on the choice of cover crop and the manner of establishment, there can be a major decline in the germinable weed seed bank [39]. Fall-seeded rye (*Secale cereal* L.) is an excellent cover crop for Iowa; it is easy to establish, provides excellent protection from soil erosion, and helps weed management by mulch and possibly allelotoxins. However, rye does not provide an opportunity for additional income. Mixtures that include rye with legumes and mustards are more costly to establish but provide similar protection from soil erosion with an additional plant nutrient benefit. Starting in 2017, the state soybean commodity group and agriculture department worked with the federal government and offered a $12 premium reduction on crop insurance per cover crop hectare planted [40]. This program was established not for herbicide resistance management, but rather to help reduce agricultural nutrient contamination in water.

(3) Tillage as a Tactic to Qualify for Insurance Premium Discounts. Tillage is a conundrum with regard to herbicide resistance management. While tillage had significant historical positive benefits for weed management, there are important environmental, economic, and time management costs that do not support farmer adoption of tillage for herbicide resistance management [27, 41]. In many situations, government regulations prohibit or discourage the use of tillage, regardless of the reason. However, there are tillage practices that would benefit herbicide resistance management and maintain significant plant residues on the soil surface, thus minimising erosion and water quality concerns [42]. For example, interrow cultivation aids weed management and reduced herbicide use without a loss of crop yield [43]. It is suggested that "site-specific" tillage for herbicide resistance management would overcome many of the concerns about increased labour cost and time requirement as well as concerns about soil erosion and water quality. Interrow cultivation or other tillage practices would only be used in fields or portions of fields that required additional weed management [22]. Importantly, tillage would help disrupt the successful biological or ecological characteristics of weeds and be easily documented for qualification for crop insurance premium discounts.

3.1.3. A Proposed Actuarial Approach for Insurance Premium Discounts: Adaptation from an Experience-Based Model. Although a majority of growers across North America are likely already dealing with herbicide resistance, reactive best management practices are as important as proactive ones. Although simulation models or decision-support systems have been developed to estimate the risk of resistance evolution for a particular weed species to a particular herbicide site of action in an agroecoregion [44], predicting resistance risk on a field basis for key economic weed species in an agroecoregion is not feasible. Moreover, monitoring herbicide-resistant weed population abundance at the field level and estimating potential crop yield loss would not be cost-effective nor practical for crop insurance purposes. Therefore, the most feasible, practical approach to recognizing and incentivising best pest management practices via reduced crop insurance premium rates is not estimating risk of resistance and cost thereof, but rather the level of farm adoption of academia-recommended best management practices for that agroecoregion.

Adverse selection and moral hazard are key considerations in setting crop insurance premium rates. As described previously, premium rates for Risk Management Agency-approved policies are set by the Federal Crop Insurance Corporation, and the policies are offered to farmers by

Approved Insurance Providers. The loss-cost rating methodology sets premium rates according to the average historical rate of loss, e.g., if, on average, policies pay out 10% of their value, then charge a 10% rate. Adverse selection occurs if premiums do not accurately reflect an individual farmer's likelihood of loss. Because growers are better able to ascertain their likelihood of suffering losses than are insurers, it remains a serious problem affecting the actuarial soundness of crop insurance programs [45]. Moral hazard refers to the problem that occurs if growers alter their behaviour (e.g., reduce crop inputs) after buying insurance to increase their likelihood of collecting indemnities (claim payout).

An innovative actuarial approach in calculating crop insurance risks and premiums was reported in 2006 [46]. The actuarial model describes an experience-based premium rate discount system for crop insurance in the U.S. The study was funded in part by the United States Department of Agriculture Risk Management Agency. The three measures of experience are the following: (1) loss ratio index—claim/indemnity costs vs. premium revenues of an individual insured grower over a 5-year period relative to that for all growers of the same crop type in a jurisdiction; (2) yield variance index—ratio of an individual grower's 10-year yield variance to a weighted average yield variance for other growers of the same crop type in a jurisdiction; and (3) number of years of continuous participation (for the previous 8 years). However, the study ultimately recommended that only the loss ratio index was needed as a basis for an experience-based discount. We believe this tested actuarial approach is directly applicable to discounted insurance premiums for best pest management practices, which facilitate favourable loss ratio and yield variance indices. Based on the agency's national database from 1991–2002, the predicted average premium discount was 10% for corn and soybean (Table 1). Therefore, a corn or soybean grower having 5 years with the best rating for experience would receive a 10% premium discount.

Table 1: Percentiles of predicted good experience insurance premium discount factors for corn (maize), soybean, cotton, and wheat (source: United States Department of Agriculture Risk Management Agency database 1991–2002; adapted [46]).

	Predicted discount factor			
Percentile	Corn	Soybean	Cotton	Wheat
95	0.980	0.977	0.996	0.990
90	0.963	0.957	0.991	0.981
75	0.919	0.910	0.978	0.957
50 (median)	0.900	0.896	0.949	0.929
25	0.896	0.894	0.918	0.916
10	0.892	0.884	0.911	0.911
5	0.892	0.876	0.906	0.911

Corn (*Zea mays* L.); soybean (*Glycine max* L. Merr.); cotton (*Gossypium hirsutum* L.); wheat (*Triticum aestivum* L.).

We propose that this actuarial system be expanded to include an additional measure of experience, i.e., a best pest management practice index, based on degree of adoption of best management practices outlined previously. Like measure (3) above, this proposed index would not require a peer group for comparison. This index would need to be phased in over time, allowing collection of this additional agronomic data across years. We believe this adaptation or expansion of a sound actuarial model is a good first modest step—fiscally, realistically, logistically, and practically—for incentivising best management practices for pesticide resistance mitigation or management. The maximum premium discount may be significantly greater than 10%; for example, insurance program participants in Saskatchewan can receive a maximum premium discount of 50%, as described below.

3.2. Saskatchewan, Canada: Overview. Saskatchewan encompasses 65 million ha, but only 32% is considered farm land; annual field crops were grown on 15 million ha in 2017 [47]. The top two crops are canola and wheat (*Triticum aestivum* L.), with production representing 53 and 43% of the national totals, respectively. Saskatchewan had 34,523 farms in 2016, with a similar trend as that of Iowa in declining numbers and increasing size over time.

In a random survey of 400 fields in the province in 2014-2015, 57% had an herbicide-resistant weed biotype. The most abundant and troublesome multiple-resistant weed is wild oat (*Avena fatua* L.), found in 25% of Saskatchewan fields or covering 2.5 million ha [48]. This biotype is resistant to acetyl-CoA carboxylase (ACCase) and ALS inhibitors, thus potentially eliminating all postemergence herbicides registered for use in wheat or barley (*Hordeum vulgare* L.). The cost of herbicide-resistant weeds to farmers averaged $\$24\,\mathrm{ha}^{-1}$ through increased herbicide use, crop yield/quality loss, or both; the majority of surveyed farmers indicate that herbicide-resistant weeds negatively impact crop production [48].

Saskatchewan crop insurance (similar to the other provinces) is a federal/provincial government program, cost-shared with 60% contribution by both levels of government and 40% by farmers/land managers [49]. In the 2017 crop year, 77% (11.5 million ha) of annual field crops in Saskatchewan were insured [50]. This rate may increase if yield guarantees accurately reflected innovations within crop breeding. For example, canola yield guarantees have not fully incorporated the commercialization of higher yielding hybrid canola varieties, resulting in some farmers foregoing insurance. There are some farmers who do not purchase crop insurance due to farm enterprise size or philosophies.

As in the U.S., crop insurance covers crop losses (production or quality) from uncontrollable causes such as drought, excess moisture, insects, or frost. Farmers may select insurance coverage for 50, 60, 70, or 80% of their average yields for most crops. Yield-loss payments are based on the shortfall between the production guarantee and the total net harvested production, adjusted for quality, for all hectares of the insured crop. Additional crop insurance coverage, such as for hail damage, is offered by private sector companies.

Premium discounts and surcharges acknowledge risk differences among customers, reducing premiums for those without a history of repeated claims. As outlined previously, experience discounts and surcharges are calculated using an individual's history of losses and a comparison of individual loss history to area losses. When an increase in the number or size of losses is experienced, the discount, if present, is reduced or the surcharge is increased. The maximum number of debits or credits a customer can accumulate is 16. The maximum number of credits equates with a 50% premium discount, whereas the maximum number of debits confers a 50% premium surcharge.

In a customer's signed production declaration (due after harvest: November 15), the only agronomic practices that need to be listed on a field basis are (1) crop variety; (2) seeding date; (3) fertilizer-use rate (i.e., nitrogen, phosphorus, potassium, and sulphur); (4) herbicides (i.e., name and number of applications); and (5) fungicides/insecticides (i.e., name and number of applications). The crop variety grown must be currently registered. The deadline for seeding spring crops is June 20 because of risk of frost damage in the fall. Rates of fertilizer or use of pesticides deemed insufficient for adequate growth and yield of the insured crop may nullify payment of a yield-loss claim (i.e., moral hazard described above).

3.2.1. Best Management Practices That Could Qualify for Insurance Premium Discounts. As previously indicated, two principles that best management practices must adhere to are (1) not distort the marketplace and (2) be verifiable. Insurance premium discounts should not subsidise the production of one crop over another or contravene World Trade Organization rules. Verification through customer-signed declarations and audits are designed to discourage program abuse. Some highlighted best herbicide resistance management practices described below address three issues impacting the selection for herbicide resistance: (1) crop rotation diversity and crop competitiveness against weeds; (2) pesticide-use diversity; and (3) weed sanitation practices. These issues are part of the top 10 herbicide resistance management practices recommended in the Northern Great Plains [51].

As described in Section 2, crop rotations have changed considerably following the commercialization of transgenic crops and the removal of millions of hectares of fallow in Western Canada, as weed control and soil conservation improved to such a degree that fallowing is no longer as important as it was 30 years ago. In a 2012–2014 survey of prairie farmers, canola rotations had markedly shortened since then (Table 2). Prior to transgenic canola in 1996, crop insurance programs would only insure a field of canola if there were 3 years in between the crop; that is, a farmer could only grow canola once in 4 years to have it insured. That stipulation no longer applies. Today, over 50% of prairie growers plant canola every second year or to a much lesser extent, every year. Many in the agriculture industry have indicated that if canola area passes 8 million ha in the Canadian prairies, too many farmers are growing canola in a 2-year rotation. Canola area passed this threshold in 2012 and has subsequently remained above this level [52].

Table 2: Field rotations with herbicide-resistant (glufosinate, glyphosate, and imidazolinone) canola (*Brassica napus* L.) in Western Canada: 2012–2014 (n = 220 respondents).

Rotation	Frequency (%)
Every year	4
Once every 2 years	46
Once every 3 years	23
Once every 4 years	17
Once every 5 years or more	10

The most common crop rotation across the Canadian prairies is now herbicide-resistant (glufosinate, glyphosate, and imidazolinone) canola-wheat. In the eastern Prairies, rotations that frequently include glyphosate-resistant crops (canola, soybean, corn) are at increased risk of glyphosate resistance in weed populations [53].

One potential incentive to ensure that farmers are not moving into crop rotation patterns that are overly reliant on one crop and/or chemical is to offer discounts on crop rotations of cereals/oilseeds/pulses. Insurance premium discounts could be offered to clients who do not grow the same crop back-to-back in a field, such as canola-canola or wheat-wheat. An alternative policy is to simply refuse insurance in that situation. Numerous studies have documented the agronomic benefits of following one crop with a different crop, in terms of pest incidence, soil health, or overall yield benefit. Herbicide resistance is strongly correlated with crop monoculture. Therefore, this best management practice should be the foundation in accreditation for crop insurance premiums. It is easily verifiable for those clients previously enrolled in the crop insurance program. With software advances, monitoring rotation variation would be quite straightforward, and any farmer that practices rotation mixes of cereals, oilseeds, and pulses could be rewarded for this practice through lower insurance premiums (Table 3).

This incentivised insurance premise does have the potential for some limitations. Standardised insurance premium reductions would tend to homogenize crop production, essentially indicating that a rotation of the three crop types (cereals, oilseeds, and pulses) is relatively equally feasible at any location. Geographic location and soil type can enhance and restrict the potential to produce some types of crops. For example, there are parts of Western Canada that have high rates of precipitation, making the production of some pulse crops problematic due to disease incidence or seed quality.

Although fallow in crop rotations may be justified in drier regions, it has been linked with soil degradation (tilled fallow) or herbicide resistance (chemical fallow), notably glyphosate resistance. For example, repeated applications of high rates of glyphosate (alone) combined with no crop competition facilitated the selection of glyphosate-resistant kochia (*Kochia scoparia* L. Schrad.) in the Great Plains [54, 55]. Premium discounts for cover crops (e.g., green feed and green manure) to discourage fallowed land would help address both soil conservation and resistance management goals.

Table 3: Hypothetical crop insurance proportional or weighted discounts for varying levels of implementation of three potential best herbicide resistance management tactics and practices in annual crop systems in the Northern Great Plains of Canada.

	Discount (proportion)
(i) Crop rotation and weed competition:	
Threshold crop seeding rate[a]	0.06
Two crop types: cereal-oilseed or cereal-pulse	0.06
Three crop types: cereal-oilseed-pulse	0.18
Inclusion of cover crop in fallowed land	0.10
(ii) Pesticide use:	
Not back-to-back high-risk[b] herbicide use in-crop	0.12
Herbicide mixtures or sequences[c]	0.12
Two modes of action in chemical fallow	0.06
(iii) Weed sanitation:	
Certified or cleaned seed	0.06
Harvest weed seed control	0.12
Site-specific weed management	0.12
Total	1.0

Degree of adoption (maximum of 1.0) would be reflected in a best management practice index added to the loss ratio index in calculating a farmer's insurance premium discount, similar to the actuarial approach proposed in the United States (Section 3.1.3). [a]Established for the different prairie soil climatic zones. [b]Acetyl-CoA carboxylase or acetolactate synthase inhibitor herbicides. [c]Meeting specified resistance management criteria.

In addition to insurance premium discounts to encourage crop diversity, discounts given to promote crop seeding rate and therefore weed-competitiveness potential would be beneficial for herbicide resistance management. In the Northern Great Plains, crop seeding rate is one of the most consistently effective cultural weed management practice [56]. Verification is not as simple as for crop rotation diversity, but can be accomplished through random audits of stored grain reports required by the crop insurance program and seed purchase or seed cleaning receipts.

Crop rotation diversity would facilitate a diversified portfolio of chemical weed control options that would contribute to minimising the potential for the evolution of herbicide resistance in weed populations. Best management practices related to pesticide use include mixtures or sequences within a growing season (pre- and postemergence) that meet the criteria for herbicide resistance management or herbicide rotations over crop years based on effective sites of action or wheat selectivity to mitigate target-site and non-target-site (metabolic) resistance, respectively. For example, discounts for not using herbicides classified at high risk for selection of herbicide resistance (e.g., ACCase inhibitors; ALS inhibitors) in consecutive years in crop would reduce the selection pressure for herbicide resistance [51] (Table 3). Moreover, encouraging glyphosate tank-mixtures in chemical fallow fields would reduce the selection pressure for glyphosate resistance.

To reduce the potential for moral hazard, the crop insurance program potentially penalizes clients who do not apply herbicides in a given year or who apply herbicide treatments deemed insufficient to prevent yield loss. Similarly, the United States Department of Agriculture Risk Management Agency policy is to insure against yield loss caused by pests such as weeds, whether or not populations are resistant [16]. Yet, overreliance on herbicides at the expense of other weed management tools has led to the herbicide-resistant weed predicament we face today, especially the challenge of managing multiple-resistant weed populations. Some compromise is needed in these situations, which may be aided by field scouting records of weed abundance prior to herbicide application.

Another area that could be addressed via insurance premium discounts is weed sanitation [51] (Table 3). The goal is to reduce weed propagule immigration into a field, weed spread across fields, or entry into the soil seed bank. Sanitation can take many forms, such as using weed-free crop seed or controlling weeds along field borders or in small patches (site-specific management). One area that is receiving increasing attention globally is harvest weed seed control practices, such as chaff carts, weed clipping (above the crop canopy), or weed seed destruction [57]. In addition to crop insurance premium discounts, the highest rate for capital cost allowance, a tax deduction from farm income, would incentivise purchase of these types of harvest weed seed control equipment.

In summary, crop insurance proportional or weighted discounts should be offered to incentivise these potential best herbicide resistance management practices in annual crop systems in the Northern Great Plains of Canada (Table 3). The magnitude of a discount for a specific best management practice should reflect its current degree of adoption (primary criterion) and estimated cost of implementation in an agroecoregion, i.e., greatest discounts for practices with lowest adoption, greatest cost, or both. Degree of adoption of best management practices (maximum of 1.0) would be reflected in a best management practice index combined with the existing loss ratio index in calculating a farmer's premium discount, similar to the actuarial approach proposed in the U.S (Section 3.1.3).

4. A Time for Action

The purpose of crop insurance is to mitigate or manage financial risk. Clearly, pesticide resistance is an increasing risk to sustainable crop production. The basic reason for crop insurance providers to finally become engaged is reduced future indemnities for crop losses due to pesticide resistance. We have suggested possible enhancements to crop insurance programs in the U.S. (case study jurisdiction: Iowa) and Canada (case study jurisdiction: Saskatchewan). Specifically, we advocate premium rate changes to incentivise farmers or land managers to adopt best herbicide resistance management practices as recommended by academia. We have outlined some possible suitable best management practices in these two case study jurisdictions that could be eligible for crop insurance premium discounts. Because the level of adoption of many of these recommended best management practices is generally low, we believe additionality has good potential (i.e., best management practices that are adopted only if the farmer receives a discount). As stated previously, discounts for low-adoption best management practices should be the greatest to realize additionality. *A posteriori* audits and surveys will need to be conducted for iterative adjustments in discount schemes so that they are actually changing the adoption "needle" while maintaining actuarial soundness. The intent is to incentivise adoption of key resistance management practices, not subsidise the entire cost of their implementation. Similar to many government budget measures, you introduce a new policy or program typically as a pilot project initially, then collect data to determine if the actual outcome was close to the target outcome. The opportunity cost of inaction is rarely factored into the economics of programs to incentivise grower behaviour.

Continued inaction by all levels of government in addressing the crisis of herbicide resistance is not an option. The attitude of a "wait and see" approach to herbicide resistance management over the past 50 years must change. The public good is not well served in the long run by relying solely on price discounts for bundled crop inputs by agribusinesses, who are often conflicted between maximising sales and ensuring academia-recommended practices are objectively relayed to farmers. Ultimately, however, decisions are made by the farmer or land manager, who must deal with the consequences. Much greater interaction and collaboration is needed between public policy-makers and the multidisciplinary scientific community actively engaged in addressing this issue. Politicians of all levels of government must become engaged in an issue that threatens to diminish agricultural productivity and food security in the near and long term.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

[1] P. W. B. Phillips and G. G. Khachatourians, *The Biotechnology Revolution in Global Agriculture: Invention, Innovation and Investment in the Canola Sector*, CABI Publishing, Wallingford, UK, 2001.

[2] S. O. Duke, "Taking stock of herbicide-resistant crops ten years after introduction," *Pest Management Science*, vol. 61, no. 3, pp. 211–218, 2005.

[3] S. Fransoo, "Pulse producer decision making under risky conditions: will end-point royalties change preferences? M.Sc. thesis, University of Saskatchewan, Saskatoon, SK Canada, 2017, https://harvest.usask.ca/handle/10388/8298.

[4] S. O. Duke and S. B. Powles, "Glyphosate-resistant crops and weeds: now and in the future," *AgBioForum*, vol. 12, no. 3-4, pp. 346–357, 2009.

[5] O. O. Olfert, M. K. Mukerji, and J. F. Doane, "Relationship between infestation levels and yield loss caused by wheat midge, *Sitodiplosis mosellana* (Géhin) (Diptera: Cecidomyiidae), in spring wheat in saskatchewan," *The Canadian Entomologist*, vol. 117, no. 5, pp. 593–598, 2012.

[6] K. Lewis, *"Five Years of Midge Tolerance," Country Guide Magazine*, Glacier FarmMedia LP, Winnipeg, MB, Canada, 2015, https://www.country-guide.ca/2015/04/23/five-years-of-midge-tolerance/46541.

[7] D. Doohan, R. Wilson, E. Canales, and J. Parker, "Investigating the human dimension of weed management: new tools of the trade," *Weed Science*, vol. 58, no. 4, pp. 503–510, 2017.

[8] S. Ward, "Human dimensions of herbicide resistance," *Weed Science*, vol. 64, no. sp1, p. 551, 2016.

[9] S. B. Powles and T. A. Gaines, "Exploring the potential for a regulatory change to encourage diversity in herbicide use," *Weed Science*, vol. 64, no. sp1, pp. 649–654, 2016.

[10] H. D. Coble and J. Schroeder, "Call to action on herbicide resistance management," *Weed Science*, vol. 64, no. sp1, pp. 661–666, 2016.

[11] R. P. Zentner, S. A. Brandt, and C. A. Campbell, "Economics of the Scott long-term crop rotation systems," in *Proceedings of Soils and Crops Conference*, Saskatoon, SK, Canada, 1995, http://www.usask.ca/soilsncrops/conference-proceedings/previous_years/Files/95/1995docs/039.pdf.

[12] Anonymous, *Crop Rotation*, Canola Council of Canada, Winnipeg, MB, Canada, 2018, https://www.canolacouncil.org/canola-encyclopedia/field-characteristics/crop-rotation.

[13] C. Meyer, B. Matzdorf, K. Müller, and C. Schleyer, "Cross compliance as payment for public goods? Understanding EU and US agricultural policies," *Ecological Economics*, vol. 107, pp. 185–194, 2014.

[14] European Commission, "Regulation (EU) No 1306/2013 of the European Parliament and of the Council of 17 December 2013 on the financing, management and monitoring of the common agricultural policy and repealing Council regulations (EEC) No 352/78, (EC) No 165/94, (EC) No 2799/98, (EC) No 814/2000, (EC) No 1290/2005 and (EC) No 485/2008," *Official Journal of the European Union*, vol. 347, pp. 549–607, 2013.

[15] S. Locke, *Fledgling Multi-Peril Crop Insurance Industry Looks Forward to Government Subsidies on Premiums*, ABC Rural–ABC News, Sydney, Australia, 2017, http://www.abc.net.au/news/rural/2017-01-10/fledgling-multiperil-crop-insurance-industry-looks-forward/8172524.

[16] M. Barrett, J. Soteres, and D. Shaw, "Carrots and sticks: incentives and regulations for herbicide resistance management and changing behavior," *Weed Science*, vol. 64, no. sp1, pp. 627–640, 2016.

[17] Anonymous, *Loss Adjustment Manual Standards Handbook 2017 and Succeeding Crop Years*, United States Department of Agriculture, Washington, DC, USA, 2017, https://www.rma.usda.gov/handbooks/25000/2017/17_25010.pdf.

[18] Anonymous, *2017 Crop Insurance Handbook*, United States Department of Agriculture, Washington, DC, USA, 2017, https://www.rma.usda.gov/handbooks/18000/2017/17_18010.pdf.

[19] Anonymous, *Good Farming Practice Determinations Standards Handbook*, United States Department of Agriculture Risk Management Agency, Washington, DC, USA, 2014, http://www.rma.usda.gov/handbooks/14000/2015/14060.pdf.

[20] J. G. Arbuckle Jr., *Iowa Farm and Rural Life Poll: 2017 Summary Report*, Iowa State University, Ames, IA, USA, 2017, https://store.extension.iastate.edu/product/Iowa-Farm-and-Rural-Life-Poll-2017-Summary-Report.

[21] Anonymous, *2017 State Agriculture Overview*, United States Department of Agriculture National Agriculture Statistics Service, Washington, DC, USA, 2018, https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=IOWA.

[22] M. D. K. Owen, “Diverse approaches to herbicide-resistant weed management,” *Weed Science*, vol. 64, no. sp1, pp. 570–584, 2016.
[23] M. D. K. Owen, “Weed management update for 2018 and beyond: the more things change,” in *Proceedings of Integrated Crop Management Conference*, B. Pringnitz, Ed., pp. 77–88, Iowa State University, Ames, IA, USA, December 2017, https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1262&context=icm.
[24] J. G. Arbuckle Jr., *Farmers Perspectives on Pesticide Resistance*, Iowa State University, Ames, IA, USA, 2014, http://lib.dr.iastate.edu/extension_communities_pubs/25.
[25] Anonymous, *Final Agency Determination: FAD-72*, United States Department of Agriculture Risk Management Agency, Washington, DC, USA, 2007, https://www.rma.usda.gov/regs/533/2007/fad-72.html.
[26] J. K. Norsworthy, S. M. Ward, D. R. Shaw et al., “Reducing the risks of herbicide resistance: best management practices and recommendations,” *Weed Science*, vol. 60, no. sp1, pp. 31–62, 2017.
[27] J. G. Arbuckle Jr. and P. Lasley, *Iowa Farm and Rural Life Poll: 2013 Summary Report*, Iowa State University, Ames, IA, USA, 2013, https://lib.dr.iastate.edu/extension_communities_pubs/26.
[28] G. B. Frisvold, T. M. Hurley, and P. D. Mitchell, “Adoption of best management practices to control weed resistance by corn, cotton, and soybean growers,” *AgBioForum*, vol. 12, no. 3-4, pp. 370–381, 2009.
[29] T. M. Hurley, P. D. Mitchell, and G. B. Frisvold, “Characteristics of herbicides and weed- management programs most important to corn, cotton, and soybean growers,” *AgBioForum*, vol. 12, no. 3-4, pp. 269–280, 2009.
[30] T. M. Hurley, P. D. Mitchell, and G. B. Frisvold, “Weed management costs, weed best management practices and the Roundup Ready weed management program,” *AgBioForum*, vol. 12, no. 3-4, pp. 281–290, 2009.
[31] M. Liebman and E. R. Gallandt, “Many little hammers: ecological management of crop- weed interactions,” in *Ecology in Agriculture*, L. E. Jackson, Ed., pp. 291–343, Academic Press, San Diego, CA, USA, 1997.
[32] R. L. Anderson, “A multi-tactic approach to manage weed population dynamics in crop rotations,” *Agronomy Journal*, vol. 97, no. 6, pp. 1579–1583, 2005.
[33] K. Segerson, “When is reliance on voluntary approaches in agriculture likely to be effective?,” *Applied Economic Perspectives and Policy*, vol. 35, no. 4, pp. 565–592, 2013.
[34] J. C. Streibig, “Numerical methods illustrating the phytosociology of crops in relation to weed flora,” *Journal of Applied Ecology*, vol. 16, no. 2, pp. 577–587, 1979.
[35] R. H. Gulden, D. W. Lewis, J. C. Froese et al., “The effect of rotation and in-crop weed management on the germinable weed seedbank after 10 years,” *Weed Science*, vol. 59, no. 4, pp. 553–561, 2017.
[36] A. S. Davis, J. D. Hill, C. A. Chase, A. M. Johanns, and M. Liebman, “Increasing cropping system diversity balances productivity, profitability and environmental health,” *PLoS One*, vol. 7, no. 10, Article ID e47149, 2012.
[37] M. Liebman, L. R. Gibson, D. N. Sundberg et al., “Agronomic and economic performance characteristics of conventional and low-external-input cropping systems in the Central Corn Belt,” *Agronomy Journal*, vol. 100, no. 3, pp. 600–610, 2008.
[38] S. S. Snapp, S. M. Swinton, R. Labarfta et al., “Evaluating cover crops for benefits, costs and performance within cropping system niches,” *Agronomy Journal*, vol. 97, no. 1, pp. 322–332, 2005.
[39] S. B. Mirsky, E. R. Gallandt, D. A. Mortensen, W. S. Curran, and D. L. Shumways, “Reducing the germinable weed seedbank with soil disturbance and cover crops,” *Weed Research*, vol. 50, no. 4, pp. 341–352, 2010.
[40] Iowa Farm Bureau, *Iowa Program Offers Crop Insurance Discounts for Cover Crop Planting*, Iowa Farm Bureau, West Des Moines, IA, USA, 2017, https://www.iowafarmbureau.com/Article/Iowa-program-offers-crop-insurance-discounts-for-cover-crop-planting.
[41] A. L. Cerdeira and S. O. Duke, “The current status and environmental impacts of glyphosate-resistant crops,” *Journal of Environment Quality*, vol. 35, no. 5, pp. 1633–1658, 2006.
[42] R. T. Bates, R. S. Gallagher, W. S. Curran, and J. K. Harper, “Integrating mechanical and reduced chemical weed control in conservation tillage corn,” *Agronomy Journal*, vol. 104, no. 2, pp. 507–512, 2012.
[43] R. G. Hartzler, B. D. Van Kooten, D. E. Stoltenberg, E. M. Hall, and R. S. Fawcett, “On-farm evaluation of mechanical and chemical weed management practices in corn (*Zea mays*),” *Weed Technology*, vol. 7, no. 4, pp. 1001–1004, 2017.
[44] P. Neve, J. K. Norsworthy, K. L. Smith, and I. A. Zelaya, “Modelling evolution and management of glyphosate resistance in *Amaranthus palmeri*,” *Weed Research*, vol. 51, no. 2, pp. 99–112, 2010.
[45] B. K. Goodwin, “Premium rate determination in the federal crop insurance program: what do averages have to say about risk?,” *Journal of Agriculture Resource Economics*, vol. 19, no. 2, pp. 382–395, 1994.
[46] R. M. Rejesus, K. H. Coble, T. O. Knight, and Y. Jin, “Developing experience-based premium rate discounts in crop insurance,” *American Journal of Agricultural Economics*, vol. 88, no. 2, pp. 409–419, 2006.
[47] Statistics Canada, *Estimated Areas, Yield, Production, Average Farm Price and Total Farm Value of Principal Field Crops (Table 001-0017); Number and Area of Farms and Farmland Area (Table 004-0001)*, Statistics Canada, Ottawa, ON, Canada, 2017, http://www5.statcan.gc.ca/cansim/a47.
[48] H. J. Beckie, S. W. Shirriff, and J. Y. Leeson, “Saskatchewan weed survey of herbicide- resistant weeds in 2014-2015,” in *Weed Survey Series Publication 17-1*, Agriculture and Agri-Food Canada, Saskatoon, SK, Canada, 2017.
[49] *Saskatchewan Crop Insurance*, Saskatchewan Crop Insurance Corporation, Regina, Saskatchewan, Canada, 2018, http://www.saskcropinsurance.com.
[50] *Annual Report for 2017-18 Saskatchewan Crop Insurance Corporation*, Saskatchewan Crop Insurance Corporation, Regina, Saskatchewan, Canada, 2018, http://www.saskcropinsurance.com.
[51] H. J. Beckie and K. N. Harker, “Our top 10 herbicide-resistant weed management practices,” *Pest Management Science*, vol. 73, no. 6, pp. 1045–1052, 2017.
[52] Canola Council of Canada, *Canadian Canola Harvested Acreage*, Canola Council of Canada, Winnipeg, MB, Canada, 2017, https://www.canolacouncil.org/markets-stats/statistics/harvest-acreage.
[53] H. J. Beckie, K. N. Harker, L. M. Hall, F. A. Holm, and R. H. Gulden, “Risk assessment of glyphosate resistance in western Canada,” *Weed Technology*, vol. 25, no. 1, pp. 159–164, 2011.
[54] H. J. Beckie, R. E. Blackshaw, R. Low et al., “Glyphosate- and acetolactate synthase inhibitor-resistant kochia (*Kochia*

scoparia) in western Canada," *Weed Science*, vol. 61, no. 2, pp. 310–318, 2013.

[55] L. M. Hall, H. J. Beckie, R. Low et al., "Survey of glyphosate-resistant kochia (*Kochia scoparia* L. Schrad.) in Alberta," *Canadian Journal of Plant Science*, vol. 94, no. 1, pp. 127–130, 2014.

[56] R. E. Blackshaw, K. N. Harker, J. T. O'Donovan, H. J. Beckie, and E. G. Smith, "Ongoing development of integrated weed management systems on the Canadian prairies," *Weed Science*, vol. 56, no. 1, pp. 146–150, 2008.

[57] B. D. Tidemann, L. M. Hall, K. N. Harker, and H. J. Beckie, "Factors affecting weed seed devitalization with the Harrington Seed Destructor," *Weed Science*, vol. 65, no. 5, pp. 650–658, 2017.