Developing a Pesticide Risk Assessment Tool to Monitor Progress in Reducing Reliance on High-Risk Pesticides

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ABSTRACT

A methodology is presented for the development of a pesticide risk assessment tool that was used to monitor progress in reducing use of high-risk pesticides in Wisconsin potato production. Multi-attribute toxicity factors are calculated that reflect each pesticide's acute and chronic toxicity to mammals, birds, fish and small aquatic organisms, and compatibility with biointensive Integrated Pest Management. These factors are then multiplied by the pounds of active ingredient of a given pesticide applied to estimate pesticide-specific toxicity units. Wisconsin potato industry baseline toxicity units by type of pesticide and for 11 targeted higher-risk pesticides are presented for 1995. Reductions in toxicity units from this baseline are reported for 1997 and 1999, as are reductions achieved in a commercial-scale field experiment in 2000.

RESUMEN

Se presenta una metodología para el desarrollo de una herramienta de evaluación de riesgos de los plaguicidas que fue usada para vigilar los progresos en la reducción del uso de plaguicidas de alto riesgo en la producción de papas de Wisconsin. Se calculan los atributos múltiples de los factores de toxicidad, que reflejan la toxicidad aguda y crónica de cada plaguicida para los mamíferos, aves, peces y organismos acuáticos pequeños, y la compatibilidad con un biointensivo Manejo Integrado de Plagas. Estos factores son luego multiplicados por las libras del principio activo del plaguicida aplicado, con el fin de calcular las unidades de toxicidad específicas del plaguicida. Se presenta el punto de comparación para 1995 de las unidades de toxicidad de la industria de papa de Wisconsin por tipo del plaguicida y para 11 plaguicidas seleccionados por ser de más alto riesgo. Se reportan las reducciones del punto de comparación en las unidades de toxicidad para 1997 y 1999, como reducciones logradas en un experimento de campo de escala comercial en el 2000.

INTRODUCTION

Potatoes are produced in Wisconsin under irrigation on predominately sandy soils. The Central Sands, a major potato-growing region, is characterized by shallow, vulnerable groundwater and high-quality surface waters that support a variety of fish and bird species, as well as an active tourist industry (Lynch et al. 2000). Potatoes are grown in rotation with a number of field crops and canning vegetables in intensive, high-yield production systems. Pest pressure is often intense and poses major management challenges with significant regional economic and environmental consequences (Shields et al. 1984; Stevenson et al. 1994).

For more than two decades, Wisconsin water-quality-monitoring results have highlighted the need for careful management of nitrogen inputs and soil-incorporated pesticides (Fixen and Kelling 1981; Kelling et al. 1981; Wyman et al. 1985). Groundwa-

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ter contamination with the insecticide aldicarb in the early 1980s threatened the industry's survival and triggered heightened regulatory activity (Wyman *et al.* 1985). It also convinced growers and industry leaders that more should be done to develop and support adoption of "softer" prevention-based IPM systems and technologies (Sexson 2001; Stevenson et al. 1994).

Grower check-off funds have helped support a multidisciplinary team of University of Wisconsin-Madison researchers addressing potato IPM. The team works closely with growers and pest management consultants on a range of applied on-farm pest management and cropping system research projects. In close cooperation with the UW potato IPM team, the Wisconsin Potato and Vegetable Growers Association (WPVGA) established a collaborative project with the World Wildlife Fund (WWF) in 1996. The WPVGA-WWF collaboration set goals for reducing use of 11 pesticides and for progress along the IPM continuum toward biointensive IPM (Benbrook et al. 1996). A key goal was to develop methods to monitor and to document grower adoption of biointensive IPM practices and to explore linkages between IPM adoption and reduced pesticide use.

The collaboration formed a multi-stakeholder advisory committee in 1996, and this group has met several times since. Criteria were established to identify "high-risk" pesticides used in Wisconsin potato production that should be targeted for reduced use based on acute and chronic mammalian toxicity, ecological risks, and compatibility with biointensive IPM systems. A high-risk pesticide active ingredient is one that is significantly more toxic or potentially damaging per unit of exposure than other registered active ingredients in one or more category of risk. Government regulatory agencies and international organizations have classified pesticides according to a variety of relative risk measures (e.g., see the International Programme on Chemical Safety's 1997 LD_{50}-based acute mammalian toxicity classification systems [IPCS 1996], or the U.S. EPA's system for classifying pesticides as "restricted use" based on worker and environmental risks [Office of Pesticide Programs 2001]).

Four pesticides used in Wisconsin potato production in 1995 met the acute toxicity criterion: methamidophos, azinphos-methyl, carbofuran, and oxamyl. Seven pesticides triggered the chronic mammalian toxicity criteria: the fungicides mancozeb, maneb, chlorothalonil, and triphenyltin hydroxide, the insecticides permethrin and endosulfan, and the herbicide metribuzin.

Incremental Wisconsin potato industry goals for reducing the toxicity units associated with use of high-risk pesticides were established for 1997, 1999, and 2001. Pesticide use in 1995 was used to establish the baseline because the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA/NASS) did not survey potato pesticide use in Wisconsin in 1996. Hence, the "first year" goal applies to changes in pesticide use from 1995 to 1997. The acute, chronic, and combined toxicity percentage reduction goals for 1997 were 25%, 15%, and 20%, respectively. In 1999 third-year goals were 50%, 30%, and 40% reductions, respectively, and the five-year (2001) goal called for 100% reductions. Recently set goals incorporated in the 2001 ecolabel program are based on incremental reductions in the toxicity units per acre of fresh market potatoes.

In addition to monitoring industry-wide changes in pesticide use and corresponding toxicity units, the impacts of changes in pest management systems on average per acre pesticide use and toxicity units have been studied. In response to grower-interest, the team is incorporating the costs of alternative pesticides and management systems into the analysis, producing estimates of the marginal economic costs of reducing toxicity units through adoption of lower-risk pesticides and IPM system changes.

BACKGROUND

Interest is growing worldwide in the potential for IPM to reduce the direct and indirect health and environmental costs associated with pesticide use. State, federal, and international agencies are funding or participating in programs designed to promote IPM adoption (Benbrook et al. 1996). Environmental and consumer groups are exploring ways to promote and reward IPM adoption through marketplace initiatives (Consumers Union 2001; Hoppin 1996). The WWF/WPVGA/UW collaboration is developing standards for potato production and pest management in preparation for marketing eco-labeled fresh market potatoes in 2001 (Lynch et al. 2000).

Pest managers, researchers, and policy-makers need better tools to monitor the consequences of changes in pest pressure, resistance, and the use of IPM strategies (Ehler and Bottrell 2000). Two traditional measures of pesticide use — pounds of active ingredient applied per acre and number of applications — are inadequate for estimating the agronomic, environmental, and public health consequences of pesticide use (Barnard et al. 1997). A review of several efforts to develop new measurement tools appears in the Consumers Union book *Pest Management at the Crossroads* (Benbrook et al. 1996). Levitan (1997) prepared a detailed comparative assessment of pesticide impact measurement systems under development both in the Untied States and abroad.

Improved measurement systems and tools are needed to track trends in IPM system performance and address tradeoffs as growers adopt more complex, prevention-based IPM systems reliant largely on reduced-risk pesticides. Many exogenous factors can alter pest pressure and/or pest management efficacy, such as landscape diversity, pesticide resistance, emergence of new, more aggressive strains of pests, new pesticides changes in pesticide prices, novel IPM tactics, and resistant cultivars (Benbrook et al. 1996). Potato processors, buyers, and farm lenders also periodically impose contract or loan provisions affecting pest management systems.

Measurement systems need to be dynamic and should focus, in particular, on documenting impacts of IPM system changes on the use of higher-risk pesticides over time (Ehler and Bottrell 2000). Such systems are a structured framework within which to pose and answer questions about the human health, environmental, ecological, and cost-related impacts of changes in pest management systems. The components of a pesticide risk measurement system will vary as a function of cropping systems, soil and climatic conditions, and the dominant risk and environmental concerns in the geographic region under study. There is no inherently "right way" to measure pesticide toxicity and risks. Ideally all systems should take into account the volume of pesticides applied, when and how pesticides are applied, pesticide environmental fate, when and the extent to which nontarget organisms are exposed, and the toxicity of active ingredients. A variety of factors can influence exposure levels and frequency, and hence risk. Our measure, "toxicity units," reflects potential toxic impact per pound of active ingredient applied of a given pesticide; factors affecting exposures, such as whether a pesticide is applied as a soil-incorporated granular or sprayed as a liquid formulation, will determine which organisms are adversely affected.

Several assumptions and subjective judgments are required in developing a multi-attribute pesticide-risk index. The basic purpose of the index will help determine which toxicity, environmental fate, and risk factors should be taken into account, to the extent possible, and which can be ignored without undermining the utility of the index in light of a particular application. Consistent logic and transparent decision-rules should govern the analyst or project team as various decisions are made. Toxicity factor values, coupled with data on pesticide use, are particularly useful in monitoring changes over time and in highlighting possibly high-risk pesticide uses in contrast to those posing modest or no risks to nontarget organisms. Toxicity unit-based measurement systems can also provide a framework to assess alternative ways for growers or regulators to achieve a given risk-reduction goal. The current reassessment of organophosphate (OP) insecticide uses and related dietary exposures, driven by the Food Quality Protection Act (FQPA), is a contemporary example.

MATERIALS AND METHODS

Calculating Toxicity Factor Values

The equation used in our measurement system to estimate an active ingredient's toxicity factor value contains four component indices: acute mammalian toxicity (AM), chronic mammalian toxicity (CM), ecological impacts (ECO), and impacts on beneficial organisms and IPM systems (BioIPM). The latter two components are, in turn, made up of multiple subindices as explained later in this report.

Several issues typically arise in calculating pesticide toxicity index values focusing on a single risk component, like acute mammalian toxicity. Additional issues arise when combining different risk indices (e.g., acute and chronic mammalian toxicity and avian toxicity) into a multi-attribute measure of relative pesticide toxicity (Landy 1995).

The multi-attribute system used in Wisconsin is evolving. It is structured such that larger values imply higher toxicity or risk. In the case of toxicological measures of dosage such as LD_{50s} (lethal dosage at which 50% of test animals are killed) or EC_{50s} (environmental concentration at which 50% of test organisms are killed), inverse LD_{50} or EC_{50} values are calculated so that rising index values equate with rising toxicity. In doing so, many problems can arise. For some pesticides, acute mammalian toxicity tests were carried out years ago, using mostly or exclusively rats. Results are not directly comparable to current protocols or data from mouse tests. In other cases, acute toxicity data are available just on formulated products or on active ingredients that differ somewhat from the chemicals in older pesticide formulations.

Sometimes aquatic invertebrate or fish EC_{50} values are reported for tests lasting 24 h and in other cases shorter or longer periods of exposure are used. Sometimes data cover 100% pure technical-grade active ingredient, while in others 95% or 70% pure formulations. For some pesticides and test organisms the Environmental Protection Agency (EPA) has limited or no ecotoxicological data in its files; for others, it has multiple studies on the same organism, often producing somewhat different results and requiring either a way to choose between several studies or average results across equally valid studies.

Scaling issues arise in establishing values within an index and when combining results across several indices. Scaling is a necessary step to keep one component index – chronic mammalian toxicity (CM), for example — from dominating multi-attribute toxicity factor values. For example, if CM index values fall within a range of 10 and 1,000, with values for 20 pesticides falling between 200 and 1,000, while all other component values fall within a range of 1 and 100, multi-attribute toxicity factors will be heavily weighted toward chronic mammalian risk simply as an artifact of differences in the range of toxicity values reported across risk parameters and pesticides.

When there are large differences in the range and variability of values across indices, analysts must determine whether it is appropriate to allow one or a few categories of risk to dominate values while others play little or no role in setting values. Such an outcome might be appropriate in a case where there is evidence that a single risk is by far the most important, given the pesticides used and exposure patterns within an agricultural system.

In the case of Wisconsin potato production, the multi-stakeholder advisory committee recommended that the four component indices should include values in roughly the same range, so that any decisions to alter the weights assigned to a given component index could be made explicitly through the addition of a weighting factor in the multi-attribute toxicity-factor equation. Accordingly, component index values and subindices were scaled so that individual active ingredient values fell within roughly the same range in each index and subindex; in some cases, scaling reduced index values, in other cases it raised them.

Outlier values in an index also require attention to assure that one or a few extremely high values are an accurate and realistic reflection of actual differences in toxicity from use of one or a few pesticides compared to most others. Any maximum value in an index that is more than twice as large as the next highest value was reviewed as a potential outlier. In such cases, available and relevant data were reviewed to determine if the difference in values is consistent

TABLE 1—*Acute (AM) and chronic mammalian (CM) toxicity index components and values.*

	LD-50 values (mg/kg)	Scaled inverse LD-50+ (AM)	Chronic reference dose or cPAD (mg/kg/day)	Oncogenic potency factor	Chronic toxicity (CM)
2,4-D	375	1.33	0.003		100
alachlor	930	0.54	0.01		30
azinphos-methyl	16	31.25	0.0015		66.67
azoxystrobin	5,000	0.1	0.18		0.56
basic copper sulfate	2,500	0.2	0.33		0.3
carbofuran	8	62.5	0.005		60
chlorothalonil	5,000	0.1	0.02	0.0077	8.85
chlorpropham	3,800	0.13	0.05		2
clethodim	1,360	0.37	0.01		10
copper ammonium	300	1.67	0.33		0.3
copper hydroxide	1,000	0.5	0.33		0.3
copper resinate	5,000	0.1	0.33		0.3
copper sulfate	300	1.67	0.33		0.3
cyfluthrin	500	1	0.008		12.5
cymoxanil	960	0.52	0.013		7.69
diazinon	300	1.67	0.0007		142.86
dimethoate	150	3.33	0.0005		200
dimethomorph	3,900	0.13	0.1		1
diquat	231	2.16	0.005		20
disulfoton	3	192.31	0.0001		200
endosulfan	80	6.25	0.006		50
endothal	51	9.8	0.02		5
EPTC	1,652	0.3	0.0025		40
esfenvalerate	67	7.46	0.02		5
ethoprophos	26	19.23	0.0001	0.0281	200
fludioxonil	5,000	0.1	0.03		3.33
fonofos	8	62.5	0.002		50
glufosinate ammonium	1,510	0.33	0.02		5
glyphosate	4,230	0.12	2		0.05
imidacloprid	450	1.11	0.019		5.26
linuron	4,000	0.13	0.008		12.5
malathion	2,100	0.24	0.024		12.5
maleic hydrazide	5,000	0.1	0.25		0.4
mancozeb	5,000	0.1	0.003	0.06	130
maneb	5,000	0.1	0.005	0.06	90
mefenoxam	490	1.02	0.08		1.25
metalaxyl	670	0.75	0.074		1.35
metam sodium	285	1.75	0.01	0.198	109
methamidophos	30	16.67	0.0001		200
metiram	5,000	0.1	0.0003		200
metolachlor	2,780	0.18	0.1		1
metribuzin	2,200	0.23	0.013		23.08
oxamyl	6	83.33	0.001		100
paraquat dichloride	283	1.77	0.0045		22.22
pendimethalin	1,050	0.48	0.1		3
permethrin	500	1	0.05	0.0184	10.6
petroleum oils	5,000	0.1	0.25		0.4
phorate	2	200	0.0002		200
phosmet	230	2.17	0.011		9.09
piperonyl butoxide	5,000	0.1	0.0175		17.14
propamocarb hydrochloride	5,000	0.1	0.1		1
pymetrozine	5,820	0.09	0.0013		76.92
pyrethrins	1,500	0.33	0.064		4.69

TABLE 1—*Continued*

	LD-50 values (mg/kg)	Scaled inverse LD-50+ (AM)	Chronic reference dose or cPAD (mg/kg/day)	Oncogenic potency factor	Chronic toxicity* (CM)
quintozene	1,700	0.29	0.003		33.33
rimsulfuron	5,000	0.1	0.818		0.12
sethoxydim	3,200	0.16	0.09		1.11
spinosad	3,738	0.13	0.0268		3.73
sulfur	300	1.67	0.33		0.3
sulfuric	acid	1,000	0.5	0.33	0.3
thiamethoxam	1,563	0.32	0.013		7.69
thiophanate-methyl	5,000	0.1	0.08		1.25
trifloxystrobin	5,050	0.1	0.05		2
trifluralin	5,000	0.1	0.024	0.0077	14.43
triphenyltin hydroxide	156	3.21	0	2.8	200

Notes: + "Scaled inverse LD_{50} is ($500/LD_{50}$)

with other differences observed in comparable toxicology studies carried out on closely associated organisms, or instead reflects how one particular study was carried out or how the results of certain studies were interpreted.

In adjusting outlier values, guidance was sought from the project advisory committee and experts in the relevant disciplines. As shown in the Table 1, maximum values were set at 200 in one case in the acute mammalian (AM) index (phorate), and in six cases in the chronic mammalian index (CM). One scaled fish subindex value was set at 200 (esfenvalerate, Table 2), and overall 2001 Ecotox index values were truncated at 200 in two cases (esfenvalerate and cyfluthrin). The esfenvalerate BioIPM index was also set at 200 (Table 3).

Data gaps are pervasive when calculating pesticide toxicity index values. For example, even basic mammalian toxicity data are lacking for most biopesticides (active ingredients that work through a nontoxic mode of action [e.g., an insect growth regulator] and/or that are naturally derived biochemicals [e.g., *Bacillus thuringiensis* (Berliner)]) and for copper-based fungicides, since the EPA has exempted pesticides containing these ingredients from testing and tolerance requirements (set forth in Code of Federal Regulations, section 180.1001). Fish toxicity data for fungicides are limited and relatively few herbicides have been tested for impacts on beneficial arthropods. Default values have been established in such cases, as discussed in each of the following sections.

Component Indices

The acute mammalian (AM) toxicity index is based on oral LD_{50} from rat assays. LD_{50} values are derived predominantly from the *WHO Recommended Classification of Pesticides by Hazard and Guidelines to Classification 1996-1997* (International Programme on Chemical Safety 1996). LD_{50} values for recently registered active ingredients are derived from EPA tolerance documents published in the Federal Register. In a few cases, LD_{50} values were derived from *Farm Chemicals Handbook 2000* (Meister 2000), suppliers, or other sources.

Table 1 reports LD_{50} values, inverse LD_{50} values, and AM index values for pesticides used in Wisconsin potato production. A scaling factor of 500 was used in calculating acute mammalian (AM) values. For example, the LD_{50} of the organophosphate insecticide azinphos-methyl is 16 mg/kg, so the scaled inverse acute mammalian toxicity index value is 31.25 (500/16). The most acutely toxic pesticide used in Wisconsin potato production is phorate, which has an LD_{50} of 2 mg/kg and a scaled inverse LD_{50} value of 250 (capped in Table 1 at the maximum allowed value, 200). The least acutely toxic pesticides have LD_{50} values of 5,000 mg/kg or higher (5,000 mg/kg is typically the highest dose tested). When scaled, AM values are 0.1 for these active ingredients (e.g., chlorothalonil, the EBDCs, and strobilurin fungicides). The table shows that acute mammalian toxicity contributes little to the total toxicity factor values for many widely used pesticides. AM values for 28 active ingredients are below 1. Only two organophosphate insecticides – phorate and disulfoton – have values over 100.

The chronic mammalian (CM) toxicity index measures risks stemming from longer-term, low-level drinking water, occupational, and dietary exposures (Benbrook et al. 1996). It encompasses the capacity of an active ingredient to cause adverse health impacts such as cancer or impaired immune system function and is driven largely by EPA population-adjusted chronic Reference Doses, otherwise referred to as "cPADs" (chronic Population Adjusted Doses are chronic Reference Doses modified by any FQPA-driven added safety factors) (Office of Pesticide Programs 2000).

The index is a composite variable developed and first calculated to evaluate long-term trends in the chronic toxicity of pesticides as part of the analysis reported in the Consumers Union book *Pest Management at the Crossroads* (Benbrook *et al.* 1996). The CM index formula is

TABLE 2—*EcoToxicity factor values from 1997 to 2001 and percentage change from 2000 to 2001.*

Active ingredient	AI type	2001 component indices (scaled) Daphnia (col. C)	Fish (col. D)	Avian (col. E)	2001 index [col C+D+E]	1998 EcoTox index	Percent change to 2001
triphenyltin hydroxide	Fungicide	25.00	52.60	40.61	118.20	118.20	0.00
azoxystrobin	Fungicide	1.00	5.60	1.29	7.89	41.29	-0.81
trifloxystrobin	Fungicide	1.00	5.60	1.29	7.8994		
chlorothalonil	Fungicide	3.57	22.70	1.55	27.82	27.82	0.00
quintozene (PCNB)	Fungicide	14.80	0.33	1.17	16.30		
dimethomorph	Fungicide	1.00	10.00	1.44	12.44	12.44	0.00
basic copper sulfate	Fungicide	0.25	1.47	6.37	8.09	8.09	0.00
maneb	Fungicide	0.07	7.08	0.87	8.02	8.02	0.00
fludioxonil	Fungicide	0.23	5.03	1.44	6.70		
copper sulfate	Fungicide	0.30	0.90	6.40	7.60	2.50	2.04
mefenoxam***	Fungicide	0.00	0.02	3.37	3.39		
metalaxyl	Fungicide	0.00	0.02	3.37	3.39	3.39	0.00
copper hydroxide	Fungicide	0.25	0.92	1.37	2.54	2.54	0.00
mancozeb	Fungicide	0.25	1.57	0.42	2.24	2.24	0.00
copper resinate	Fungicide	0.25	0.12	1.43	1.80	1.80	0.00
copper ammonium	Fungicide	0.25	0.12	1.40	1.77	1.77	0.00
cymoxanil	Fungicide	0.01	0.12	1.28	1.41	1.41	0.00
metiram	Fungicide	0.04	0.01	1.20	1.25	1.25	0.00
propamocarb hydrochloride	Fungicide	0.00	0.00	0.93	0.94	0.94	0.00
thiophanate-methyl	Fungicide	0.01	0.08	0.62	0.71		
sulfur	Fungicide	0.00	0.01	0.01	0.02	0.02	0.00
trifluralin	Herbicide	0.42	171.50	1.22	173.14		
diquat	Herbicide	0.04	0.01	16.84	16.89	16.89	0.00
EPTC	Herbicide	0.03	0.08	11.85	11.96		
pendimethalin	Herbicide	0.89	4.98	5.00	10.87	10.87	0.00
endothal	Herbicide	0.00	0.04	10.27	10.31	10.31	0.00
metribuzin	Herbicide	0.06	0.02	7.14	7.22	7.22	0.00
linuron	Herbicide	1.25	0.30	4.61	6.16	6.16	0.00
paraquat dichloride	Herbicide	0.21	0.11	3.39	3.71	3.71	0.00
2,4-D	Herbicide	0.05	0.32	2.26	2.63	2.63	0.00
chlorpropham	Herbicide	0.07	0.31	1.55	1.93		
rimsulfuron	Herbicide	0.00	0.00	1.87	1.87	1.87	0.00
metolachlor	Herbicide	0.01	0.25	1.24	1.50	1.50	0.00
clethodim	Herbicide	0.01	0.06	1.29	1.36		
glufosinate ammonium	Herbicide	0.00	0.02	1.29	1.31		
glyphosate	Herbicide	0.00	0.01	1.29	1.31	1.31	0.00
Alachlor	Herbicide	0.01	0.25	0.91	1.17	1.17	0.00
sethoxydim	Herbicide	0.00	0.01	0.62	0.63	0.63	0.00
cyfluthrin	Insecticide	177.30	156.86	0.06	200.00		
esfenvalerate	Insecticide	166.67	200.00	0.23	200.00	200.00	0.00
phorate	Insecticide	0.68	86.46	88.24	175.37	180.56	-0.03
carbofuran	Insecticide	0.74	1.30	140.58	142.62	144.90	-0.02
endosulfan	Insecticide	0.15	115.08	3.15	118.38	118.38	0.00
diazinon	Insecticide	2.60	0.71	50.85	54.16		
permethrin	Insecticide	13.30	28.16	0.01	41.47	41.47	0.00
oxamyl	Insecticide	0.01	0.03	38.46	38.50	38.50	0.00
disulfoton	Insecticide	0.36	0.00	37.04	37.40	36.35	0.03
azinphos-methyl	Insecticide	0.01	16.69	13.13	29.84	29.84	0.00
fonofos	Insecticide	12.50	5.81	7.77	26.09	28.80	-0.09
phosmet	Insecticide	0.00	0.00	24.19	24.20	24.20	0.00
methamidophos	Insecticide	0.74	0.00	17.62	18.36	18.36	0.00
dimethoate	Insecticide	10.00	0.03	5.19	15.22	15.22	0.00
ethoprophos	Insecticide	0.37	0.11	12.46	12.94	12.95	0.00
pyrethrins	Insecticide	2.16	8.86	0.03	11.05	11.05	0.00
pymetrozine	Insecticide	3.00	4.00	0.14	7.14		
thiamethoxam	Insecticide	0.00	0.00	3.56	3.56		
imidacloprid	Insecticide	0.00	0.00	3.56	3.56	3.56	0.00
spinosad	Insecticide	0.00	0.45	0.11	0.56		
malathion	Insecticide	0.10	0.10	0.22	0.42	0.42	0.00
piperonyl butoxide	Insecticide	0.02	0.04	0.11	0.18	0.18	0.00
Bacillus thuringiensis	Insecticide	0.00	0.08	0.06	0.14	0.14	0.00
metam sodium	Other	0.11	2.47	5.17	7.74	7.74	0.00
maleic hydrazide	Other	0.00	0.02	1.38	1.40	1.40	0.00
sulfuric acid	Other	0.00	0.01	0.01	0.02	0.02	0.00

TABLE 3—*BioIPM factor values for 2001, changes since 1997, and percentage change from 2000 to 2001.*

Active ingredient	AI type	2001 component indices Resistance (col. C)	Beneficials (col. D)	Bee toxicity (col. E)	2001 BioIPM [(C+D+E) x0.5]	1997 BioIPM	1998 BioIPM Index	2000 BioIPM	Percent 2000 to 2001
mefenoxam	Fungicide	100	50	0.1	**75**	113.0	113.0	113.0	-33.6%
metalaxyl	Fungicide	100	50	0.1	**75**	113.0	113.0	113.0	-33.6%
sulfur	Fungicide	6	80	0.0	**43**	45.2	45.2	45.2	-4.9%
mancozeb	Fungicide	10	60	0.6	**35**	41.6	43.5	43.5	-18.7%
triphenyltin hydroxide	Fungicide	18	70	0.1	**44**	38.4	43.2	43.2	1.9%
maneb	Fungicide	10	60	0.8	**35**	44.1	42.9	42.9	-17.4%
azoxystrobin	Fungicide	40	10	0.1	**25**		34.8	34.8	-28.0%
trifloxystrobin	Fungicide	40	10	0.1	**25**				
metiram	Fungicide	10	60	0.6	**35**	32.7	33.0	33.0	7.1%
propamocarb hydrochloride	Fungicide	30	30	1.0	**31**	32.4	32.4	32.4	-5.9%
chlorothalonil	Fungicide	10	50	0.1	**30**	30.4	30.0	30.0	0.0%
cymoxanil	Fungicide	14	30	0.4	**22**	34.2	27.8	27.8	-20.0%
quintozene (PCNB)	Fungicide	15	30	0.1	**23**				
copper hydroxide	Fungicide	5	40	1.0	**23**	30.1	29.7	29.7	-22.6%
copper resinate	Fungicide	5	40	1.0	**23**	30.1	29.7	29.7	-22.6%
copper ammonium	Fungicide	5	40	1.0	**23**	30.0	29.6	29.6	-22.3%
fludioxonil	Fungicide	15	20	0.0	**18**				
dimethomorph	Fungicide	14	20	0.1	**17**		21.6	21.6	-21.2%
thiophanate-methyl	Fungicide	20	20	0.1	**20**				
basic copper sulfate	Fungicide	5	10	1.0	**8**		22.8	22.8	-64.9%
copper sulfate	Fungicide	5	10	1.0	**8**	23.2	22.8	22.8	-64.9%
rimsulfuron	Herbicide	100	51	0.1	**86**	53.1	96.4	96.4	-11.3%
pendimethalin	Herbicide	100	17	0.2	**69**	96.4	78.9	78.9	-13.0%
metribuzin	Herbicide	60	51	0.6	**56**	64.5	64.7	64.7	-13.7%
paraquat dichloride	Herbicide	6	65	0.2	**36**	38.1	52.5	52.5	-32.2%
sethoxydim	Herbicide	45	15	1.0	**31**	38.8	48.4	48.4	-37.0%
linuron	Herbicide	6	51	0.6	**29**	38.8	39.1	39.1	-26.2%
alachlor	Herbicide	6	41	0.6	**24**		51.2	51.2	-53.2%
glyphosate	Herbicide	6	41	0.1	**24**	51.0	51.0	51.0	-53.5%
glufosinate ammonium	Herbicide	6	41	0.1	**24**				
endothal	Herbicide	6	40	1.0	**24**	26.8	26.8	26.8	-12.3%
diquat	Herbicide	6	40	0.6	**23**	30.4	26.7	26.7	-12.5%
chlorpropham	Herbicide	10	30	0.6	**20**			24.3	-16.2%
metolachlor	Herbicide	9	17	0.1	**13**	30.4	30.4	30.4	-57.1%
trifluralin	Herbicide	6	20	0.1	**13**				
2,4-D	Herbicide	6	17	0.1	**12**		41.2	41.2	-72.0%
EPTC	Herbicide	6	15	0.6	**11**				
clethodim	Herbicide	6	15	0.1	**11**				
esfenvalerate	Insecticide	192	67	166.7	**200**	126.7	182.1	182.1	9.8%
cyfluthrin	Insecticide	168	100	100.0	**184**			159.2	15.6%
permethrin	Insecticide	168	103	90.9	**181**	141.2	156.8	156.8	15.4%
disulfoton	Insecticide	54	67	166.7	**144**		138.9	138.9	3.4%
azinphos-methyl	Insecticide	48	70	166.7	**143**	79.0	130.0	130.0	9.6%
pyrethrins	Insecticide	108	100	76.9	**142**	100.4	126.0	126.0	13.1%
spinosad	Insecticide	50	15	100.0	**83**			112.0	-26.3%
oxamyl	Insecticide	45	139	32.3	**108**	94.0	106.5	106.5	1.5
imidacloprid	Insecticide	72	40	87.5	**100**	163.6	200.0	99.8	-0.1%
thiamethoxam	Insecticide	72	40	87.5	**100**				
dimethoate	Insecticide	36	71	83.3	**95**	81.3	92.3	92.3	3.3%
carbofuran	Insecticide	45	71	62.5	**89**	112.0	111.4	111.4	-19.9%
malathion	Insecticide	40	100	37.0	**89**		82.8	82.8	6.9%
diazinon	Insecticide	48	70	45.5	**82**		0.0	81.6	0.5%
phorate	Insecticide	24	100	37.0	**81**	85.1	96.4	96.4	-16.5%
methamidophos	Insecticide	48	77	11.6	**68**	62.1	74.6	74.6	-8.5%
endosulfan	Insecticide	63	61	1.4	**63**	71.2	66.3	66.3	-5.2%
ethoprophos	Insecticide	45	67	2.4	**57**	65.6	77.6	77.6	-26.5%
phosmet	Insecticide	45	33	16.4	**47**		49.9	49.9	-5.1%
fonofos	Insecticide	23	56	3.0	**41**	60.8	64.4	64.4	-37.1%
piperonyl butoxide	Insecticide	9	40	0.6	**25**	28.0	27.9	27.9	-10.9%
pymetrozine	Insecticide	30	10	5.0	**23**			26.0	-13.5%
bt	Insecticide	8	5	0.6	**7**			7.5	-8.5%
metam sodium	Other	6	60	0.3	**33**	58.5	58.5	58.5	-43.4%
maleic hydrazide	Other	6	40	0.6	**23**	26.5	26.7	26.7	-12.5%
sulfuric acid	Other	6	20	1.0	14	18.8	18.8	18.8	-28.2%

$$\text{CM for Pesticide}_x = [(0.1/\text{cRfD}_x) \times \text{ED}_x] + [Q^*_x \times 50 \times \text{CLASS}_x]$$

Where:

cRfD = EPA chronic Reference Dose or chronic Population Adjusted Dose (or a default value or provisional estimate)

ED = Endocrine disruptor — if yes, value=3; if no information or no evidence from appropriate assays, value=1

Q* = EPA oncogenic potency factor (slope of the dose-response curve)

CLASS = EPA Oncogenicity Classification. If Class A or B_2, value=10;

if C, value=5; if D, value=2.

Table 1 reports CM values by active ingredient, chronic Reference Doses (cRfD) or cPADs, and oncogenic potency factors for those active ingredients deemed carcinogenic by EPA. Chronic RfDs/cPADs are derived from Federal Register notices (pesticide Federal Register notices are accessible at http://www.epa.gov/fedrgstr/EPA-PEST/index.html) and are current through July 2000. Oncogenic potency factors are from EPA's periodic summary of data on pesticides shown to cause cancer (Burnam 1999) or recent Federal Register documents reporting revised risk assessments.

Pesticides known to be endocrine disruptors are treated differently in calculating CM values in that the cRfD/cPAD portion of the above CM formula includes an added three-fold safety factor for such pesticides. An EPA-sponsored symposium in 1995 adopted the following consensus definition of endocrine disruptor:

> An exogenous agent that interferes with the production, release, transport, metabolism, binding, action, or elimination of natural hormones in the body responsible for the maintenance of homeostasis and the regulation of developmental processes (Kavlock et al. 1996:716).

The WWF/WPVGA/UW collaboration relies on the WWF's Wildlife and Contaminants Program (WWF-WCP) staff, and their extensive endocrine disruptor research database, to identify pesticides that are endocrine disruptors. A member of the WWF-WCP team, Dr. Francoise Brucker-Davis has published a thorough review on endocrine-related thyroid effects (Brucker-Davis 1998). This review discussed evidence of thyroid effects covering nine of the 12 pesticides now identified by the collaboration as known or suspect endocrine disruptors. The collaboration's original 1995 list of five endocrine disruptors was derived from Colborn et al. (1993) and has twice been updated on the basis of new information. A review of the estrogenic potential of four synthetic pyrethroids supported inclusion of esfenvalerate and permethrin on the list (Go *et al.* 1999). Pesticide impacts on neural development can also be endocrine related and support the placement of several organophosphate and carbamate insecticides on the list (Bigbee et al. 1999; Repetto and Baliga 1996). Colborn et al. (1999) supports the collaboration's current list of endocrine disruptors, as well as the possible need to add a few additional active ingredients to the list in future updates.

In setting cRfDs/cPADs, the EPA assesses evidence of heightened toxicity to pregnant and/or young animals (Kimmel 1995). The most common tests where such effects are seen include two-generation reproduction studies and developmental neurotoxicity studies. In such cases, EPA often adds a three- to ten-fold added safety factor to account for endocrine-related risks and other heightened risks faced by vulnerable populations (Office of Pesticide Programs 1999). The ten-fold provision in the 1996 Food Quality Protection Act (FQPA) codified EPA's existing practice of adding an additional ten-fold safety factor in stetting the RfDs of chemicals that are more toxic to young or pregnant animals or for chemicals with significant data gaps. Prior to passage of the FQPA, EPA had imposed a three-fold added factor in 21 cases, a ten-fold added factor in 22, and greater than ten-fold in six cases involving widely used pesticides (Office of Pesticide Programs 1995). In the majority of these cases, the added safety factors were imposed because of poorly designed studies, a lack of a "No Observed Effect Level," or a major data gap (see Groth et al. [2001] for details on pre-FQPA and FQPA safety factors [Table 2.2] and why safety factors have been imposed on organophosphate insecticides [Appendix 1]).

When the FQPA is fully implemented, pesticide cRfDs/cPADs will presumably reflect heightened risk faced by pregnant or young animals, including endocrine effects. This process will take at least another five to seven years, given the time needed for EPA to develop new endocrine disruptor test protocols and for industry to generate new data, followed by EPA evaluation of the new data. In the interim, the collaboration advisory committee felt it appropriate to include a three-fold safety factor reflecting potential endocrine effects. While this safety factor is less than the ten-fold factor called for by the FQPA, in many cases EPA has already added an additional safety factor for reasons that overlap to some degree with endocrine-related concerns.

The ecological (ECO) toxicity index is the sum of avian, aquatic and small invertebrate subindex values and is shown in Table 2. Avian toxicity values were provided by Dr. Pierre Mineau, Canadian Fish and Wildlife Service. While there are more than 10,000 bird species in the world, pesticides are generally tested in just one to three species for acute toxicity (Mineau et al. 2001). With an international team, Mineau developed an avian toxicity model, drawing on a database with more than 2,300 acceptable LD_{50} values for 872 pesticides (Mineau et al. 2001). These LD_{50} studies were used to estimate dosage levels expected to protect 95% of the bird species within an ecosystem. The resulting values are a robust index of relative avian toxicity following acute exposures. Work is underway to expand the model to encompass sub-acute and reproductive effects. As in the case with other parameters, updated values will be incorporated in our estimates of avian toxicity when available.

Impacts of pesticides on small aquatic organisms are estimated based on data on water fleas, *Daphnia magna* (Straus), the most frequently listed crustacean species in the EPA-Ecotoxicology database (Montague 1999). Comparable studies were selected from the EPA database in terms of the most common concentration of the material tested in a given species (typically at least 90% concentration and usually 100% technical material), as well as the length of exposure (usually 48 h). Average values were calculated when more than one study was available.

Data on pesticide impacts on several fish species are available from studies in EPA files, much of it from a comprehensive report by Mayer and Ellersieck (1986). Rainbow trout, *Oncorhynchus mykiss* (Walbaum) and bluegill, *Lepomis macrochirus* (Rafinesque), are the two most widely used test species and are common in Wisconsin surface waters. Comparable studies were selected by active ingredient involving the most frequently tested concentration. When there were two or more studies, LC_{50} values in trout and bluegill studies were averaged.

To produce *Daphnia*, trout, and bluegill subindices, LC_{50} values were inverted, so that the higher the subindex value, the more toxic the pesticide in a given assay. The resulting inverted values vary over as many as seven orders of magnitude, with values for insecticides routinely much higher than for herbicides and fungicides. For example and as expected, the average insecticide *Daphnia* subindex value is more than 50 times greater than the average fungicide value.

Different scaling factors were applied to narrow the wide range across subindex values shown in Table 2. A ten-fold lower scaling factor was used for insecticides in contrast to herbicides and fungicides, e.g., the *Daphnia* scaling factor for insecticides was 0.025 and for herbicides and fungicides, 0.25. Even with the lower insecticide-scaling factor, five of 23 insecticides have *Daphnia* values greater than 10, while the highest herbicide value is just 1.25 and 18 of 21 fungicides have a value of one or lower. The trout-scaling factor was 0.1 for insecticides and 1.0 for other pesticides. The bluegill values were 0.25 and 2.5 for insecticides and other pesticides, respectively. The esfenvalerate fish value was capped at 200 and the overall Ecotox index (the sum of the *Daphnia*, fish and avian subindex values) was capped at 200 in the case of cyfluthrin and esfenvalerate.

Better data are needed on secondary and tertiary ecosystem impacts of pesticides to estimate ecotoxicity values more accurately. Developing study protocols and supporting needed research warrant more attention by regulators, federal research agencies, and the pesticide industry. Priority research topics should include decreased abundance and diversity of invertebrates; impairment of long-term reproductive success; and reduction in the number of plants that serve as hosts for invertebrates or as critical elements in the food chain.

The biointensive Integrated Pest Management (BioIPM) index encompasses impacts of pesticides on the ability of farmers to progress along the IPM continuum toward more biologically and prevention-based IPM systems such as those described by Lewis et al. (1997). The components of the BioIPM index include resistance management, impacts on beneficial non-target organisms, and bee toxicity. With the exception of bee toxicity, data needed to calculate the other two BioIPM subindices are incomplete. A team of Wisconsin potato growers, pest management experts, and university faculty was convened to develop preliminary estimates based on collective knowledge and experience. Values in Table 3 reflect pesticide use patterns, soils, and cropping systems in central Wisconsin and are not necessarily appropriate for other potato-growing regions. The team developed an estimate of each pesticide's likelihood of triggering resistance in target pests (third column, Table 3). For insecticides, values were computed from estimates of the ability of insects to adapt to each insecticide's mode of action (value of 1, "less likely" to 3, "prone to develop resistance"), the active ingredient's spectrum of activity (scale 1 to 10, few species impacted to many species), and foliar half-life values. The pyrethroid, esfenvalerate had the highest score of 192. For fungicides, values were computed taking into account leaf-half lives and an estimate of the ability of pathogens to adapt to each fungicide's mode of action. A scale of 1 to 5 was used, with 1 assigned to active ingredients with a "remote" chance of leading

to resistance and 5 assigned to those "likely" to lead to resistant phenotypes. Metalaxyl, mefenoxam, rimsulfuron, and pendimethalin have the highest subindex value of 100; the use of each active ingredient has led to documented cases of resistance (Brent 1995; Brent and Hollomon 1998; IRAC 2001; FRAC 1999; Weed Science Society of America 2001).

Another subindex estimates insecticide impacts on beneficial arthropods and was derived from the "Toxic Effect" index developed at Oregon State University (Theiling and Croft 1988) using the formula:

"Impact on Beneficials Pesticide_x" = 100/(5-Toxic Effect Pesticide_x) Toxic Effect values were not available for most herbicides and fungicides. Values in column four, Table 3 for these other classes of pesticides are derived predominantly from the Kovach et al. (1992) "Environmental Impact Quotient." The team of experts in Wisconsin projected values not otherwise available, drawing on field experience.

Many species of soil microorganisms play important roles in enhancing nitrogen retention and availability, promoting healthy root development, and suppressing nematodes and related plant pathogens. Further work is needed to develop a BioIPM subindex that captures pesticide impacts on soil microorganisms. Development of such a subindex remains a collaboration priority.

Pesticide toxicity to bees is among the most significant economic losses associated with pesticide use, especially where fruit and vegetable yields depend on pollination. Bee toxicity data was obtained from Dr. Pieter Oomen, a scientist working for the Dutch Ministry of Agriculture. The Oomen dataset is considered one of the most authoritative in the world and includes data on both contact and oral routes of exposures (Heneghan 1998). In a few cases, values were also extrapolated from the acute bee toxicity ratings in *Farm Chemicals Handbook '99* and *Farm Chemicals Handbook 2000* (Meister 1999, 2000).

The bee toxicity value for imidacloprid required adjustment because of the large difference in bee toxicity as a function of formulation and when and how this pesticide is applied. If applied as a liquid foliar spray, imidacloprid's bee toxicity value would be the highest of any pesticide used in Wisconsin potato production. But applied as a soil insecticide at or soon after planting, there is little risk of exposure to bees. The at or near planting use pattern accounts for more than 75 % of imidacloprid pounds of active ingredient applied and results in a bee toxicity rating of 50 (National Agricultural Statistics Service 2000). A weighted average imidacloprid bee impact value of 87.5 was calculated using the formula [0.75(50) +0.25(200)]. The scaled bee toxicity value for spinosad was set at 100, a mid-range value based on conflicting data on bee toxicity levels (Heneghan 1998; Montague 2001).

BioIPM index values are calculated by summing the values of the three subindices as reported in Table 3, and then multiplying the result by 0.5, a scaling factor used in order to bring most values under 200. In general and as expected, insecticide BioIPM values are on average substantially higher than herbicide and fungicide values.

Some recently registered pesticides classified by EPA as "reduced risk" active ingredients score relatively high in the BioIPM index. These scores reflect the potential for newer, often more selective pesticides to select for resistance, as well as sometimes-significant impacts on non-target organisms, particularly bees. The project advisory committee decided that values for resistance and/or bee toxicity should be adjusted in cases where clear label directions preclude use of a pesticide in a way that gives rise to resistance or significant bee exposure. For example, the azoxystrobin and spinosad labels contain an explicit resistance management practice (rotation with another product that works through an alternative mode of action). Ongoing work is needed to review other new and revised pesticide product labels that may also contain use pattern restrictions that markedly lesson the risk of impacts on bees or beneficials, or the risk of selecting resistant pest biotypes.

Final multi-attribute toxicity factors are calculated from the four component indices: AM, CM, ECO, and BioIPM and are reported in Table 4. The equation used to calculate the Wisconsin collaboration's multi-attribute index is

$$\text{Multi-attribute Toxicity Factor}_x = (0.5)*\text{AM}_x + \text{CM}_x + \text{ECO}_x + (1.5)*\text{BioIPM}_x$$

The collaboration's advisory committee applied a (0.5) weight to the acute mammalian toxicity component because of the relative lack of circumstances leading to acute worker and applicator exposure in Wisconsin potato-production systems. In addition, U.S. Department of Agriculture pesticide residue data were reviewed and show low frequency and levels of residues of acutely toxic pesticides in potatoes, especially after washing, peeling, cooking and/or processing (Agricultural Marketing Service 1996). A weight of (1.5) was placed on the BioIPM component index in light of the importance of pesticide compatibility with biointensive IPM as Wisconsin growers strive to adopt more sophisticated, prevention-based IPM systems.

BioIPM values account, on average, for about 65% of multi-attribute factor values across the pesticides used in Wisconsin

TABLE 4—*Multi-attribute toxicity factor values for 2001.*

Pesticide	A.I Type	Acute toxicity	Bio IPM	Chronic Index (col. e)	2001 Four Component Indices: Acute Index (.5 x Acute Tox) (col.F)	EcoTOX Index (col. G)	BioIPM Index (1.5 x BioIPM) (col. H)	2001 Multi-attribute Index [col. E+F+G+H]	2000 Multi Index	% change 2000 to 2001
triphenyltin hydroxide	Fungicide	3.2	44	200	1.6	118	66	**386**	384	0.5%
metiram	Fungicide	0.1	35	200	0.1	1.3	53	**254**	251	1.2%
mancozeb	Fungicide	0.1	35	130	0.1	2.2	53	**185**	197	-6.4%
maneb	Fungicide	0.1	35	90	0.1	8.0	53	**151**	162	-7.3%
metalaxyl	Fungicide	0.7	75	1.4	0.4	3.4	113	**118**	175	-32.7%
mefenoxam	Fungicide	0.1	75	1.3	0.0	3.4	113	**117**	175	-32.9%
quintozene (PCNB)	Fungicide	0.3	23	33.3	0.1	16.3	34	**84**		
chlorothalonil	Fungicide	0.1	30	8.9	0.1	27.8	45	**82**	82	0.0%
sulfur	Fungicide	1.7	43	0.3	0.8	0.0	65	**66**	68	-3.8%
trifloxystrobin	Fungicide	0.1	25	2.0	0.0	7.9	38	**47**		
propamocarb hydrochloride	Fungicide	0.1	31	1.0	0.1	0.9	46	**48**	51	-5.6%
azoxystrobin	Fungicide	0.1	25	0.6	0.1	7.9	38	**46**	94	-51.1%
cymoxanil	Fungicide	0.5	22	7.7	0.3	1.4	33	**42**	50	-14.5%
dimethomorph	Fungicide	0.1	17	1.0	0.1	12.4	26	**39**	46	-15.0%
fludioxonil	Fungicide	0.1	18	3.3	0.1	6.7	26	**37**		
copper hydroxide	Fungicide	0.5	23	0.3	0.3	2.5	35	**38**	48	-21.2%
copper ammonium	Fungicide	1.7	23	0.3	0.8	1.8	35	**37**	47	-21.0%
copper resinate	Fungicide	0.1	23	0.3	0.1	1.8	35	**37**	47	-21.6%
thiophanate-methyl	Fungicide	0.1	20	1.3	0.1	0.7	30	**32**		
copper sulfate	Fungicide	1.7	8	0.3	0.8	7.6	13	**21**	43	-50.1%
basic copper sulfate	Fungicide	0.2	8	0.3	0.1	8.1	13	**21**	43	-50.4%
trifluralin	Herbicide	0.1	13	14.4	0.1	173	20	**207**		
2,4-D	Herbicide	1.3	12	100	0.7	2.6	17	**121**	165	-27.0%
rimsulfuron	Herbicide	0.1	76	0.1	0.1	1.9	113	**115**	147	-21.4%
metribuzin	Herbicide	0.2	56	23.1	0.1	7.2	84	**114**	127	-10.4%
pendimethalin	Herbicide	0.5	59	3.0	0.2	10.9	88	**102**	132	-23.0%
paraquat dichloride	Herbicide	1.8	36	22.2	0.9	3.7	53	**80**	106	-24.0%
diquat	Herbicide	2.2	23	20.0	1.1	16.9	35	**73**	103	-29.5%
EPTC	Herbicide	0.3	11	40.0	0.2	12.0	16	**68**		
alachlor	Herbicide	0.5	24	30.0	0.3	1.2	36	**67**	108	-37.7%
linuron	Herbicide	0.1	29	12.5	0.1	6.2	43	**62**	77	-19.9%
endothal	Herbicide	9.8	24	5.0	4.9	10.3	35	**55**	60	-8.2%
sethoxydim	Herbicide	0.2	31	1.1	0.1	0.6	46	**48**	74	-36.1%
glufosinate ammonium	Herbicide	0.3	24	5.0	0.2	1.3	35	**42**		
glyphosate	Herbicide	0.1	24	0.1	0.1	1.3	36	**37**	78	-52.5%
chlorpropham	Herbicide	0.1	20	2.0	0.1	1.9	30	**34**		
clethodim	Herbicide	0.4	11	10.0	0.2	1.4	16	**27**		
metolachlor	Herbicide	0.2	13	1.0	0.1	1.5	20	**22**	48	-54.1%
phorate	Insecticide	200	81	200	125	175	121	**621**	620	0.2%
disulfoton	Insecticide	192	144	200	96	37	216	**549**	542	1.3%
esfenvalerate	Insecticide	7	200	5	4	200	300	**509**	482	5.6%
cyfluthrin	Insecticide	1	184	13	1	200	276	**489**		
carbofuran	Insecticide	63	89	60	31	143	134	**368**	401	-8.3%
dimethoate	Insecticide	3	95	200	2	15	143	**360**	355	1.3%
oxamyl	Insecticide	83	108	100	42	39	162	**342**	340	0.7%
methamidophos	Insecticide	17	68	200	8	18	102	**329**	339	-2.8%
azinphos-methyl	Insecticide	31	143	67	16	30	214	**326**	307	6.1%
permethrin	Insecticide	1	181	11	1	41	271	**324**	288	12.6%
diazinon	Insecticide	2	82	143	1	54	123	**321**	320	0.2%
ethoprophos	Insecticide	19	57	200	10	13	86	**308**	339	-9.1%
endosulfan	Insecticide	6	63	50	3	118	94	**266**	271	-1.9%
pyrethrins	Insecticide	0	142	5	0	11	214	**230**	205	12.1%
fonofos	Insecticide	63	41	50	31	26	61	**168**	204	-17.6%
thiamethoxam	Insecticide	0	100	8	0	4	150	**161**		
imidacloprid	Insecticide	1	100	5	1	4	150	**159**	159	0.0%
malathion	Insecticide	0	89	13	0	0	133	**146**	137	6.2%
spinosad	Insecticide	0	83	4	0	1	124	**128**	172	-25.7%
pymetrozine	Insecticide	0	23	77	0	7	34	**118**	123	-4.3%
phosmet	Insecticide	2	47	9	1	24	71	**105**	109	-3.5%
piperonyl butoxide	Insecticide	0	25	17	0	0	37	**55**	59	-7.7%
Bacillus thuringiensis	Insecticide	0	7	0	0	0	10	**10**	10	0.0%
metam sodium	Other	2	33	109	1	8	50	**167**	205	-18.5%
maleic hydrazide	Other	0	23	0	0	1	35	**37**	42	-12.0%
sulfuric acid	Other	1	14	0	0	0	20	**21**		
							Average change 2000-2001			**-14.3%**

potato production. For 19 of 67 active ingredients studied, BioIPM values account for over 90% of multi-attribute toxicity factor values. The ecological toxicity component accounts for the smallest share, just under 13%, while the two mammalian toxicity components account for about 23%. Multi-attribute toxicity factor values per pound of active ingredient in Table 4 vary from below 40 for several fungicides, a few herbicides, and the foliar insecticide *Bacillus thuringiensis*, to as high as 621 for the organophosphate insecticide phorate (used rarely in Wisconsin).

RESULTS AND DISCUSSION

Further work is clearly needed to refine the formulas used to calculate subindices and indices and in seeking out more robust data on pesticides used in Wisconsin potato production. The selection of scaling and weighting factors have a significant impact on relative multi-attribute factor values and stem from subjective judgments that another group of people might view differently. Still, a wide variety of equations and assumptions would likely produce a similar relative ranking of pesticide toxicity, since the most toxic pesticides are so much more toxic than most other active ingredients in most of the parameters included in this analysis.

The purpose of active-ingredient-specific toxicity factor values is to set goals and monitor changes in aggregate industry-wide pesticide toxicity units, capturing changes in both the pounds of active ingredient of pesticide applied and the toxicity of pesticides relied upon most widely. Toxicity units are calculated by multiplying the pounds of active ingredient of each pesticide applied by its multi-attribute factor value and are a measure of potential adverse impacts likely to be associated with pesticide use over time. Once multi-attribute toxicity factors are set, changes in the mix of pesticides applied and the pounds of active ingredient applied of various pesticides account for all variability in toxicity units.

Table 5 summarizes industry-wide trends since 1995 in reducing pesticide use and aggregate toxicity units by active ingredient and type of pesticide. Toxicity units per planted acre resulting from fungicide use declined 4% and 19% in 1997 and 1999, respectively, compared with the 1995 baseline and despite severe pathogen pressure (Stevenson and James 1998). In 1997 there was less use of mancozeb but greater reliance on chlorothalonil, resulting in little change in fungicide toxicity units. In 1999 azoxystrobin was registered and 83% of potato acreage was treated an average of three times with this low-risk fungicide (National Agricultural Statistics Service 2000). The low toxicity factor value for azoxystrobin (46, Table 4) and its low application rates (0.11 lbs AI/A) combine to generate only five toxicity units per acre-treatment, compared with about 185 and 254 toxicity units from typical 1-lb applications of mancozeb and metiram, respectively. Adoption of azoxystrobin largely accounts for the 19% drop in fungicide toxicity units per acre in 1999 compared to 1995. In part because azoxystrobin must be alternated with broad-spectrum fungicides to avoid selection for resistance, chlorothalonil and metiram use increased in 1999 relative to 1995. As growers learn to use newly registered low-risk strobilurin fungicides in rotation with established products such as chlorothalonil and new fungicides in development, further reductions in toxicity units from disease management should be achieved. However, since there are concerns for the development of resistance to these new fungicides, they must be applied in rotation with chemistries with different modes of action to maintain the effectiveness of the reduced-risk materials as long as possible.

Toxicity units associated with insecticide use varied considerably between years (Table 5). In 1997, a 62% decrease in total toxicity units per planted acre occurred, resulting largely from the registration of imidacloprid in 1995. The excellent efficacy of imidacloprid against key potato pests, including the Colorado potato beetle, *Leptinotarsa decemlineata* (Say), green peach aphid, *Myzus persicae* (Sulzer), and potato aphid, *Macrosiphum euphorbiae* (Thomas), resulted in widespread application of imidacloprid and accompanying reductions in the use of insecticides that had been targeted at these pests previously. The most significant changes in insecticide use included elimination of azinphos-methyl, carbofuran and oxamyl, an 83% reduction in endosulfan toxicity, and, a 75% reduction in methamidophos toxicity units. The total drop in insecticide toxicity units would have been greater if growers had not needed to almost triple the pounds of active ingredient applied of dimethoate for potato leafhopper, *Empoasca fabae* (Harris), control in 1997 (Wyman et al. 1998).

Toxicity units per acre from insecticide use rose from 279 in 1997 to 505 in 1999, still a 31% decline from the 1995 baseline. The increase in insecticide use in 1999 also resulted from intense pest pressure from potato leafhopper, which migrated into Wisconsin earlier and in higher numbers than had been previously recorded, along with heavy Colorado potato beetle pressure (Wyman et al. 1998). Imidacloprid use increased by 43% over 1997, but high Colorado potato beetle populations in fields not treated with imidacloprid required more foliar applications than

TABLE 5—*Industry-wide Wisconsin potato pesticide use and toxicity units: 1995, 1997, and 1999.*

Acres planted 1995: 83,000 1997: 78,000 1999: 86,000	Toxicity factor values	1995 pounds applied	1995 toxicity units	1997 pounds applied	1997 toxicity units	1999 pounds applied	1999 toxicity units
Herbicides:							
glyphosate	37	4,000	148,000	9,000	333,000	3,000	111,000
linuron	62	7,000	434,000	3,000	186,000	1,000	62,000
metolachlor	22	21,000	462,000	7,000	154,000	16,000	352,000
metribuzin	114	39,000	4,446,000	34,000	3,876,000	37,000	4,218,000
pendimethalin	102	24,000	2,448,000	16,000	1,632,000	21,000	2,142,000
rimsulfuron	115	0	0	0	0	1,000	115,000
sethoxydim	48	2,000	96,000	0	0	5,000	240,000
Total: all herbicides		97,000	8,034,000	69,000	6,181,000	84,000	7,240,000
per planted acre		1.17	97	0.88	79	0.98	84
Insecticides:							
azinphos-methyl	326	26,000	8,476,000	0	0	6,000	1,956,000
carbofuran	368	13,000	4,784,000	0	0	0	0
Diazinon	321	0	0	0	0	5,000	1,605,000
dimethoate	360	11,000	3,960,000	30,000	10,800,000	27,000	9,720,000
endosulfan	266	60,000	15,960,000	10,000	2,660,000	53,000	14,098,000
esfenvalerate	509	3,000	1,527,000	2,000	1,018,000	6,000	3,054,000
imidachloprid	159	0	0	8,000	1,272,000	14,000	2,226,000
methamidophos	329	69,000	22,701,000	17,000	5,593,000	15,000	4,935,000
oxamyl	342	5,000	1,710,000	0	0	5,000	1,710,000
permethrin	324	4,000	1,296,000	0	0	1,000	324,000
phosmet	105	0	0	0	0	27,000	2,835,000
piperonyl butoxide	55	3,000	165,000	7,000	385,000	18,000	990,000
pyrethrins	230	166	38,180	0	0	68	15,640
Total: all insecticides		194,166	60,617,180	74,000	21,728,000	177,068	43,468,640
per planted acre		2.3	730	0.95	279	2.06	505
Fungicides:							
azoxystrobin	46	0	0	0	0	22,000	1,012,000
basic copper sulfate	21	13,000	273,000	8,000	168,000	25,000	525,000
chlorothalonil	82	408,000	33,456,000	591,000	48,462,000	501,000	41,082,000
copper hydroxide	38	40,000	1,520,000	52,000	1,976,000	14,000	532,000
copper resinate	37	12,000	444,000	2,000	74,000	0	0
cymoxanil	42		17,940	5,000	210,000	5,000	210,000
mancozeb	185	412,000	76,220,000	287,000	53,095,000	278,000	51,430,000
maneb	151	76,000	11,476,000	62,000	9,362,000	0	0
mefenoxam	117	0	0	0	0	3,000	351,000
metalaxyl	118	4,000	472,000	0	0	3,000	354,000
metiram	254	0	0	0	0	49,000	12,446,000
propamocarb hydrochloride	48	9,000	432,000	0	0	0	0
triphenyltin hydroxide	386	12,000	4,632,000	8,000	3,088,000	2,000	772,000
Total: all fungicides		986,000	128,942,940	1,015,000	116,435,000	902,000	108,714,000
per planted acre		12	1,554	13	1,493	10	1,264
Other chemicals:							
diquat	73	28,000	2,044,000	26,000	1,898,000	46,000	56,160
endothall	55	7,000	385,000	0	0	5,000	0
maleic hydrazide	37	13,000	481,000	0	0	0	0
metam-sodium	167	970,000	161,990,000	0	0	0	0
paraquat	80	3,000	240,000	0	0	0	0
sulfuric acid	21	1,632,000	34,272,000	2,770,000	58,170,000	0	14,040
Total: other chemicals		2,653,000	199,412,000	2,796,000	60,068,000	51,000	70,200
per planted acre		32	2,403	35.8	770	0.59	0.82
Herbicides, insecticides, and fungicides							
Total: H+I+F		1,277,166	197,594,120	1,158,000	144,344,000	1,163,068	159,422,640
per planted acre		15.4	2,381	14.8	1,851	13.5	1,854
All chemicals							
Total		3,930,166	397,006,120	3,954,000	204,412,000	1,214,068	159,492,840
per planted acre		47.4	4,783	50.7	2,621	14.1	1,855

typically needed. As a result, endosulfan use increased almost to 1995 levels, esfenvalerate use doubled compared to 1995 levels (accompanied by an 500% increase in piperonyl butoxide to combat resistance) and small acreages were treated with azinphos-methyl, oxamyl and phosmet.

The year-to-year variability in toxicity units associated with insect control reflects the routine, often extreme variability in insect population pressure. Our experience in Wisconsin confirms that fluctuations in individual pesticide use patterns should be anticipated and that three- to five-year average measures of pesticide use should be tracked whenever possible in large-scale IPM implementation and pesticide risk reduction projects. Otherwise it is likely that growers, researchers, and other stakeholders will be overly encouraged in years when population pressure is low, and inappropriately alarmed over use in years when populations are high. Projects need to focus on the overall trend in average per acre toxicity units, a measure that has clearly declined over the last five years in Wisconsin potato production, despite sometimes quite dramatic year-to-year swings and an increase in blight disease pressure. Newly registered low-risk insecticides such as spinosad for Colorado potato beetle (8 toxicity units/application) and pymetrozine for aphids (20 toxicity units/application) will continue to contribute to this downward trend in average toxicity units per acre.

Toxicity units associated with herbicide use are relatively low with current weed management systems. Major products applied are metribuzin (58 toxicity units/application), rimsulfuron (3 toxicity units/application) and sethoxydim (9 toxicity units/application), and variable and less frequent use of metolachlor (43 toxicity units/application), linuron (31 toxicity units/application) and pendimethalin (85 toxicity units/application). Weed management typically generates a total of 80-110 toxicity units/acre. Metribuzin and pendimethalin use have remained relatively constant since 1995 and account for the bulk of herbicide toxicity units (Table 5). Rimsulfuron was registered during this period and represents an effective low toxicity herbicide alternative that has been widely adopted by growers. Concerns over resistance and the spectrum of weeds controlled, however, dictate that rimsulfuron be used in combination with other herbicides and thus limit its potential to reduce toxicity units.

Using Toxicity Values to Obtain Marketplace Rewards

Toxicity factor values coupled with pesticide use data have proven useful in determining grower and industry-wide progress toward specific reduction goals such as those set forth in Lynch et al. (2000). The collaboration's first year goal was to reduce the toxicity units associated with use of 11 targeted pesticides by 20% , a goal exceeded by the 28% reduction in toxicity units in 1977 (Lynch et al. 2000). The three-year goal called for a 40% toxicity unit reduction by 1999 from the 1995 baseline; the actual reduction was 37%. This reduction was achieved despite increases in 1999 insecticide use that erased 21.8 million of the 38.9 million decline in insecticide toxicity units that had occurred from 1995 to 1997 (Table 5).

Toxicity units are also useful when analyzing changes in pest pressure and pesticide product availability and efficacy. In 2001, the collaboration is taking another step in ongoing efforts to capture market place rewards for grower innovation. IPM adoption and pesticide toxicity unit-based ecolabel standards have been established for fresh market potatoes (Sexson and Dlott 2001). About 20 growers worked in the 2001 season to meet the ecolabel standards and a third-party certifier has assessed progress. Growers producing short-season fresh market potatoes (less than 90 days from emergence to vine-kill) must remain within a cap of 800 total toxicity units per acre for the season; long-season growers (more than 90 days from emergence to vine-kill) must remain under 1,200 toxicity units. In 2001, participating fresh market growers within 25 miles of a field with late blight will have 400 more toxicity units to cover fungicide use if 18 severity values for late blight are reached on their farm by 1 June, or 200 more units if late blight hits 18 severity values by 15 June. These adjustments reflect a first attempt to build pest pressure into the measurement system. Other adjustments are likely to be developed and applied in the future.

In addition all ecolabel program growers need to comply with a "Do Not Use" list including 12 active ingredients (aldicarb, azinphos-methyl, disulfoton, methamidophos, carbofuran, carbaryl, oxamyl, endosulfan, phorate, diazinon, permethrin, and paraquat). Resistance management conditions are placed on several other moderate- to high-risk pesticides including dimethoate, esfenvalerate, the EBDC fungicides, triphenyltin hydroxide, azoxystrobin, and the soil fumigant metam-sodium.

Ecolabel growers also face IPM implementation challenges. Short-season growers must score a minimum of 204 points in an IPM practices survey, and long-season growers must score 211 points if the potatoes are being stored. Short season growers who do not store their potatoes must receive 195 points and long season growers must earn 202 points. The points are derived from an extensive survey of IPM practices, with each practice assigned weights (points) reflecting its

importance in supporting progress along the IPM continuum (Sexson and Dlott 2001).

Evaluating Reduced-risk Transition Strategies in Commercial Potatoes

In addition to activities supporting the emergence of ecolabeled Wisconsin potatoes in 2001, growers, crop consultants, and University of Wisconsin pest management specialists are currently developing and testing multitactic transition strategies applicable to major potato pests. Toxicity factor values, coupled with data on costs per acre treated with alternative pesticides or cultural practices, are proving helpful in evaluating the potential impact of various pest management system changes.

Reduced-risk insect and disease management programs integrating the basic components of successful potato IPM (crop scouting, pest prediction, and thresholds) with use of low-toxicity pesticides have been developed with growers and tested in large-scale replicated trials. Various insect and disease management programs have been evaluated separately and in combination on 12 commercial fields in 2000 and 2001. Data follow from a combined insect/disease evaluation conducted in central Wisconsin in 2000. Russet Burbank variety potatoes were planted on 25 April 2000 in a center-pivot irrigated field at Coloma, Wisconsin. Conventional and reduced-risk foliar disease programs, combined with conventional and reduced-risk systemic (Table 6) and foliar (Table 7) insect programs were applied to 48-row x 1200-ft plots (3.3 acres) replicated three times in a randomized complete block design. Treatment decisions were based on weekly scouting and disease prediction and pesticide applications were made by the grower.

Disease pressure was high in 2000 with moderate early blight in the field and late blight in the immediate vicinity. Late blight severity valves passed the threshold of 18 in early June, and spray programs were initiated on 9 June and continued on a 7-day schedule until 5 September. The conventional fungicide program required 17 applications, primarily mancozeb, chlorothalonil, and tin and cost $111 per acre. Toxicity units totaled 2,421 per acre, about twice the level allowed in the ecolabel standard for season-long potatoes. The reduced-risk program used three applications of azoxystrobin in early season in rotation with chlorothalonil and relied on chlorothalonil thereafter for a toxicity unit total of 1,169 (60% reduction) at a cost of $153 per acre (27% increase). Disease control was more effective in the reduced-risk program with significantly lower incidence of early blight. No late blight was found in either program.

Two insect management approaches involving foliar and systemic insecticides were evaluated. Insect populations were moderate in this field. Colorado potato beetle larvae in the conventional foliar program required one application of esfenvalerate for first generation control, timed to target second instar larvae and a follow-up application of cyfluthrin for second-generation larvae. In the reduced-risk foliar program two applications were also required using spinosad and *Bacillus thuringiensis* subsp. *tenebrionis*. Toxicity units were 55% lower in the reduced-risk foliar program and costs were increased by $12 per acre. Both programs held Colorado potato beetle larvae at low levels throughout the season and no defoliation was recorded. Potato leafhopper populations were held below threshold (1 adult/sweep) with a single insecticide application in both programs. Aphids did not require treatment.

In the systemic treatment evaluation, imidacloprid performed well in both conventional and reduced-risk programs (where the imidacloprid rate was reduced) with few larvae and no defoliation observed. Potato leafhoppers required one application in both programs to hold adults and nymphs below threshold. Toxicity units were 31% lower in the reduced-risk program and pesticide costs were also $10 per acre lower.

The impact of the combined insect and disease programs on yield and costs are shown in Tables 6 and 7. For systemic insect and foliar disease control, the reduced-risk program was more expensive ($32 per acre), but yield was significantly higher (15 cwt/A) as a result of the improved early blight control associated with use of azoxystrobin. The cost of the reduced-risk program per cwt was only marginally higher (5.6 cents per cwt) (Table 6), and at a $5/cwt selling price this reduced-risk program would thus result in a net gain of $43/A. The toxicity units associated with this program were reduced by 51% (Table 6).

TABLE 6—*Cost/benefit of reduced-risk pest control,. Coloma, WI, 2000.*

	Fungicide/systemic insecticide			
Program	Cost of materials ($/A)	Yield (cwt)	Cost/cwt (cents)	Toxicity units
Conventional	$182	443 b	41.8	2,494
Reduced risk	$214	458 a	46.7	1,242
Outcome of reduced risk	+ $32 / Acre	+ 15 cwt	+ 5.6/ cwt	-1,252

Bottom line: Reduced risk costs 5.6 cents/cwt more, but the net financial gain from reduced-risk programs (@$5.00/cwt) is $43 /A

TABLE 7—*Cost/benefit of reduced-risk pest control, Coloma, WI, 2000.*

	Fungicide/foliar insecticide			
Program	Cost of materials ($/A)	Yield (cwt)	Cost/cwt (cents)	Toxicity units
Conventional	$136	444 b	30.6	2,557
Reduced risk	$190	464 a	40.9	1,229
Outcome of reduced risk	+ $54 / Acre	+ 20 cwt	+ 10.3 / cwt	-1,328

Bottom line: Reduced risk costs 10.3 cents/cwt more, but the net financial gain from reduced-risk programs (@$5.00/cwt) is $46 / A

For foliar insect and disease control (Table 7), reduced-risk program costs were $54 per acre higher, reflecting the increased cost of low-risk foliar insecticides, but yields were again increased (20 cwt/A), and the cost/cwt was increased by only 10.3 cents/cwt (Table 7). At $5/cwt, the reduced-risk foliar program would result in a net gain of $46/A to growers based on the significant yield increase achieved. Toxicity units associated with the reduced-risk foliar program were reduced by 1,328 per acre (52%).

CONCLUSIONS

Pesticides pose highly variable environmental and human health risks. A wide range of activity is underway to promote more biologically based, less disruptive and hazardous pest management systems. Most entail setting goals for reduction in high-risk pesticide use and/or IPM adoption, and ways to monitor progress. All will benefit from new tools to track changes in the toxicity of pesticides required to support a given IPM system (Ehler and Bottrell 2000).

The toxicity-unit methodology developed by the collaborative potato project in Wisconsin has produced information now serving several useful purposes. Progress in reducing reliance on high-risk pesticides has been monitored since 1995. Trade-offs are made explicit as new pesticides and technologies replace older, higher-risk products. Growers and researchers are calculating the per acre toxicity units associated with alternative IPM systems. By factoring cost consequences into the equation, the Wisconsin project is working toward analytical tools responsive to the needs of both farmers and environmentalists.

Despite data gaps and less than complete coverage of environmental and BioIPM impacts, the methodology does highlight the potential to reduce the impact of pesticides on a given field, or industry-wide, through targeted research, use of new pesticide chemistry, and IPM implementation. A longer-term goal is establishment of an information base to forge consensus on future regulatory, research, and education priorities.

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