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Commentary

Reduced Herbicide Rates—A Canadian Perspective[1]

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Abstract: Identification of the appropriate use rate is a critical first step in the herbicide development process because use rates affect product utility, market value, and the various risk assessments within the regulatory review process prior to registration. For a given herbicide to be commercially successful, it must provide consistent and sustained efficacy based on a use rate structure that meets customer requirements over a wide range of conditions. Recently, recommendations have been made that advocate the use of herbicide use rates below those outlined on registered product label text. Such advice tends to be based on field work and predictive models designed to identify specific conditions where reduced herbicide use rates are theoretically optimized as dictated by threshold values with assumed levels of commercially acceptable weed control. Unfortunately, many other studies indicate that the use of reduced herbicide rates is not without variability of herbicide efficacy and economic risk. Consequently, reduced use rate theories and related predictive models are often of limited practical value to growers. Aside from inconsistent performance, weed control strategies based on reduced herbicide use rates are not a solution to prevent or even delay target site resistance. In fact, prolonged use of sublethal use rates may select for metabolic resistance and add future weed management challenges by replenishing the weed seed bank. Much effort in terms of development time and resources are invested before product commercialization to ensure that product labels are easily understood and provide value to growers. In this regard, every effort is made to identify the lowest effective use rate that will consistently control target weeds and lead to economic optimization for both the grower and manufacturer.

Additional index words: Lowest effective use rate.

Abbreviations: MC, marginal cost; MR, marginal revenue; PMRA, Pest Management Regulatory Agency.

INTRODUCTION

Registrants of crop protection products determine herbicide use rates on the basis of three decision criteria: product utility, market value, and regulatory requirements. Selection of the correct use rate early in the product development process is crucial because highly consistent herbicide efficacy is paramount in meeting the economic prerequisites of long-term product utility and established market value. Regulatory requirements are also an integral factor because Canadian authorities must review field trial data and approve a lowest effective use rate for each weed control claim before registration.

A review of published literature outlines some of the short- and long-term challenges associated with the application of reduced use rate theory to predictive weed control models. Although examples were included to highlight the many differing aspects of this interesting subject, a key theme was to provide an overview and perhaps a different perspective of the process by which registrants identify, optimize, and eventually support herbicide use rates within the Canadian marketplace. Reviews of published studies on sublethal herbicide rates and associated economic considerations and inherent challenges demonstrate that companies involved in the development, manufacture, and sale of herbicides in Canada have every incentive to identify, support, and sell products based on lowest effective use rates. Where possible, examples have been provided to illustrate points discussed within this context.

THE BASIS FOR USE RATE SELECTION

During the course of developing and supporting registered crop protection products in Canada, manufactur-

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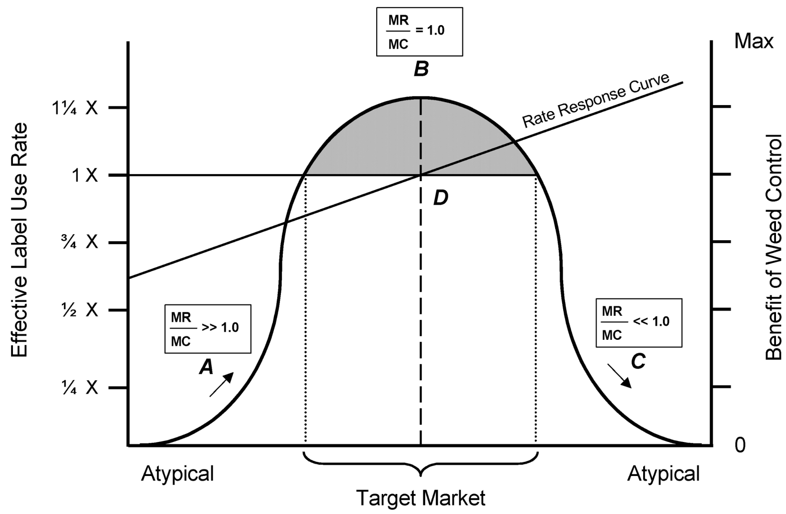

Figure 1. Market distribution and herbicide response curves.

ers conduct many experiments to identify the optimum use rate(s) that best support label claims. Without exception, and regardless of product type or use pattern (i.e., preemergence or postemergence applications), the singular objective is to identify the rate(s) that maximize product value and minimize the required use rate.

To successfully register and sell a herbicide in Canada, registrants must select a use rate structure that meets three essential criteria (1) product utility, (2) market value, and (3) regulatory requirements.

Product Utility. It takes an estimated 8 to 12 yr to develop a commercial product from initial chemical synthesis to global product launch. Considering that development costs can reach US $150 million and that key patents remain intact for approximately 20 yr (from first synthesis), the time that manufacturers have to recoup the investment in developing a new product is actually quite short (Copping 2002). It is therefore in a manufacturer's best economic interest to always register and support the lowest effective use rate for a given product. Consider the alternatives:

No manufacturer would introduce a product based on an excessive use rate. Experience in such cases has shown that growers quickly identify the disparity and optimize the use rate structure at the farm gate leading to widespread rate reductions. Subsequent lost sales and market devaluation would then erode the product's long-term value and effectively destroy or dramatically reduce the product's lifecycle.

Conversely, it is impossible to sustain sales of a product with a sublethal use rate because the inherent gap between product efficacy and market expectations would lead to widespread product performance failures. In fact, experience has shown that the market would simply not support a product that does not meet a minimum set of standards. The following quote helps to illustrate this point: ''It is true that a herbicide becomes a successful product because of the biological effect that it offers growers. Growers do not buy the tris(2-hydroxyethyl)ammonium salt of 2,4-dichlorophenoxyacetic acid as such; they buy cost-effective broad-leaf weed control in cereals. Hence, it is biological effect and commercial advantage that determine whether a compound launch will be successful.'' (Copping 2002).

After registration, additional research is conducted to further optimize use rates and define product labels on the basis of adjustments in formulation, surfactant types, application techniques, etc. Label claims are therefore based on a continuous evaluation of a product's efficacy over a range of conditions relative to established performance standards of existing products in the marketplace. These ongoing efforts help to ensure that growers are always offered the best and most competitive products possible.

Market Value. Registrants focus field trial research on target weeds and conditions that represent the broadest range of the classic bell-curve distribution (Figure 1). This distribution confirms a product's value on the target weed species, weed population densities, growing conditions, application techniques, etc. that have the greatest economic impact on the actual market. Consequently, fewer resources are devoted to examining product performance under atypical conditions that do not apply to the largest target market segment.

Rates are therefore selected on the basis of maximized product value. As a rate response curve is determined, a rate structure is chosen, which, on average, provides an optimal return on investment for the predominant conditions in the target market. Classic production economics has confirmed that growers will only use an input that provides maximized value per dollar invested (Cramer and Jensen 1985). Consider the relationship between costs and values derived from the use of each additional ''unit'' of a given resource. When the value output, or marginal revenue (MR), of a herbicide is greater than its associated marginal cost (MC), there is more derived benefit to use the product than not to use it (***A***, Figure 1, where MR/MC $\gg$ 1.0). As total productivity increases, and as the economic benefit from weed control approaches equilibrium, a point of optimized product value is reached (***B***, Figure 1, where MR/MC = 1.0). After this point, it is possible to demonstrate the effect of the ''law of diminishing returns'' as the cost of the product begins to exceed the associated benefits (***C***, Figure 1, where MR/MC $\ll$ 1.0).

Registrants have recognized that consistently perfect weed control is not possible in all circumstances. As such, manufacturers select the ''1×'' lowest effective use rate (point ***D***) at the point that is: (1) most representative of the intended market conditions and (2) as close as possible to optimized product value. It can be demonstrated and argued that the shaded area represents the ''industry risk factor'' associated with selecting rates below the absolute ideal, point ***B*** (Figure 1). The industry risk factor can then be defined as the probability of inadequate weed control, where a given customer's expectations in terms of product performance have not been met, resulting in a dissatisfaction in product performance.

Although this may appear to be limited to economic theory, detailed reviews of crop–weed competition outline similar relationships between weed density and crop yield (Froud-Williams 2002). This model is further proven by previous investigations, which have confirmed that the greatest rate of yield reduction per weed occurs at relatively low weed densities (***A***, Figure 1). Yield losses per weed plant have been demonstrated to decrease accordingly (***B***, Figure 1) as intense intraspecific competition associated with increased weed density lowers overall yield potential (Cousens 1985).

Regulatory Requirements. Before a herbicide is registered for use in Canada, the Pest Management Regulatory Agency (PMRA) must review a wide range of product-specific studies and render a decision based on product merit. Applicants initiate the process by providing an extensive range of highly specific test results under a set of 12 standard data code requirements.

Canadian regulatory requirements include the submission of: proposed label text, chemistry studies, chronic and acute toxicology studies, studies and assessments of exposure, metabolism studies, residue trial studies, environmental chemistry and ecotoxicology studies, a complete efficacy–value assessment, and copies of foreign reviews from other regulatory agencies within the Organization for Economic Cooperation and Development.

One of the first steps within this process is the review of product efficacy studies relative to prerequisite product efficacy data requirements (e.g., DIR2003-04) as established by Canadian regulatory authorities (PMRA 2003). Before PMRA approval of a herbicide label, Canadian registrants must conduct a minimum of 10 replicated small plot field trials tested during a 2-yr period to generate necessary field trial data to support each proposed control claim. Field trials must cover a range of representative growing and application conditions. Each proposed label claim must also be supported by rate–response data based on sublethal and proposed 1.0× use rates demonstrating commercially acceptable product consistency, duration of weed control, and overall performance. Upon receipt of the data package, the Canadian PMRA evaluates field test data and confirms that the lowest effective use rate has been determined for each weed control claim on the proposed label text. Herbicide label claims are therefore established on a weed-specific basis with registered use rates that inherently cover various weed growth stages, growing conditions, target weed populations, and host crop–weed interactions.

During the review process, PMRA is free to request additional rate response data if the proposed 1.0× use rate is deemed not representative of the lowest effective use rate for a given weed species. If the required new data are not provided, the submission is considered unacceptable for further review and is returned to the applicant.

Once the efficacy review is completed and a satisfactory lowest effective use rate is established for each control claim, the various risk assessments required for the remainder of the submission review are completed. In this sense, efficacy data are pivotal because all risk assessments are based on the established use rate structure. Considering the importance of the efficacy review to the entire submission and the potential effect on review time, there would be absolutely no benefit for a registrant to initially propose and support anything other than the lowest effective use rate.

EFFECTS ON PRODUCTION

Reduced Use Rate Studies. A large body of knowledge and a range of opinions exist on the benefits and risks associated with reduced herbicide use rates. Depending on the study design or initial objective, information has been published, which either supports or rejects the notion of reduced herbicide rates. The following examples have been provided to highlight some recent studies, which represent both supportive and nonsupportive results.

Field trials established to examine the efficacy of 25, 50, 100, 150, and 200 (minimum registered rate) g ai/ha rates of tralkoxydim have indicated that visual wild oat (*Avena fatua*) control in excess of 85% can be achieved with 100 g ai/ha (or 0.5×) use rates in barley (*Hordeum vulgare*) (Belles et al. 2000). Similarly, field trials conducted in central Alberta on wild oat populations averaging 30 to 55 plants/m² suggested that net returns were either higher at sublethal tralkoxydim use rates or were unaffected by use rate (O'Donovan et al. 2001). This study confirmed the results of similar research that demonstrated the possibility of using relatively low herbicide rates to manage low wild oat densities under optimal conditions (Holm et al. 2000; Wille et al. 1998; Zhang et al. 2000).

Australian research, which focused on the interaction of increased crop competition relative to the efficacy of 25, 50, and 75% of the recommended use rates of clodinafop propargyl and tralkoxydim (30 and 200 g ai/ha, respectively), gave similar results (Walker et al. 2002). However, favorable results tended to be limited to reduced weed populations that were sprayed under ideal growing conditions with little consideration given for more adverse conditions. Related studies have also suggested that it was possible to increase economic returns in a soybean (*Glycine max*)–cereal rotation with the use of reduced herbicide use rates coupled with modified tillage and seedbed preparation techniques (Boström et al. 2000; Popp et al. 2000).

Although studies have been published to demonstrate the benefits of reduced herbicide rates, it is also important to consider studies with dissimilar results. Furthermore, one must also account for the additional time and effort required to manage the elements of variability in herbicide performance and economic risk associated with reduced herbicide rates. All factors considered, it can be argued that potential economic gains associated with sublethal herbicide use rates tend to diminish if one includes the opportunity cost associated with time not spent managing other aspects of commercial farming operations.

The following examples help further illustrate these points. Harker and Blackshaw (1997) have published results based on the measurement of new leaf elongation of wild oats to identify optimum conditions for the application of reduced herbicide rates in barley. Initial results suggested that applications of 25 and 50% of the registered use rates of tralkoxydim and imazamethabenz-methyl provided effective control when applied on actively growing wild oats. However, in a follow-up report, the same researchers cautioned that even at high leaf growth rates, weed control at low herbicide rates could, in fact, be poor (Harker and Blackshaw 2000).

Similar results were noted in field trials designed to evaluate the effect of reduced herbicide (tralkoxydim) use rates on wild oat seed production, crop yield, and overall return on investment. Although 100 g ai/ha, or half use rates of tralkoxydim, led to revenue savings of $7 to 18/ha at two locations in 1 yr, similar experiments at another location led to economic losses ranging from $37 to 129/ha with the same reduced use rate over separate years. Researchers concluded that reduced herbicide rates can occasionally increase profitability, but any enhanced profitability was, in most cases, relatively small and not without significant risk (O'Donovan et al. 2003). These results are in agreement with experiments which examined the effect of increased seeding rates combined with reduced rates of tralkoxydim, fluazifop, and metribuzin on weed growth, crop yield, and net return (Kirkland et al. 2000). Similar results were recorded in examining the response of velvetleaf (*Abutilon theophrasti*) and green foxtail (*Setaria viridis* L.) to reduced rates of alachlor and atrazine in corn (*Zea mays*) (Roggenkamp et al. 2000). Yields of all hybrids tested showed similar reductions when the registered rates of alachlor and atrazine, 2.2 and 1.5 kg ai/ha, respectively, were reduced to 67 or 33% of registered use rates. Thus, it may be concluded that potential benefits associated with reduced rates tend to be both variable and very limited in terms of overall economic return.

Predictive Models. A number of simulation models have been developed to quantify the theoretical effects of reduced herbicide rates on weed populations and crop yield (Belles et al. 2000; Bussan and Boerboom 2001; Kim et al. 2002). The development of such models is the result of growing interest in developing systems to provide practical recommendations and predict the effect of reduced herbicide use rates on crop yield.

Unfortunately, the establishment of a general framework of practical recommendations to confirm the widespread use of reduced herbicide rates can be a difficult

Table 1. Effect of reduced (80%) and high (98%) herbicide efficacy on surviving wild oat population and percent yield loss in wheat and rapeseed.

	Reduced efficacy			High efficacy		
		Yield loss[a]			Yield loss[a]	
Initial population	Density	Wheat	Rapeseed	Density	Wheat	Rapeseed
		%			%	
0	0	—	—	0	—	—
50	10	11	9	1	—	—
100	20	15	13	2	—	—
200	40	22	19	4	<8	<7
500	100	34	30	10	11	9
1,000	200	>41	>37	20	15	13

[a] From Dew (1972) and Dew and Keys (1976) as outlined by Sharma and Vanden Born (1978).

task (Kim et al. 2002). A review of various articles covering the effect of different crop types (Boström and Fogelfors 2002; Brain et al. 1993; Christensen 1993; Lemerle et al. 1996; Richards and Davies 1991; Salonen 1992), seeding rates (Barton et al. 1992; Brain et al. 1999), crop cultivars (Christensen 1993; Lemerele et al. 1996; Richards and Davies 1991), and row spacing (Barton et al. 1992) on the effectiveness of reduced rates, confirmed this point. With few exceptions, each study demonstrated the possibility of successful weed control with sublethal herbicide rates, but only for very specific, and often ideal conditions.

To help manage inherent variability, programs developed in Europe have integrated the concept of ''factor adjusted doses'' as part of weed control models associated with reduced rate recommendations. For example, the Danish decision-support system ''PC Plant Protection'' uses log-logistic dose–response curves to link reduced rate recommendations with expected conditions in the field. As with most models, a series of open assumptions were considered in the system to capture the expected effects of climate, crop competition, herbicide mixtures, adjuvants, application technique, growth stage, weed density, etc. on expected herbicide efficacy. Furthermore, herbicide dose–response curves were assumed to be parallel for different weed species (Kudsk 2002). Given the economic diversity of Canadian agriculture and the inherent climatic variability from year to year, one would be wise to question the potential for lost profitability associated with the use of such models on a widespread basis.

Acceptable Herbicide Efficacy. Predictive herbicide use models and threshold studies inherently define required weed control on the basis of an arbitrary or predefined level of weed density or biomass reduction. Unfortunately, the assumed application of a predefined 80 to 85% reduction in weed biomass or initial weed density as a standard level of ''commercially acceptable control'' is not universally applicable. Consider the following examples. By definition, western Canadian canola (*Brassica napus* L.) growers require highly effective (99.9%) control of weeds such as wild mustard (*Sinapis arvensis* L.) or cleavers (*Gallium* spp.) to prevent weed seed contamination at harvest. Also, pedigree and foundation seed growers, who must certify that their product is weed-free before sale, will inherently demand very high levels of weed control from herbicide inputs. Conversely, producers who grow crops for silage may accept 70% control because the effects of weed competition and seed production may not be of much concern.

Aside from specific weed–crop interactions, it is also important to consider economic thresholds as applied to the size of the initial weed population before defining a commercially acceptable level of weed control. For example, if the economic threshold of wild oats was established at 20 plants/m^2 (Froud-Williams 2002) and a grower had a weed population ranging from 100 to 500 weeds/m^2, it is obvious that a herbicide treatment with 80% control will result in populations at, or well above, the threshold level after application. Conversely, application of a herbicide with over 98% efficacy would reduce populations well below the economic threshold (Table 1) resulting in a greater economic benefit. It is possible to further characterize economic effects associated with sublethal use rates through the use of more sophisticated threshold models which account for the prolonged competitive effects of partially controlled target weeds within the developing crop canopy.

Considering the relatively low cost of applying a highly efficacious product to minimize lost yield potential, and the probable negative long-term effect on the weed seed bank, which scenario would a producer most likely find ''commercially acceptable''? Would opinions change for highly competitive broadleaf weeds such as wild buckwheat (*Polygonum convolvulus* L.) (Hume et al. 1983) or Canada thistle (*Cirsium arvense* L.) (Moore 1975)? Thus, the competitiveness of a weed species and initial population densities are critical factors that must be considered when defining an acceptable level of control.

Short- and Long-Term Considerations. *Weed escapes–target site resistance.* Target site resistance as imposed by the repeated use of highly efficacious herbicides has prompted the development of numerous models to simulate the evolution, spread, and subsequent dynamics of herbicide resistance (Gressel and Segel 1990; Jasieniuk and Maxwell 1994; Maxwell et al. 1990). A common theme in much of this work was based on techniques established to lower selection pressure in an effort to prevent, delay, or reduce target site resistance within susceptible weed populations. Recommended techniques included use of more competitive crops, leaving untreated strips during herbicide application, reduced herbicide use rates, and even ceasing herbicide use to provide for enough healthy susceptible individuals within the population to reduce resistance levels through fitness and gene flow processes (Maxwell et al. 1990).

Some models go so far as to suggest that the use of herbicide treatments with reduced selection pressure help prevent or delay the eventual appearance of resistant populations by leaving behind enough susceptible weeds to dilute out resistant biotypes within the overall population. For example, the results of models established to simulate optimum thresholds of green foxtail in spring wheat (*Triticum aestivum* L.) determined that a herbicide efficacy threshold of 75% would help to minimize the development of herbicide resistance and projected crop yield reduction. In effect, leaving 25% of the weed population untreated was projected to reduce the maximum proportion of resistance in a weed population based on increased competition between susceptible and resistant plants during a 5-yr period (Maxwell 1992).

Not all agree with these recommendations. In the concluding remarks of their article summarizing the evolution and genetics of herbicide resistance in weeds, Jasieniuk et al. (1996) commented, ''differences in fitness between resistant and susceptible plants during the 'herbicide off' periods will significantly delay resistance only if the susceptible plants are substantially more fit than resistant plants. Similarly, maintaining a source of susceptible plants is not likely to be effective or desirable.''

Morrison and Friesen (1996) developed a model to assess the long-term effects of the use of reduced weed control. They commented that weed populations were likely to ''burgeon out of control'' if this practice was followed, which suggests that the use of reduced herbicide rates could have long-term adverse effects on weed seed banks. Weed densities were calculated where seed return was reduced by 80% (reduced efficacy) or 98% (high efficacy) in 2 out of 3 yr. Under the reduced efficacy regimen, in time, wild oat densities quickly exceeded acceptable levels, offsetting any perceived advantage gained in terms of delaying or avoiding resistance. The authors conclude by stating that: ''The most important conclusion is that rate cutting is not a reasonable way to avoid or delay resistance evolution.''

In addition, as part of their overview of strategies for reducing the risk of herbicide-resistant wild oats, Moss et al. (2001) commented that as dose was reduced and application timing delayed, the risk of inadequate control increased, especially on resistant weed populations. Perhaps for these reasons, very few agronomists have actually recommended reduced herbicide use rates in extension publications or print media as a means of lowering selection pressure in areas where herbicide resistance has surfaced. It is also noteworthy to mention that most comprehensive reviews of strategies to prevent the onset of herbicide resistance fail to mention the benefits of reduced herbicide rates as a strategy to prevent herbicide resistance (Gressel 1987; Jasieniuk et al. 1996; Moss and Rubin 1993).

Enhanced metabolism–systemic resistance. Even if it was possible to lower the incidence of target site resistance by lowering selection pressure, one must also consider the effect of reduced use rates on other forms of herbicide resistance. More recent studies suggest that weeds have the potential to develop resistance to herbicides as the result of metabolic processes, which rapidly degrade or conjugate (or both) the herbicide to less toxic compounds. This response should come as no surprise as it is well established that differential or enhanced metabolism is a major mechanism of plant selectivity to herbicides.

In fact, it is possible to demonstrate that the treatment of wild-type plants with sublethal herbicide doses can induce defense responses based on enhanced metabolic pathways to confer enhanced herbicide tolerance (Molina et al. 1999). Similar results were noted in research established to develop herbicide-tolerant crops. For example, Toldi et al. (2000) used in vitro selection techniques based on sublethal concentrations of the phosphionthricin herbicide to invoke elevated activity of the enzyme glutamine synthetase to confer herbicide tolerance in rice (*Oryza sativa* L.).

It would seem that very little direct research has been conducted to examine the interaction and effects of sublethal rates on multisite or polygenetic herbicide resistance on weed populations in the long term (I. Heap, personal communication). Despite this, many prominent weed scientists affirm that reduced rates may pose adverse effects. For example, I. Heap (personal communication) has stated that sublethal control in the long term will select for low-level resistance based on metabolic or multigentic resistance: ''. . . throughout the world, the worst cases of resistance to deal with are the metabolic cases, as rotation to another mode of action does not necessarily provide control. Metabolic resistance is more difficult to deal with. Examples of this are multiple resistance in *Lolium*, *Alopecurus* and *Echinochloa* spp.''

Other scientists have also argued that reduced rates have the potential to select for polygenetic or multifactorial resistance based on the gradual accumulation of several genes, each encoding for a small, incremental increase in resistance (Gressel 2002; Morrison and Friesen 1996). Some have described this as ''creeping resistance,'' which is most likely to occur under conditions of reduced selection pressure from the intentional use of sublethal doses or in cases where herbicide performance is consistently insufficient. Because a portion of the target weed population either escapes or recovers from herbicide injury, genetic recombination over several generations has the potential to produce plants that exhibit increased levels of herbicide resistance (Gressel 1995).

If it is demonstrated that resistance is the result of enhanced metabolic detoxification, it is entirely possible that weeds may also develop cross-resistance to herbicides with different modes of action. Such appears to be the case for populations of blackgrass (*Alopecurus myosuroides*) in the UK (Moss and Rubin 1993), ryegrass (*Lolium rigidum*) in Australia (Powles and Preston 1995), and canarygrass (*Phalaris minor*) in India (Gressel 1995).

Unfortunately, resistance mechanisms based on enhanced metabolism may result in reduced herbicide activity that may go underrecorded until widespread failures occur. This type of resistance, which is most likely polygenetic, is considered to evolve slowly but may ultimately be of the greatest significance because the effects can potentially extend to many different herbicide groups in an unpredictable fashion (Moss 2002).

Perhaps for these reasons, a recent review of the current state of knowledge regarding the ecological and population genetics of herbicide resistance has called for additional research based on a multidisciplinary approach and has proposed innovative new ways of looking at the evolution of herbicide resistance beyond selection pressure (Neve and Powles 2002).

It is therefore our position that reduced herbicide use rates are not an effective way to prevent the onset of herbicide-resistant weeds. Manufacturers support recommendations as outlined by Thill et al. (1994) and Moss (2002) and by organizations such as the Herbicide Resistance Action Committee (HRAC 2004), which serve to prevent or delay the occurrence of both metabolic and target site weed resistance. Such integrated weed management strategies to manage herbicide resistance include: (1) avoidance of repeated use of herbicides from the same chemical family; (2) increased crop rotation; (3) adoption of cultural control techniques; (4) use of weed-free seed; (5) adjusted seeding and tillage practices; (6) use of tank mixtures or sequential application of herbicides with different modes of action; (7) maintenance of detailed records of herbicide use and weed control patterns; (8) prevention of seed movement by cleaning harvest equipment, tarping grain trucks, etc.; (9) managed soil fertility levels; and, of course (10) always read and follow herbicide label use instructions.

Weed seed bank. The weed seed bank is a very complex subject. The effect of seed bank ecology on weed population dynamics is seemingly infinite because variation in any one of many diverse factors can have a dramatic effect on the means that weeds adapt to any given control mechanism. In the course of time, any given change to seed loss rate (longevity and aging), dispersal mechanisms, dormancy effects, germination patterns, microclimate, tillage systems, soil fertility regimes, herbicide use patterns, herbicide use rates, cropping practices, and seeding dates will affect the weed seed bank and will therefore affect future weed control strategies (Grundy and Jones 2002).

It is well established that seed banks are a means by which weed species survive unfavorable conditions. Thus, the weed seed bank exerts a strong genetic dispersal mechanism with time. This effect has been termed ''ecological memory'' and is believed to enable the seeds of many weed species with varying degrees of susceptibility to herbicides or other control mechanisms to survive with time (Naylor 2002). Weed seed banks therefore exert a strong buffering effect on both the germination patterns and susceptibility of target weeds to various control measures with time. In this regard, the longer the life in the seed bank, the greater the expected buffering effect of weed seed from previous years (Gressel and Segel 1990).

There has been much debate as to the success of the use of herbicides to reduce weed seed bank levels or to ''clean up'' a given field. Many believe that the use of herbicides as part of a well-executed weed control strategy can do just this. In fact, one could argue that land values for specific fields have been established solely on the basis of previous efforts to reduce the weed seed banks over the long term. Alternatively, many believe that this simply is not the case because once established, weeds simply do not go away.

Notwithstanding, if the use of reduced herbicide use rates leads to an increased number of seeds returning to topsoil and has the potential to confer metabolic resistance to further strengthen the seed bank's ecological memory, is it not in a grower's best short- and long-term interest to avoid the use of reduced herbicide rates?

Product Liability. Finally, one must consider the inherent variability associated with the many factors that can affect herbicide performance under field conditions. Experience has shown that any given change in herbicide use rate, climatic–growing conditions (e.g., hot vs. cold, wet vs. dry), tillage practice, seeding rate, weed emergence period, use of a product performance aid (e.g., water conditioners, adjuvants), spray carrier quality or volume, product delivery system (e.g., nozzle types, nozzle angles), application timing (i.e., pre- or posttreatment, growth stage, time of day), and registered tank mixtures can affect product efficacy and overall weed control.

On the basis of these reasons, it would simply be impossible to devise product labels and provide a commercial warranty to support the use of reduced herbicide rates specific to a unique and predetermined set of ''ideal'' conditions. To do so would increase the industry risk factor (Figure 1) and the associated financial liability beyond what is acceptable for a commercial product. Conversely, if a specific use rate were provided for every possible combination of conditions where reduced rates may provide efficacious weed control, product labels would become extremely complex and difficult to use.

Recently, there have been increasing incidents where certain private and public individuals (i.e., dealers, government agronomists) have been advising growers that products can be applied at use rates less than stated on registered label text.

It is the registrant's view that by making recommendations for what is essentially ''off label'' use of products, those individuals who would advise growers to use sublethal herbicide use rates leave themselves open to actions being commenced against them (or to third-party claims for indemnity by the manufacturer) for causes of action such as negligent misrepresentation or breach of fiduciary duty, should their off label recommendations lead to losses such as poor weed control or reduced crop yield. It is clear that although these individuals would not have a contractual relationship with the growers, they would certainly owe growers a ''common law duty of care'' not to make representations that suggest that growers pursue a course of action not approved by either the PMRA or the product's registrant.

CONCLUSIONS

Canadian growers use herbicides to manage weeds and minimize the negative economic effect on their crops. Growers require and expect products to perform consistently year after year under a wide range of growing conditions to provide the value, convenience, and performance that they were designed to deliver. Registrants invest a great deal of resources to identify the lowest effective use rate that will lead to long-term economic optimization for both the grower and registrant. Although it is theoretically possible to monitor threshold levels and identify potential cases where reduced herbicide use rates may provide commercially acceptable control, one cannot assume that growers are willing to invest the extra management time or, more importantly, risk long-term crop production goals to use herbicides at reduced rates. Growers are risk adverse and base their product decisions and efficacy requirements on crop production goals established with years of experience and not on theoretical models or predetermined threshold values. Reduced rates do not appear to be a solution to help manage target site resistance and may actually select for metabolic resistance, which is believed to add future challenges to production agriculture by charging the weed seed bank. Finally, crop protection product labels must be easily understood by all so that unnecessary complexities as related to recommendation of sublethal use rates are avoided.

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