



# An index method to evaluate growers' pesticide use for identifying on-farm innovations and effective alternative pest management strategies: a case study of winegrape in Madera County, California\*

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**Abstract:** Winegrape is an important perennial crop in California, USA. Each year California winegrape farming consumes about 20 million kilograms of pesticides that have been a pollutant source to the fresh water systems of the state. The variation of pesticide use among winegrape growers has been significant. It has been observed that some growers have developed effective ways to reduce pesticide use, yet control pests efficiently to ensure harvest. Identification of the growers with low and high pesticide use is very helpful to extension programs that aim on reducing pesticide environmental risk. In this study, an index approach is proposed to quantitatively measure pesticide use intensity at grower level. An integrated pesticide use index is developed by taking pesticide quantity and toxicity into account. An additive formula and a multiplying formula were used to calculate the pesticide use index, i.e., PUI and PUIM. It was found that both PUI and PUIM were capable of identifying the low and high pesticide users while PUI was slightly more conservative than PUIM. All pesticides used in California winegrape farming were taken into account for calculating the indices. Madera County, one of the largest winegrape producers in California, was taken as an example to test the proposed approach. In year 2000, among the total 208 winegrape growers, 28 with  $PUI \leq 10$  and 34 with  $10 < PUI \leq 20$  were identified as low pesticide users who were characterized with both low quantity and low toxicity of pesticide use. Most of the growers had small-sized vineyards, i.e., one field and small planted areas. Furthermore, they had very low pesticide use intensity, used only 1–2 types of pesticides (mainly fungicides), applied few pesticides (1–3 only), and emphasized the use of low toxicity compounds. Meanwhile, 19 growers with  $PUI > 60$ , identified as high pesticide users, had large-sized vineyards, i.e., more fields and large planted areas. They used all types of pesticides and many compounds, which indicated that their pest controls heavily depended on pesticides rather than on-farm management. Through the case study, the proposed approach proved to be useful for analyzing the growers' pesticide use intensities and interpreting their pesticide use behaviors, which led to a new start point for further investigation of searching ways to reduce pesticide environmental risk.

**Key words:** Pesticide use index, Toxicity, Compound, Pesticide environmental risk, California

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## 1 Introduction

California's 2.6 billion-dollar output of winegrape farming needs pesticide application to ensure harvest. Each year about 20 million kilograms of

pesticides are used for winegrape in California. Madera County is one of the largest winegrape producers. In 2000, there were  $2.4 \times 10^4$  ha of vineyards in the county, and  $2.386 \times 10^6$  kg pesticides were used for winegrape farming, ranking among the top counties of California.

The large amount of pesticides used in California carries significant risk to the environment, ecosystem, and public health. A number of important water bodies in California, such as the San Joaquin River, have been contaminated with pesticides (Domagalski and Dubrovsky, 1992; Domagalski, 1996; 1997a; 1997b; Zhang *et al.*, 1997). Many efforts have been made to protect the scarce fresh water resources in the state (Clark *et al.*, 1998). Contamination of pesticides to surface water and ground aqua had also been reported in many places of the world (Thrupp, 1990; 1991; Leonard, 2000; Reus *et al.*, 2002; Kong *et al.*, 2004). In order to balance pesticide application and environmental protection, emphasis on low-risk farming to reduce pesticide use through alternative farm management practices has gained more and more encouragements from governmental agencies, scientists, farm management advisers, farmers, and the public (Lewis *et al.*, 1997a; 1997b; Fitt, 2000; Gamliel *et al.*, 2000; MacHardy, 2000). Some government departments, such as the United States' Environmental Protection Agency (US EPA), California's Department of Food and Agriculture (CDFA), and California's Department of Pesticide Registration (CDPR), have made great efforts in reducing pesticide environmental risk. Several programs in the extension of low-risk farming practices, such as Biologically Integrated Orchard Systems (BIOS) (Santer, 1995; Epstein *et al.*, 2001), have been initiated in California. Success of these programs requires identifying the farmers with low pesticide use and analyzing their farming management practices, because their practices might serve as valuable models to the rest of the farming community.

Farming management practice varies among crops, geographic regions, and individual farmers, which results in various intensities in pesticide use. For example, in 2000, the pesticide use intensity of winegrape farming was 129.17 kg/ha in Merced and 99.12 kg/ha in Madera, while it was 63.07 kg/ha in Santa Barbara and 36.84 kg/ha in Napa. Among the other main cropping counties in California the intensity was as follows: Sacramento 103.54 kg/ha, Monterey

88.92 kg/ha, Fresno 81.87 kg/ha, Kern 73.88 kg/ha, Sonoma 68.63 kg/ha, Mendocino 65.95 kg/ha, and San Luis Obispo 6.84 kg/ha. It can be seen that the highest intensity was 14 times more than the lowest.

It has been proved that effective farming management practices can reduce the dependence on pesticides. Hendricks (1995) studied the relationship between grower's practice and pesticide use in Merced County and found that almond growers altered many aspects of farm management by developing production strategies, which could successfully reduce or eliminate insecticide use. The interrelated alterations in floor management, orchard sanitation, and harvest timing are the core of an extension program called BIOS (Santer, 1995). The locally adapted almond growing practices initiated by BIOS proved to be a useful way for reducing insecticide use (Hendricks, 1995; Pence and Grieshop, 2001). The direct outcome for those participants of BIOS was to decrease dependence on agrochemicals (pesticides and fertilizers), enrich knowledge on local ecological processes, and understand how orchard management interacts with the local ecological processes (Bugg and van Horn, 1998). Epstein *et al.* (2000) reported that the BIOS program introduced an alternative to reduce the use of organophosphates not only in dormant seasons, originally recommended by University of California's Integrated Pest Management (UC IPM) program, but also in growing seasons. In the following years after BIOS was implemented, Merced County achieved the largest percentage reduction in organophosphate usage (Epstein *et al.*, 2000). California owns the most complete pesticide use reporting (PUR) system in the world and a huge PUR database has been developed. Detailed information of farmers' pesticide use at field level can be found in PUR database. Thus, the database has been widely used in farming pest control, pesticide application, and environmental studies. However, use of the information of the PUR database to identify on-farm innovations in reducing pesticide environmental risk has not yet been reported.

A number of studies have been devoted to assessing pesticide environmental risk (SETAC, 1994; Levitan and Merwin, 1995; Solomon *et al.*, 1996; Giesy *et al.*, 1999; Cory, 2000; Hall *et al.*, 2000; Levitan, 2000). Vercruyssen and Steurbaut (2002) proposed several indices to assess pesticide risks for workers, bystanders, and aquatic organisms. Based on

the separate indices, a comprehensive index for general assessment of environmental risks was also developed. Solomon *et al.* (2000) proposed an ecological risk assessment method by using probability distribution functions to independently describe exposure concentrations and toxicological responses of aquatic organisms to pesticide compounds. An environmental yardstick had been developed in the Netherlands as a practical indicator for farmers to select pesticides with the least environmental impacts (Reus and Leendertse, 2000). Eight indicators had been compared for the evaluation of pesticide environmental risk in Europe (Reus *et al.*, 2002). Most of these evaluations were conducted on the pesticide level and none was on the grower level.

This study aims to develop an index approach for assessing the pesticide use of winegrape growers in order to identify on-farm innovations that help to reduce pesticide environmental risk. There are two important aspects in pesticide usage: the application dosage of pesticides (quantity) and the toxicity of the pesticide applied. In reality, there are more than 150 pesticides used in winegrape farming in Madera County, and each individual grower has his own preference in pesticide application. Furthermore, different compounds have different toxicities after releasing to environment. Therefore, different compounds, various dosages, different toxicities of the compounds, and incomparability among the compounds create complexity in assessing pesticide use at the grower level. The proposed index approach tries to provide a tool for this kind of pesticide use assessment. In developing the approach, the hypothesis relies on the following assumptions: those growers with large application dosage of pesticide and those with a preference for using higher toxic pesticides have larger impacts on the environment. Based on the case study in Madera County, the proposed approach for assessing grower pesticide usage and identifying low and high pesticide users at grower and field levels is presented and discussed in the following sections.

## 2 Materials and methods

### 2.1 Principles

In agricultural practice, it has been observed that some farmers are likely to look for alternative farming

management strategies, and some farmers have already found useful ways to reduce pesticide use while keeping a profitable economic output. It is very necessary to identify low and high pesticide users. The low pesticide users can serve as candidates for further investigation to identify valuable farming management practices that can be used as model farming systems for extension programs. The high pesticide users can serve as main targets of the extension programs. If the pesticide usages of the high users are significantly reduced through the extension of the experiences and practices of the low users, the total use of pesticides would be remarkably reduced, and hence the risks of pesticides on environment would also be reduced.

In order to develop an applicable approach for assessing pesticide use at the grower level, a case study was carried out based on the data of years 1999, 2000, and 2001 of Madera County. The data source is PUR database. For the low pesticide users mentioned in the paper, the criteria involve two aspects: quantity and toxicity.

By quantity, low pesticide user means that the dosage of pesticides applied in a specific area (hectare) within a period (year) is low. Some farmers used the same pesticide several times in their fields, while others used only it once a year. For a comparable scale of measuring pesticide use, kilogram per hectare (kg/ha) planted within a year was used to indicate the pesticide use intensity in the winegrape farming systems in Madera County. Therefore, the low pesticide user in the following analysis means low intensity at the grower level. Since different pesticide compounds have different effects in pest control, application amounts of different pesticides are not simply comparable. Thus, when several compounds are in use, it is not meaningful to compare the overall intensity for the assessment.

The toxicities of different pesticides are different. Therefore, the amount of pesticides used in an area unit cannot be used as the only criteria, because it cannot meet the purpose of evaluating the growers' farming practice and identifying the low pesticide users. Since the purpose of identifying low pesticide users is to search farming models for extension programs of reducing pesticide environmental risk, toxicities of compounds must be taken into account. Therefore, the quantity and toxicity of the pesticide

were considered and given equal importance in the following analysis.

### 2.2 Pesticide use index

In order to establish an index to evaluate pesticide use at grower level, the quantity and toxicity of pesticide were used as the weights. Since a number of pesticide compounds were in use and the incomparability among the compounds is obvious, an integrated index was used for the evaluation. The index can be constructed in either an additive form or multiplicative one, which are

$$PUI_j = W_Q \times PUI_{Qj} + W_T \times PUI_{Tj}, \quad (1)$$

$$PUIM_j = PUI_{Qj} \times PUI_{Tj}, \quad (2)$$

where  $PUI_j$  is the integrated index of pesticide use constructed in additive form for the  $j$ th grower, and  $PUIM_j$  is the integrated index constructed in multiplying form.  $PUI_{Qj}$  is the quantity index contributed by the amounts of pesticides used,  $PUI_{Tj}$  is the toxicity index contributed by the toxicities of pesticides used, and  $W_Q$  and  $W_T$  are, respectively, the weights of the quantity index and the toxicity index. Since equal importance was given to the quantity and toxicity of the pesticide in formulating the index,  $W_Q$  and  $W_T$  were respectively defined as 0.5.

Generally speaking, the index composed by either the additive or multiplying form is supposed to indicate the same low pesticide user. Thus, the two indices should be able to correctly reflect the pesticide use level for identifying the low and high pesticide users. In order to verify this hypothesis, results from the two indices were compared in Section 3.6.

The quantity index and the toxicity index in Eqs. (1) and (2) can be computed as follows:

$$PUI_{Qj} = \sum_i W_{Qi} \times LBSA_{ij}, \quad (3)$$

$$PUI_{Tj} = \sum_i W_{Ti} \times LBSA_{ij}, \quad (4)$$

where  $W_{Qi}$  is the quantity weight of the  $i$ th pesticide;  $W_{Ti}$  is the toxicity weight of the  $i$ th pesticide;  $LBSA_{ij}$  is the  $j$ th grower's pesticide use intensity of the  $i$ th pesticide, in the dimension of kg/ha.

In Madera County, more than 150 pesticides were used in 1999–2001. Each pesticide has a different intensity in magnitude of use. If this dimension difference was omitted, it is very possible that only

those pesticides with large application dosage would be noticed. In order to give each compound the same importance in this dimension, the use intensities of all the compounds were normalized before computing the indices.

Regional average (i.e., the county average in the case) is an important indicator of pesticide use level, and was used as a benchmark in the study. The growers with pesticide use intensity higher than the regional average should be viewed as high pesticide users. Thus, it is necessary to normalize the pesticide use intensity of each grower according to the county average by using the following formula:

$$NLBSA_{ij} = LBSA_{ij} / LBSA_{ci}, \quad (5)$$

where  $NLBSA_{ij}$  is the  $j$ th grower's normalized pesticide use intensity of the  $i$ th pesticide and  $LBSA_{ci}$  is the county average of the  $i$ th compound used. Thus, Eqs. (3) and (4) for  $PUI_{Qj}$  and  $PUI_{Tj}$  can be rewritten as follows:

$$PUI_{Qj} = \sum_i W_{Qi} \times NLBSA_{ij}, \quad (6)$$

$$PUI_{Tj} = \sum_i W_{Ti} \times NLBSA_{ij}. \quad (7)$$

The higher  $PUI_{Qj}$  and  $PUI_{Tj}$ , the higher the grower pesticide use level was, which indicates that the grower brought higher risk potential to environment through pesticide use in his farming practice.

One problem arises when applying  $PUI_{Qj}$  and  $PUI_{Tj}$  to compute  $PUI_j$ , which is caused by considering equal importance to them in Eqs. (1) and (2), while they might have different scales after computing from Eqs. (6) and (7). Thus,  $PUI_{Qj}$  and  $PUI_{Tj}$  need to be projected into the same scale before computing  $PUI_j$ , which is to scale the data column according to the maximum of the column, i.e., in the following formulae:

$$PUI_{qj} = PUI_{Qj} / PUI_{Qm}, \quad (8)$$

$$PUI_{tj} = PUI_{Tj} / PUI_{Tm}, \quad (9)$$

where  $PUI_{qj}$  and  $PUI_{tj}$  are the scaled  $PUI_{Qj}$  and  $PUI_{Tj}$  of the  $j$ th grower,  $PUI_{Qm}$  and  $PUI_{Tm}$  are the maxima of  $PUI_{Qj}$  and  $PUI_{Tj}$ , respectively. Thus, Eqs. (1) and (2) can be rewritten as follows for the  $j$ th grower:

$$PUI_j = PUI_{qj} + PUI_{tj}, \quad (10)$$

$$\text{PUI}M_j = \text{PUI}_{qj} \times \text{PUI}_{ij}. \quad (11)$$

The integrated pesticide use index means that the higher either  $\text{PUI}_j$  or  $\text{PUI}M_j$ , the higher pesticide use level for the  $j$ th grower/field, and vice versa. The higher pesticide use level implies the higher environmental risk of the grower's pesticide use. Thus, to identify low pesticide users becomes to identify the growers with low PUI. Ranking the growers according to their PUIs, low and high pesticide users in the region can be easily classified.

### 2.3 Quantity weight determination

The above index is based on the quantity weight ( $W_{Qi}$ ) and toxicity weight ( $W_{Ti}$ ) for the  $i$ th pesticide compound. Thus, it is essential to determine the weights. For quantity weight, the following arguments were used when referring to pesticide environmental risk. Within a specific geographic area, such as the county in the study, the larger the amount of pesticide use, the greater impact the pesticide has on environment; hence, the higher priority of attention should be given to the pesticide in achieving the reduction of pesticide use to lower environmental risk. The argument provides a method to treat the quantity weight for establishing the index. Those pesticides with a larger amount of total use in the county have a higher weight and hence are given more attention to. Those pesticides with only a few kilograms of use have a lower weight than those with, for example, several thousand kilograms of use in formulating the quantity index.

As for Madera County, sulfur was the largest pesticide compound used in winegrape farming in the years of the study. The total amount of sulfur use was high, up to  $1.832 \times 10^6$  kg in 2000, accounting for above 90% of the total amount of pesticides used in the county. Table 1 lists the top 40 pesticides used in winegrape in Madera County during 1999–2001. And Fig. 1 plots the total amount of each pesticide in descending order.

In order to determine the quantity weight, the total weight of all pesticides was defined as 100 ( $\sum_i W_{Qi} = 100$ ) and the weight for each individual compound was estimated according to its total amount of use. For the three years of analysis, the average of the total amount was used for the computation. However, this computation could be highly

biased for the first compound, i.e., sulfur, because the amount of sulfur use was too large (accounting for above 90% of the total). Clearly, this was not expected for establishing the pesticide use index. To improve the result, one solution is to compromise the computation according to the curve shown in Fig. 1. In fact, the usages of the top 10 compounds were about  $1.709 \times 10^6$  kg, accounting for 97% of the county's total. A simulated trend for the top 10 compounds was generated according to the curve shown in Fig. 1. Then the curve was smoothed to highlight the general trend. A three-term average is the general way for this purpose. After smoothing, the total amount of all compounds (TAU) can be computed as

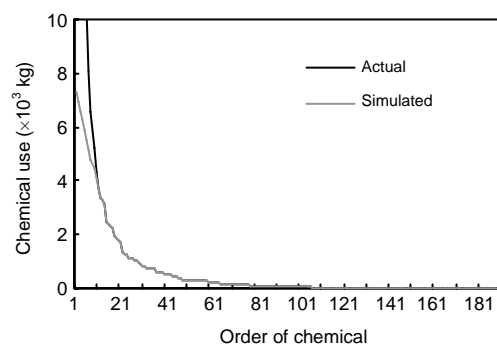
$$\text{TAU} = \sum_i \text{TAU}_i, \quad (12)$$

where  $\text{TAU}_i$  is the use amount of the  $i$ th compound. Since the total weight is 100, the weight for each unit ( $\text{WR}_Q$ ) can be calculated as

$$\text{WR}_Q = 100/\text{TAU}. \quad (13)$$

Finally, the quantity weight for the  $i$ th compound can be estimated as:

$$W_{Qi} = \text{WR}_Q \times \text{TAU}_i. \quad (14)$$



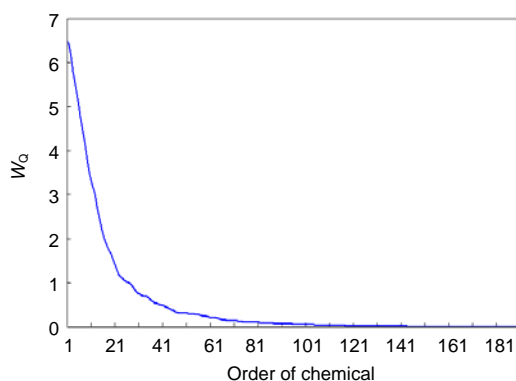
**Fig. 1 Average amounts of pesticides used for winegrape farming in Madera County during 1999–2001**

The orders of the chemicals show the ranks of the pesticides according to the amount of use. Names of the chemicals for the corresponding orders are given in Table A1

Fig. 2 plots the quantity weight from top to bottom for the compounds. As can be seen, the top compound (sulfur, a fungicide) has a quantity weight of 6.47, which changes gradually to 3.46 for the 10th top compound (oryzalin, a herbicide), and 1.49 for the 20th top compound (norflurazon, a herbicide).

**Table 1 Top 40 pesticides used for winegrape production in Madera County, California during 1999–2001**

Order	Chemical code	Chemical name	Total amount of use (kg)			
			1999	2000	2001	Average
1	560	Sulfur	1568043.4	1847072.9	1350594.0	1588570.1
2	173	Cryolite	37608.3	28288.9	15802.8	27233.3
3	2273	Sodium tetrathiocarbonate	34437.7	23619.5	3753.0	20603.4
4	1855	Glyphosate, isopropylamine salt	15838.4	22532.8	15088.6	17819.9
5	151	Copper hydroxide	22745.8	15638.0	11992.7	16792.1
6	445	Propargite	13825.5	12410.9	5162.6	10466.4
7	531	Simazine	7687.4	8873.8	7698.7	8086.6
8	1601	Paraquat dichloride	4817.3	7540.6	7310.4	6556.1
9	358	Lime-sulfur	11569.7	3454.2	575.8	5199.9
10	1868	Oryzalin	7083.4	5755.6	108.9	4316.0
11	748	Alkylaryl poly(oxyethylene) glycol	2778.8	5334.7	3054.1	3722.5
12	1973	Oxyfluorfen	3308.2	3953.8	2798.5	3353.5
13	629	Ziram	6626.0	2076.0	1118.2	3273.4
14	714	Copper	2915.6	5298.0	1164.5	3126.0
15	99	Calcium hydroxide	1773.9	1506.1	3811.0	2363.7
16	765	Petroleum oil, unclassified	1149.7	2554.7	3045.9	2250.1
17	231	Diuron	870.0	2608.9	2338.9	1939.2
18	1314	Poly- <i>i</i> -para-menthene	2079.0	2814.5	698.6	1864.1
19	158	Copper oxychloride sulfate	1905.4	3282.8	167.7	1785.3
20	2019	Norflurazon	1944.5	1754.6	1464.7	1721.3
21	1728	Napropamide	0.0	604.0	2010.1	1307.0
22	211	Mancozeb	1700.0	1131.0	1030.5	1287.2
23	1857	Fenamiphos	700.2	1745.4	1298.4	1248.0
24	2327	Glyphosate-trimesium	776.3	766.6	1860.3	1134.4
25	763	Petroleum distillates	714.8	1743.0	885.7	1114.5
26	616	Metam-sodium	0.0	960.1	1200.1	1080.1
27	1159	Modified phthalic glycerol alkyd resin	1500.4	1287.2	426.8	1071.4
28	597	Trifluralin	614.9	1635.0	383.9	877.9
29	3519	Methyl soyate	61.4	1939.1	523.1	841.2
30	3957	Tebufenozide	0.0	703.4	883.7	793.6
31	2245	Myclobutanil	702.0	996.1	559.2	752.4
32	1552	Benomyl	1026.6	1096.2	73.8	732.2
33	1743	Nonylphenoxy poly(ethyleneoxy) ethanol	485.8	701.9	963.7	717.1
34	2081	Iprodione	845.1	750.2	250.5	615.3
35	3850	Tebuconazole	374.4	941.8	466.8	594.4
36	2337	Encapsulated $\delta$ -endotoxin of <i>Bacillus thuringiensis</i> var. <i>kurstaki</i> in killed <i>pseudomonas fluorescens</i>	889.9	659.2	149.8	566.3
37	806	2,4-D, dimethylamine salt	577.9	702.1	408.8	562.9
38	342	Isopropyl alcohol	514.4	659.6	448.4	540.8
39	346	Dicofol	693.3	773.6	27.2	498.1
40	335	Phosmet	535.6	446.9	0.0	491.2



**Fig. 2 Quantity weight ( $W_Q$ ) of each compound for the pesticide use index computation**

The orders of the chemicals show the ranks of the pesticides according to the amount of use. Names of the chemicals for the corresponding orders are given in Table A1

## 2.4 Toxicity weight determination

The toxicity weight needs to be determined according to the toxicity of each compound. However, a complication arises when the target of toxicity is considered, i.e., what organism does the toxicity apply to? As a matter of fact, different life species have different tolerances for different compounds. For the study in Madera County, the website [www.pesticideinfo.org](http://www.pesticideinfo.org) was used and the pesticide compound dictionary (Meister *et al.*, 2001) was referenced for the evaluation of pesticide toxicity. The website is a national pesticide information website that contains a database for all available compounds. The database has several items related to toxicity, of which two are very important for the study: pesticide action network (PAN) bad actor chemicals and acute toxicity. The former denotes the chemicals that are either one or more of the following: highly acute toxicant, cholinesterase inhibitor, known/probable carcinogen, known groundwater pollutant or known reproductive or developmental toxicant. Because there are no authoritative lists of endocrine disrupting (ED) chemicals, EDs were not yet considered. And the latter describes the EPA toxicity criteria of the chemicals according to the rat median lethal dose ( $LD_{50}$ ), which classified the chemical toxicity levels into high, moderate, slight, and no acute toxicities. The column of toxicity rank in Table 2 was the evaluation for the toxicity weight in the study, with six for very high toxicity, and one for low toxicity. Table 3 shows the determination of the toxicity rank given in Table 2.

Then the total toxicity value (TAT) for all compounds can be computed as

$$TAT = \sum_i TAT_i, \quad (15)$$

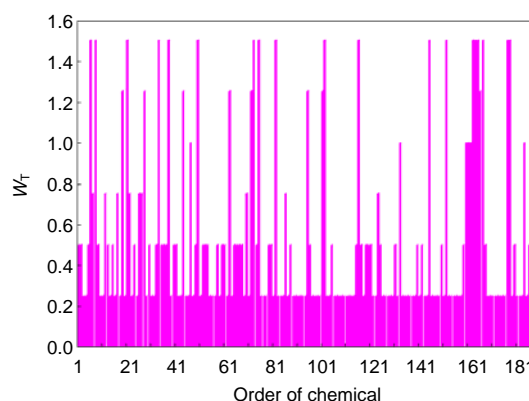
where  $TAT_i$  is the toxicity rank of the  $i$ th compound. Since total toxicity weight is 100, the weight for each unit of toxicity ( $WR_T$ ) can be calculated as

$$WR_T = 100/TAT. \quad (16)$$

Therefore, the toxicity weight for the  $i$ th compound ( $W_{Ti}$ ) can be calculated as

$$W_{Ti} = WR_T \times TAT_i. \quad (17)$$

Fig. 3 plots the toxicity weights for the pesticide compounds used for winegrape production in Madera County. In Fig. 3, it can be seen that there are six toxicity levels for the compounds. The highest toxicity weight is about 1.5 and the lowest about 0.25.



**Fig. 3 Toxicity weight ( $W_T$ ) of each pesticide compound used for winegrape farming in Madera County, California**

The orders of the chemicals show the ranks of the pesticides according to the amount of use. Names of the chemicals for the corresponding orders are given in Table A1

## 2.5 Pesticide chemical types

According to the application purposes, pesticides used for winegrape farming in the county can be categorized into four types: fungicide, insecticide, herbicide, and others. Here the others include plant growth regulators such as gibberellins, adjuvants such as trifloxystrobin, and microbiocides. In order to distinguish the relative importance of each compound

**Table 2 Toxicity and chemical types of the top 40 pesticides**

Order	Chemical code	Name of chemical	PAN bad actor chemical	Acute toxicity	Toxicity rank*	Use type
1	560	Sulfur	Not listed	Slight	2	F
2	173	Cryolite	Not listed	Slight	2	I
3	2273	Sodium tetrathiocarbonate	Not listed	NA	1	Fu
4	1855	Glyphosate, isopropylamine salt	Not listed	NA	1	H
5	151	Copper hydroxide	Not listed	Slight	2	F
6	445	Propargite	Highly toxic	High	6	I
7	531	Simazine	Highly toxic	Slight	3	H
8	1601	Paraquat dichloride	Highly toxic	High	6	H
9	358	Lime-sulfur	Not listed	NA	1	I
10	1868	Oryzalin	Not listed	Slight	2	H
11	748	Alkylaryl polyoxyethylene glycol	Not listed	NA	1	A
12	1973	Oxyfluorfen	Not listed	Slight	2	H
13	629	Ziram	Highly toxic	Moderate	5	F
14	714	Copper	Not listed	NA	1	F
15	99	Calcium hydroxide	Not listed	Slight	2	A
16	765	Petroleum oil, unclassified	Not listed	NA	1	I
17	231	Diuron	Highly toxic	Slight	3	H
18	1314	Poly- <i>i</i> -para-menthene	Not listed	NA	1	PGR
19	158	Copper oxychloride sulfate	Not listed	Slight	2	F
20	2019	Norflurazon	Highly toxic	Slight	3	H
21	1728	Napropamide	Not listed	Slight	2	H
22	211	Mancozeb	Highly toxic	Not acute toxic	3	F
23	1857	Fenamiphos	Highly toxic	High	6	I
24	2327	Glyphosate-trimesium	Not listed	NA	1	H
25	763	Petroleum distillates	Not listed	NA	1	I
26	616	Metam-sodium	Highly toxic	NA	3	Fu
27	1159	Modified phthalic glycerol alkyd resin	Not listed	NA	1	A
28	597	Trifluralin	Not listed	Slight	2	H
29	3519	Methyl soyate	Not listed	NA	1	A
30	3957	Tebufenozide	Not listed	Slight	2	I
31	2245	Myclobutanil	Highly toxic	Slight	3	F
32	1552	Benomyl	Highly toxic	Slight	3	F
33	1743	Nonylphenoxy poly(ethyleneoxy) ethanol	Not listed	Slight	2	F
34	2081	Iprodione	Not listed	NA	1	A
35	3850	Tebuconazole	Not listed	NA	1	A
36	2337	Encapsulated $\delta$ -endotoxin of <i>Bacillus thuringiensis</i> var. <i>kurstaki</i> in killed <i>pseudomonas fluorescens</i>	Not listed	Slight	2	I
37	806	2,4-D, dimethylamine salt	Highly toxic	High	6	H
38	342	Isopropyl alcohol	Not listed	Slight	2	M
39	346	Dicofol	Highly toxic	High	6	I
40	335	Phosmet	Highly toxic	Moderate	5	I

NA: no available weight-of-the-evidence summary assessment; F: fungicide; I: insecticide; Fu: fumigant; H: herbicide; PGR: plant growth regulator; A: adjuvant; M: microbiocide. \* Determination of the toxicity rank shown in Table 3



**Table 3 Determination of toxicity rank**

Toxicity rank	PAN bad actor chemical	Acute toxicity
6	Highly toxic	High
5	Highly toxic	Moderate
4	Not listed	Moderate
3	Highly toxic	Slight or NA
2	Not listed	Slight
1	Not listed	NA

NA: no available weight-of-the-evidence summary assessment

in formulating the impacts on environment, evaluation of each of the four types needs to be conducted. Thus, according to pesticide types, the total PUI can be decomposed into four components for analyzing the contribution of each chemical type to the PUI:

$$PUI_j = PUI_{Fj} + PUI_{Ij} + PUI_{Hj} + PUI_{Oj}, \quad (18)$$

where  $PUI_{Fj}$  is the fungicide PUI of the  $j$ th grower.  $PUI_{Ij}$ ,  $PUI_{Hj}$ , and  $PUI_{Oj}$  are the PUIs of insecticide, herbicide, and other chemicals, respectively.

Since the aim of the study is to identify low pesticide users at grower level, a stable PUI is needed for the identification. For this, the PUI needs to be calculated for at least three years. Due to the availability, data from the years of 1999 to 2001 were used for the calculation. The average PUI for the three years was used as an indicator of low pesticide users.

## 2.6 Data source and analysis procedure

The data source of the pesticide compounds used in the study is from California PUR database (CDPR, 2000; 2001), which possesses the complete pesticide application records at the field level for all of California. For the study, the available data were from 1990 to 2001, which are sufficient to test the applicability of the proposed approach. For each year over 2.5 million records of the pesticide applications were recorded in the PUR database, which was integrated into geographic information system (GIS) software ArcView GIS as an extension of PUR-GIS Application. At the same time, the database was anchored on the Oracle 8i SQL for fast data query. Therefore, both the PUR-GIS Application and the Oracle 8i SQL were used as tools for data mining.

The above analysis involved the following working procedures:

1. Using ArcView PUR-GIS Application to ob-

tain data of pesticides used for winegrape farming in Madera County for the years of 1999–2001. Several summary outputs can be created by the PUR-GIS Application. Among the outputs, the field summary and chemical summary reports were used for the study because the two reports informed on how many fields were there in each year and how many pesticides were used for winegrape farming. The two summary outputs were exported into a dbf file for further analysis.

2. Using an Oracle SQL code to obtain pesticide use data at field level from the PUR database. Since each pesticide had an output file, totally 160 files were obtained from the SQL query.

3. Using a C++ program to join the SQL output files. The SQL output files from Step 2 only contained the data for the fields with the pesticide use. In order to have a convenient way of analysis, the files for all the fields were joined.

4. Importing the joint files into an EXCEL sheet to show the pesticide use for all the fields.

5. Computing grower pesticide use from the EXCEL sheet. Some growers had several fields while others only have one field.

6. Computing the quantity and toxicity weights for each compound.

7. Normalizing the pesticide use intensity (kg/ha) for the growers.

8. Computing the PUI for quantity and toxicity, and for each pesticide type.

9. Scaling the quantity and toxicity PUIs.

10. Computing the integrated PUI to evaluate growers' pesticide use levels.

## 3 Results and discussion

### 3.1 Pesticide use intensities of the growers

Winegrape farming in Madera is diverse. Totally there were 733 fields of winegrape in the county in year 2000 and the fields were distributed among 208 growers. Some growers had more than one field while others had only one. For example, grower identification (ID) 2090264 had 16 fields growing winegrape with 872.51 ha, while grower ID 2402258 only has one field with 64.75 ha. The grower with the largest acreage of vineyard was grower ID 3904325, who had 1779.41 ha of vineyard. The size of the field was also

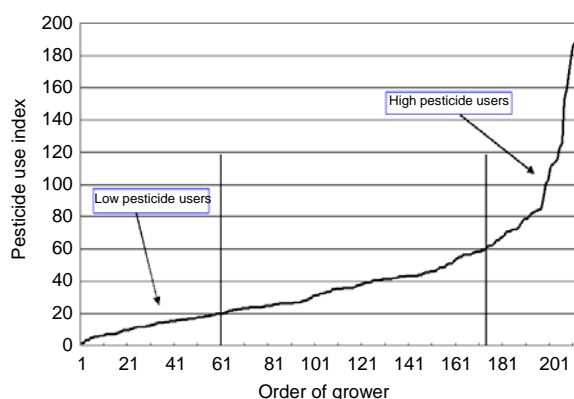
significantly different, with maximum of 259 ha owned by grower ID 2090312 who had only one field.

Fig. 4 shows the PUIs of the growers in an ascending direction. Among the 208 growers, the PUIs of 62 growers (accounting for 29.81%) were  $\leq 20$  in 2000. These growers could be termed as low pesticide users. The percentages of the low pesticide users with  $\text{PUI} \leq 20$  in 2001 and 1999 were 27.96% and 15.10%, respectively. On the other hand, the high pesticide users were those growers who had a high PUI, for example,  $\text{PUI} > 60$ . As shown in Table 4, the PUIs of 8 growers were higher than 80 in 2000, accounting for 3.84% of the total. The percentages in 2001 and 1999 were 9.48% and 21.23%, respectively. Another feature shown in Table 4 was that the number of the high pesticide users tended to decrease in the period under study. In 1999 there were 82 growers with  $\text{PUI} > 60$ . The number decreased to 19 growers in 2000 and

38 growers in 2001. As contrast, the number of the low pesticide users was increasing. In 1999, there were 61 growers with  $\text{PUI} \leq 30$  (Table 4). The number increased to 107 in 2000 and 99 in 2001, respectively. This indicates that reduction of pesticide use intensity has been extensively emphasized in winegrape farming in the recent decade.

### 3.2 Acreage and field number of each PUI group

Statistical analysis on the growers in each PUI group is given in Table 5 for acreage and Table 6 for number of fields. Though winegrape is a perennial crop, growers needed to remove some aged and less productive fields each year. Meanwhile, each year there were newly planted fields in order to keep winegrape farming and vinery industry sustainable. This situation made both the acreage and field number of winegrape dynamic. Under the three study years, the largest winegrape acreage occurred in 2000, at 24017.12 ha (Table 5), but the largest field number was in 2001, with 738 fields (Table 6). The average acreage per field was 33.12, 32.72, and 32.24 ha in the three consecutive years. Table 5 indicates that the winegrape acreage owned by low pesticide users ( $\text{PUI} \leq 20$ ) was steadily increased, being 1625.38, 2328.71, and 2753.69 ha in 1999, 2000, and 2001, accounting for 6.91%, 9.70%, and 11.57% respectively. In contrast, the acreage owned by very high pesticide users ( $\text{PUI} > 80$ ) accounted for 40.73%, 9.75%, and 22.99% in the three years, respectively, showing a declining tendency.



**Fig. 4 Pesticide use indices for the growers of winegrape farming in Madera County, California in 2000**

Orders of the growers are given according their PUI values

**Table 4 Number of growers in each PUI group**

PUI group	Number of growers			Percentage of the total		
	1999	2000	2001	1999	2000	2001
$\leq 10$	15	28	21	7.08	13.46	9.95
10–20	17	34	38	8.02	16.35	18.01
20–30	29	45	40	13.68	21.63	18.96
30–40	20	38	25	9.43	18.27	11.85
40–50	25	25	32	11.79	12.02	15.17
50–60	24	19	17	11.32	9.13	8.06
60–80	37	11	18	17.45	5.29	8.53
80–100	21	5	7	9.91	2.40	3.32
$> 100$	24	3	13	11.32	1.44	6.16
Total	212	208	211	100.00	100.00	100.00

**Table 5 Hectares planted of the growers in each PUI group**

PUI group	Hectares planted of the growers			Percentage of the total		
	1999	2000	2001	1999	2000	2001
$\leq 10$	1290.02	622.40	731.15	5.49	2.59	3.07
10–20	335.36	1706.31	2022.54	1.43	7.10	8.50
20–30	1466.22	4661.23	6113.66	6.24	19.41	25.69
30–40	3828.78	4536.57	2626.02	16.28	18.89	11.04
40–50	1803.29	3683.58	3091.18	7.67	15.34	12.99
50–60	1390.95	4531.89	1696.16	5.92	18.87	7.13
60–80	3820.65	1935.78	2043.35	16.25	8.06	8.59
80–100	2828.76	1005.18	709.01	12.03	4.19	2.98
$> 100$	6749.12	1334.18	4762.69	28.70	5.56	20.01
Total	23513.16	24017.12	23795.76	100.00	100.00	100.00

**Table 6** Field numbers of the growers in each PUI group

PUI group	Field number of the grower			Percentage of the total		
	1999	2000	2001	1999	2000	2001
≤10	47	36	31	6.62	4.90	4.20
10–20	22	52	90	3.10	7.08	12.20
20–30	46	135	157	6.48	18.39	21.27
30–40	60	121	72	8.45	16.49	9.76
40–50	47	94	119	6.62	12.81	16.12
50–60	50	128	53	7.04	17.44	7.18
60–80	122	89	49	17.18	12.13	6.64
80–100	88	41	32	12.39	5.59	4.34
>100	228	38	135	32.11	5.18	18.29
Total	710	734	738	100.00	100.00	100.00

Analysis on field numbers (Table 6) reveals that in 1999 nearly three fourths of the fields were in the hands of high pesticide users. However, the percentages of fields owned or managed by low and moderate pesticide users showed a trend of gradual increase in the following two years, implying that more and more growers started to reduce pesticide use in their winegrape farming.

### 3.3 PUI components of low pesticide users

Analysis on PUI components is very important for identifying the pesticide use behaviors of the growers. Table 7 shows the PUI components of the low pesticide users ( $PUI \leq 20$ ) in 2000. There were 62 growers in this group, of which 28 growers were the extremely low pesticide users, with  $PUI \leq 10$ , and 34 were slightly low pesticide users ( $10 < PUI \leq 20$ ). Table 7 indicates: (1) both  $PUI_Q$  and  $PUI_T$  of these growers were very low, indicating that the growers might have adopted a strategy of low amount and low toxicity of pesticide use in their winegrape farming; (2) the fact of  $PUI_Q$  higher than  $PUI_T$  implies that the growers emphasized more quantity than toxicity in selecting pesticides; and (3) most of the growers used only fungicide in their fields, a few growers used very little insecticide and herbicide, which indicates that low pesticide users might have adopted a better farm management strategy to control insects and weeds while still struggling with fungi in their vineyards.

Statistical analyses on field acreage, field number, and pesticide number reveal that most of the low pesticide users only owned one field with small

acreage and used only 1–3 compounds. Only 6 of the 62 growers' vineyards were larger than 100 ha, 8 growers' vineyards were between 50 and 100 ha, and the rest (48 growers' vineyards) were less than 50 ha (Table 7). As for field number, only 6 of the 62 growers owned no less than 3 fields (no one owned more than 5 fields) and 10 owned 2 fields. Probably because of few fields and small acreage, it was easier for the growers to practice good on-farm management and reduce insecticide and herbicide use. However, most of them used fungicide, which indicated that fungi were more difficult to control without the aid of pesticides. There were two growers (grower IDs 2090831 and 2091811) who did not use fungicide in 2000. As a matter of fact, new growers who started winegrape farming and the growers who would change their vineyards into other crops in the following year might not use pesticides. In order to examine this possibility, the 62 growers were tracked for the three consecutive years. It was found that overall there were 12 new growers and 13 growers stopped winegrape farming in the following year. Therefore, the majority of the low pesticide users stayed in the winegrape farming sector, and their behaviors of using less pesticide might indicate that good on-farm management helped them to minimize the dependence of pesticide. Thus, these low pesticide users could serve as candidates for further investigation to identify the models for extension of low pesticide use.

### 3.4 PUI components of high pesticide users

The PUI components of high pesticide users are shown in Table 8, which gives a very different picture of pesticide use among the growers. These high pesticide users heavily depended on not only fungicide, but also insecticide, herbicide, and other chemicals. Though quantity still contributed more than toxicity to PUI, the percentage of toxicity index in PUI was obviously higher than that in Table 7. It means that high quantity was accompanied with high toxicity in the growers' behaviors of pesticide use. In other words, these growers used not only large quantities of pesticides, but also highly toxic pesticides in their winegrape farming.

Table 8 also reveals that the high pesticide users were generally those big winegrape growers with large acreages and more fields. There were 38 growers with  $PUI > 50$  in 2000. Five of them had winegrape

**Table 7 Pesticide use indices of the low pesticide users in Madera County in 2000**

Order	Grower ID	PUI	PUI <sub>Q</sub>	PUI <sub>T</sub>	PUI <sub>F</sub>	PUI <sub>I</sub>	PUI <sub>H</sub>	Hectares	<i>n</i> <sub>field</sub>	<i>n</i> <sub>chem</sub>
1	2098790 <sup>@*</sup>	0.36	0.19	0.17	0.36	0.00	0.00	0.61	1	1
2	2090355 <sup>@*</sup>	1.11	0.51	0.60	0.30	0.81	0.00	8.09	1	2
3	2090331 <sup>*</sup>	1.15	0.51	0.64	0.16	0.23	0.28	30.76	1	4
4	2096325 <sup>@*</sup>	1.32	1.07	0.25	1.32	0.00	0.00	120.39	2	2
5	2090003	1.79	1.69	0.10	1.79	0.00	0.00	57.47	3	1
6	2090272 <sup>*</sup>	2.76	2.60	0.16	2.76	0.00	0.00	4.45	1	1
7	2090704	3.03	2.88	0.15	1.82	0.00	1.21	7.28	2	2
8	2090752	3.04	1.78	1.26	1.91	0.00	0.00	22.26	1	5
9	2090806	3.07	2.90	0.18	3.07	0.00	0.00	30.35	1	1
10	2090104	4.16	3.92	0.24	4.16	0.00	0.00	16.19	1	1
11	2091273 <sup>*</sup>	4.85	4.57	0.28	4.85	0.00	0.00	4.45	1	1
12	2090831	4.95	2.96	1.99	0.00	0.00	3.35	2.02	1	9
13	2090289	5.02	4.56	0.46	1.97	0.29	2.76	18.21	2	4
14	2090066 <sup>*</sup>	5.10	4.09	1.01	0.00	5.10	0.00	46.54	1	1
15	2090431 <sup>*</sup>	5.15	4.35	0.81	4.61	0.00	0.00	10.12	1	2
16	2090500	5.52	3.31	2.21	2.09	0.81	1.92	16.19	1	7
17	2091013 <sup>@</sup>	5.59	4.44	1.15	1.16	0.00	4.03	20.23	1	6
18	2090278	6.65	2.86	3.78	1.51	4.70	0.00	22.66	2	11
19	2090994	6.73	5.73	1.00	6.73	0.00	0.00	4.05	1	3
20	2091304 <sup>@</sup>	6.98	6.02	0.96	0.42	0.00	3.31	18.21	1	4
21	2091234 <sup>@</sup>	7.33	6.91	0.42	7.33	0.00	0.00	24.28	1	1
22	2090363 <sup>@</sup>	7.62	6.86	0.75	7.62	0.00	0.00	6.47	1	3
23	2090255	7.76	7.31	0.45	7.76	0.00	0.00	30.76	1	1
24	2090539	8.52	8.03	0.49	8.52	0.00	0.00	21.04	2	1
25	2090394	8.58	7.51	1.07	2.31	0.00	6.28	29.14	2	4
26	2090769 <sup>*</sup>	9.40	8.54	0.87	9.40	0.00	0.00	16.19	1	3
27	2090447	9.76	7.31	2.45	7.50	0.00	0.00	14.97	1	8
28	2091811 <sup>@</sup>	9.90	7.90	2.00	0.00	8.80	0.00	19.02	1	3
29	2090531	10.01	6.99	3.02	6.07	1.01	0.00	12.95	1	7
30	2090732 <sup>*</sup>	10.49	6.39	4.11	10.49	0.00	0.00	15.38	1	2
31	2091701	10.50	9.71	0.79	1.16	0.00	9.34	8.09	1	3
32	2090483 <sup>*</sup>	10.85	10.30	0.55	0.00	0.00	10.85	17.08	1	2
33	2090497	10.92	10.29	0.63	10.92	0.00	0.00	8.09	1	1
34	2405610	11.87	8.86	3.01	3.02	1.61	4.36	247.26	3	8
35	2090682	12.25	10.95	1.30	7.14	1.79	3.32	16.19	1	3
36	2090618	12.31	10.56	1.76	3.15	9.16	0.00	2.83	1	4
37	2090760	12.43	11.81	0.62	8.07	0.00	4.36	40.47	1	2
38	2090138	12.54	10.98	1.56	2.74	0.09	8.18	242.81	5	16
39	2090059	12.56	10.29	2.27	8.79	3.48	0.00	126.26	4	5
40	2090779 <sup>@</sup>	12.67	11.99	0.69	10.78	0.00	1.89	80.13	1	2
41	2090686	12.84	11.55	1.28	10.74	0.00	2.10	18.01	3	4
42	2090099	13.55	11.68	1.87	0.00	0.00	13.40	16.19	1	5
43	2090509	13.76	11.79	1.97	11.89	1.70	0.00	15.38	1	3
44	2090956	14.41	12.66	1.75	3.64	0.00	10.43	15.38	1	5
45	2090584	14.56	11.06	3.51	10.80	0.28	2.55	62.04	2	5
46	2090186	14.96	14.24	0.72	8.71	0.00	6.25	4.45	2	2
47	2090885	15.00	13.58	1.42	10.83	0.51	0.00	8.09	1	4
48	2090380	15.17	12.28	2.89	7.12	3.13	3.54	16.19	1	11
49	2090891 <sup>@</sup>	15.28	14.10	1.18	9.87	0.00	5.42	18.62	1	3
50	2090408	15.35	11.49	3.85	10.20	0.98	3.38	4.17	1	8

To be continued

Table 7

Order	Grower ID	PUI	PUI <sub>Q</sub>	PUI <sub>T</sub>	PUI <sub>F</sub>	PUI <sub>I</sub>	PUI <sub>H</sub>	Hectares	<i>n</i> <sub>field</sub>	<i>n</i> <sub>chem</sub>
51	2090429*	15.59	14.80	0.79	10.92	0.00	4.67	16.19	1	2
52	2090788 <sup>®</sup>	15.91	14.49	1.42	14.48	0.47	0.95	60.70	2	3
53	2090139	15.96	12.49	3.47	3.84	0.24	9.08	137.59	4	10
54	2090105	16.27	14.32	1.95	3.11	0.00	12.12	40.47	1	13
55	2090251	16.60	13.94	2.66	3.64	0.92	11.59	121.41	1	5
56	2090227*	17.01	15.66	1.35	5.50	0.00	11.11	55.08	1	6
57	2091038	17.81	15.38	2.43	7.70	0.00	9.60	13.76	1	7
58	2090352	18.42	15.99	2.43	6.64	0.84	8.84	7.28	1	8
59	1070383 <sup>®</sup>	18.72	14.81	3.91	5.59	0.00	13.13	56.66	1	5
60	2090324	18.82	16.78	2.04	8.15	7.33	3.35	89.84	2	4
61	1010090	19.58	17.71	1.87	18.10	0.00	0.00	62.73	1	5
62	2090306	19.90	14.17	5.73	2.77	0.00	11.74	48.56	1	9

*n*<sub>field</sub>: field number; *n*<sub>chem</sub>: chemical number. <sup>®</sup> New growers; \* Disappeared growers

Table 8 Pesticide use indices of the high pesticide users in Madera County in 2000

Order	Grower ID	PUI	PUI <sub>Q</sub>	PUI <sub>T</sub>	PUI <sub>F</sub>	PUI <sub>I</sub>	PUI <sub>H</sub>	Hectares	<i>n</i> <sub>field</sub>	<i>n</i> <sub>chem</sub>
1	2090307	50.22	39.54	10.68	14.67	14.58	8.13	16.19	2	14
2	1040595	50.98	41.76	9.22	15.99	11.87	14.26	64.75	2	17
3	1070404	52.35	42.71	9.65	4.54	7.22	40.59	17.81	3	6
4	2091202	52.36	42.62	9.74	14.83	9.13	19.61	974.08	13	23
5	2090436	53.00	47.28	5.72	22.48	7.63	17.38	16.19	1	11
6	2090334	53.54	42.79	10.75	16.39	16.71	19.37	135.97	3	12
7	2090249	53.58	48.62	4.95	36.84	0.26	14.76	93.89	4	8
8	2090020	54.34	47.33	7.01	14.56	10.03	21.60	152.57	6	19
9	2090062	54.58	40.15	14.42	10.12	22.29	20.52	326.18	11	22
10	2090060	55.19	47.02	8.17	19.74	15.55	16.51	743.21	21	27
11	2090819	55.45	41.81	13.64	16.88	16.81	20.78	20.64	4	13
12	2090096	55.92	46.13	9.79	16.78	22.74	15.64	411.16	10	18
13	2090282	56.72	51.29	5.43	30.69	2.59	21.60	22.26	1	9
14	2090600	56.80	46.38	10.43	38.80	16.41	0.00	287.33	3	9
15	2402258	57.13	48.42	8.71	16.33	17.32	20.77	64.75	1	17
16	2090264	57.75	49.70	8.05	20.57	4.03	20.55	872.51	17	18
17	2090424	59.38	45.68	13.70	17.77	18.08	20.94	58.68	3	16
18	2090218	59.41	49.36	10.05	16.07	9.02	30.23	13.76	3	15
19	2090398	59.59	51.03	8.56	5.14	10.70	26.09	239.98	20	14
20	1082220	60.17	48.17	12.00	15.57	16.11	18.66	281.66	9	23
21	2091217	60.33	45.53	14.81	34.52	14.24	8.78	35.61	1	18
22	2090017	62.78	47.72	15.07	21.95	30.08	7.12	151.76	8	17
23	2080421	62.85	51.66	11.19	20.21	5.89	27.94	157.83	6	16
24	2001362	64.88	56.20	8.68	12.72	20.25	22.49	266.45	6	18
25	2090115	64.93	54.55	10.38	25.69	0.58	36.63	186.16	18	19
26	2090270	64.93	56.24	8.69	8.39	10.06	31.55	46.54	2	12
27	2090333	65.69	53.10	12.59	14.10	19.34	31.25	118.57	5	16
28	2090109	76.85	66.04	10.80	8.46	2.66	64.57	16.19	1	14
29	2090503	77.42	55.07	22.34	17.61	16.97	37.12	541.47	31	16
30	2090277	77.49	63.81	13.68	24.08	7.63	38.79	133.55	2	16
31	1020037	81.59	69.60	11.99	36.86	11.43	23.45	487.41	15	17
32	2090133	83.18	67.40	15.78	22.06	14.17	35.15	11.33	3	23
33	2090132	88.65	68.72	19.93	45.75	20.36	18.75	145.08	12	12
34	2090871	95.30	76.50	18.80	21.78	12.96	49.71	82.15	4	28
35	2090131	96.78	75.34	21.45	21.42	13.95	48.24	279.23	7	35
36	1060326	111.51	96.70	14.80	18.05	33.39	33.50	330.43	17	15
37	2090070	119.16	99.99	19.17	8.82	21.70	70.74	928.47	19	24
38	2090802	142.15	42.51	99.64	30.00	100.95	4.73	75.27	2	23

*n*<sub>field</sub>: field number; *n*<sub>chem</sub>: chemical number

acreage more than 500 ha and another seventeen between 100 and 500 ha. Twelve growers owned more than 10 fields. In contrast to the low pesticide users, these high pesticide users usually applied more than 10 pesticides in their fields, and the pesticides that they applied covered all types, i.e., fungicide, insecticide, herbicide, and others (Table 8).

The identification of these high pesticide users is very helpful, because extension specialists can focus their efforts on these growers in order to increase the efficiency of pesticide use and reduce pesticide environmental risk. In this case, both reduction of application amount and emphasis on using low toxicity pesticides are alternative strategies for the high pesticide users.

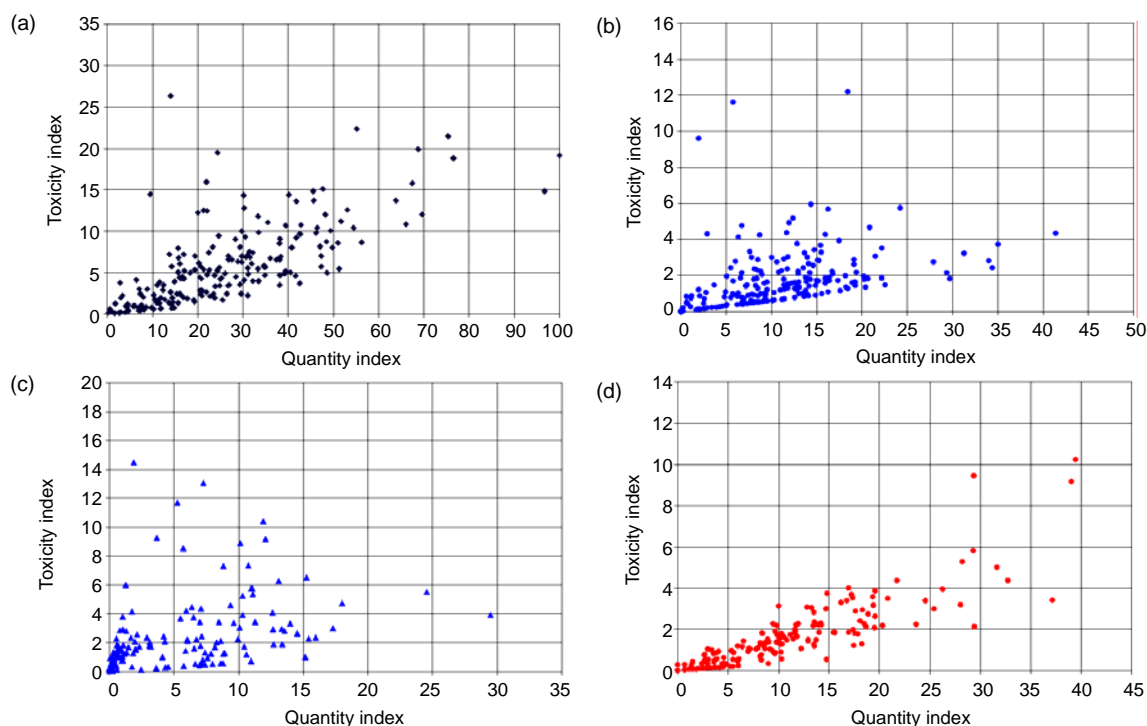
### 3.5 Relationship between toxicity index and quantity index

Examination of the relationship between the toxicity index and quantity index is useful for analyzing pesticide application patterns among the winegrape growers in Madera County. Fig. 5 shows the relationship for the integrated PUI, fungicide index, insecticide index, and herbicide index.

Fig. 5a shows two opposite behavior patterns of

low and high pesticide users. Using small quantity and low toxic pesticides is the behavior pattern of low pesticide users while using large quantity and high toxic pesticides is the pattern of high pesticide users. It hints that some growers had found efficient ways to control pests in their vineyards by using less pesticides and applying low toxic compounds, while other growers still heavily depended on pesticides in their winegrape farming.

Fig. 5b shows the relationship between quantity and toxicity of fungicide, which is very similar to Fig. 5a. It can be seen that fungicides were usually used in large quantity and many fungicides were highly toxic. Fig. 5c shows a different relation between quantity and toxicity for insecticides, because most growers chose either large quantity or high toxicity, but not both. In other words, while growers used insecticides in their vineyards, a large quantity was usually accompanied with low toxicity, and vice versa. The close relationship between quantity and toxicity of herbicide is shown in Fig. 5d, which is quite similar with Figs. 5a and 5b. This is probably attributed to the fact that weed is also a difficult problem in winegrape farming, especially for large growers in the county.



**Fig. 5 Relationship between quantity index and toxicity index for all the growers of winegrape farming in Madera County in 2000**

(a) Integrated PUI; (b) Fungicide index; (c) Insecticide index; (d) Herbicide index

### 3.6 Comparison of two methods for pesticide use index

Comparison of the two methods (additive and multiplied forms) in constructing the pesticide use index is very important to verify the applicability of the proposed approach. Fig. 6 and Table 9 give the comparison of PUI and PUIM. A very close relation between the PUI and PUIM can be seen in Fig. 6, indicating that PUI and PUIM are almost the same, and both can reflect the pesticide use levels of wine-grape growers. Since the compositions of both PUI and PUIM are the quantity index ( $PUI_Q$ ) and toxicity index ( $PUI_T$ ) of pesticide use, and both  $PUI_Q$  and  $PUI_T$  have the values between 0 and 100, thus PUI has a value between 0 and 200, while PUIM is between 0 and 10000. Regression of PUIM to PUI gives the following equations:

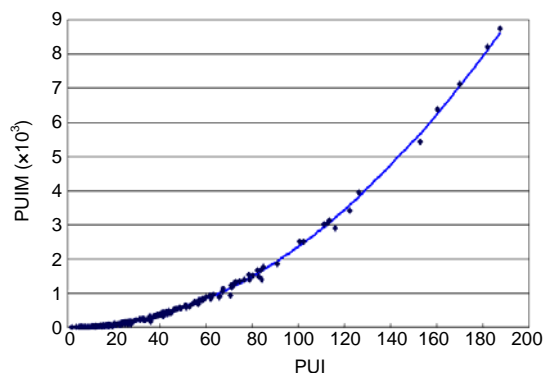
For  $PUI=0-60$ ,

$$PUIM=0.1283 \times PUI^{2.1562}, R^2=0.99; \quad (19)$$

For  $PUI=60-200$ ,

$$PUIM=0.1818 \times PUI^{2.0572}, R^2=0.99. \quad (20)$$

The high correlation between PUI and PUIM verifies that the proposed pesticide use index, constructed as either the additive or the multiplicative form, has the capability to correctly reflect the pesticide use levels of the growers for identification of the low and high pesticide users.



**Fig. 6 Comparison of the pesticide use index in the additive (PUI) and the multiplicative (PUIM) methods**  
The dots are the original data of PUI and PUIM, while the line denotes the regression trend simulating the PUIM from the PUI using Eqs. (19) and (20)

**Table 9 Comparison of PUI and PUIM in identifying the low pesticide users in 2001**

Order	Rank according to PUI			Order	Rank according to PUIM		
	Grower ID	PUI	PUIM		Growers ID	PUI	PUIM
1	2090450	1.51	0.39	1	2090788	1.79	0.30
2	2090788	1.79	0.30	2	2090450	1.51	0.39
3	1080751	3.57	1.98	3	2090305	3.70	1.00
4	2090305	3.70	1.00	4	2090465	6.28	1.29
5	2090284	4.70	3.13	5	1080751	3.57	1.98
6	2090054	5.28	4.04	6	2090284	4.70	3.13
7	2091013	5.67	7.79	7	2090054	5.28	4.04
8	2090500	5.88	4.46	8	2090500	5.88	4.46
9	2091234	6.04	6.19	9	2091234	6.04	6.19
10	2090465	6.28	1.29	10	2090394	6.63	6.42
11	2090394	6.63	6.42	11	2091013	5.67	7.79
12	2090824	7.21	12.97	12	1030724	7.25	8.91
13	1030724	7.25	8.91	13	2090373	7.25	8.91
14	2090373	7.25	8.91	14	2090539	7.37	9.22
15	2090539	7.37	9.22	15	2090601	7.58	10.19
16	2090601	7.58	10.19	16	2090720	8.92	12.94
17	2090113	8.51	17.03	17	2090824	7.21	12.97
18	2090720	8.92	12.94	18	2090186	9.66	13.46
19	2090531	9.61	19.38	19	2090709	9.64	15.75
20	2090709	9.64	15.75	20	2090113	8.51	17.03
21	2090186	9.66	13.46	21	2090531	9.61	19.38
22	2090255	10.49	27.26	22	2090447	17.42	20.79
23	2091765	10.85	29.45	23	2090497	11.33	21.75

To be continued

Table 9

Order	Rank according to PUI			Order	Rank according to PUIM		
	Grower ID	PUI	PUIM		Growers ID	PUI	PUIM
24	2090497	11.33	21.75	24	2090408	11.73	23.32
25	2090278	11.61	33.64	25	2090994	15.05	24.68
26	2090408	11.73	23.32	26	2090306	12.08	24.74
27	2090437	11.77	34.44	27	2090845	19.20	25.83
28	2090059	11.96	35.47	28	2090255	10.49	27.26
29	2090306	12.08	24.74	29	2090456	12.99	28.08
30	2090686	12.55	38.71	30	2091765	10.85	29.45
31	2090456	12.99	28.08	31	2090278	11.61	33.64
32	2090822	13.44	34.46	32	2090538	14.55	34.10
33	2090956	13.72	44.64	33	2090437	11.77	34.44
34	2090926	14.21	50.10	34	2090822	13.44	34.46
35	2090155	14.34	37.84	35	2090059	11.96	35.47
36	2090538	14.55	34.10	36	2090155	14.34	37.84
37	2090994	15.05	24.68	37	2090686	12.55	38.71
38	2090665	15.07	54.68	38	2090385	15.79	42.98
39	2090359	15.08	56.77	39	2090956	13.72	44.64
40	2090138	15.28	51.97	40	2090926	14.21	50.10
41	2090084	15.39	51.78	41	2090084	15.39	51.78
42	2090398	15.60	59.33	42	2090138	15.28	51.97
43	2090385	15.79	42.98	43	2090104	18.27	53.14
44	2090256	16.25	61.26	44	2090665	15.07	54.68
45	2090937	16.36	61.16	45	2090359	15.08	56.77
46	2091038	16.50	67.48	46	2090124	17.90	58.07
47	2090811	16.85	70.89	47	2090831	18.22	58.63
48	2090891	16.94	71.07	48	2090398	15.60	59.33
49	2090516	17.01	71.17	49	2090937	16.36	61.16
50	2090447	17.42	20.79	50	2090256	16.25	61.26
51	2090663	17.69	71.27	51	2090988	19.29	63.10
52	2090124	17.90	58.07	52	2091038	16.50	67.48
53	2090091	17.97	75.74	53	2090811	16.85	70.89
54	2090831	18.22	58.63	54	2090891	16.94	71.07
55	2090104	18.27	53.14	55	2090516	17.01	71.17
56	2090716	18.59	86.21	56	2090663	17.69	71.27
57	2090845	19.20	25.83	57	2090091	17.97	75.74
58	2090988	19.29	63.10	58	2090716	18.59	86.21
59	1070178	19.92	96.29	59	2090251	20.82	86.61
				60	2090535	22.62	87.64
				61	2090584	23.72	90.93
				62	1040595	20.53	95.77
				63	1070178	19.92	96.29
				64	2090289	27.37	97.51
				65	2091069	22.27	98.10



In Table 9 the results of using PUI and PUIM to identify low pesticide users are presented. Table 9 indicates that 21 growers' PUI values were  $\leq 10$  and another 38 growers' PUI values were between 10 and 20. These 59 growers could be classified as the low pesticide users because their PUI values were  $\leq 20$ . The comparison in Table 9 clearly shows that all the 65 growers had a PUIM value  $\leq 100$ . Since PUIM ranged from 0 to 10000, the growers with  $\text{PUIM} \leq 100$  could also be classified as the low pesticide users. Moreover, the growers with  $\text{PUI} \leq 20$  were exactly those with  $\text{PUIM} \leq 100$ , though slightly different in their relative orders in the rank. However, there were 65 growers with  $\text{PUIM} \leq 100$ , of which 6 growers had a PUI value  $> 20$ . These 6 growers could not be classified as the low pesticide users by PUI, because of their slightly higher PUI values. Therefore, it seems that it is more conservative to construct the pesticide use index from the additive form than from the multiplicative one.

Comparison of the two indices was also done in identifying high pesticide users. There were 38 growers with  $\text{PUI} > 60$ , while all of them had a PUIM value  $> 900$ . However, when the growers were ranked according to their PUIM values, it was found that 36 growers having a PUI value  $> 60$ . Thus, the identification by PUIM kept two growers out of the group of high pesticide users when compared with the identification by PUI. The result once again confirms that PUI is more conservative than PUIM in identification of high pesticide users, though both indices are capable in the identification.

#### 4 Conclusions

Pesticide usage for winegrape farming varies greatly in Madera County. Some farmers had high intensity of pesticide use while others had low intensity. Some farmers used a number of pesticides in their fields, but others used only one or two. These multi-intensities and multi-chemicals interacted with different toxicities, making it very complicated to comprehensively evaluate pesticide use at the grower level. In order to identify low and high pesticide users, an approach was proposed in the paper to compute an integrated pesticide use index. Both pesticide quantity and toxicity were considered as factors for estab-

lishment of the index. The index was formulated by the pesticide application intensity measured in kg/ha planted and the weights from quantity and toxicity of the compounds used.

Using the proposed approach, the pesticide usage in Madera County during 1999–2001 was analyzed. The low and high pesticide users in the county were identified, and their pesticide use patterns and pest management strategies were also analyzed. Relationships between the quantity index and the toxicity index of the integrated PUI and its components (fungicide, insecticide, and herbicide) were examined. Results from the analysis indicate that those growers with  $\text{PUI} \leq 20$  can be identified as low pesticide users. In 2000 there were 62 growers with 88 fields and 2328.73 ha vineyards falling into the category of low pesticide users. In contrast, the high pesticide users can be termed as the growers with  $\text{PUI} > 60$ . In 2000, there were 19 growers with 168 fields and 4275.15 ha being classified as the high pesticide users. The high pesticide users usually applied more than 10 pesticides in their fields, as a contrast to the low pesticide users who usually applied less than 5 pesticides.

The analysis also reveals that the number of low pesticide users steadily increased while the high pesticide users decreased in the three years under study. This indicates that the reduction of pesticide use was on the way in the county. It was also found that there was a close relationship between the quantity and toxicity contributing to the pesticide use index, with the contribution of quantity index slightly higher than that of toxicity index. The low pesticide users not only used a small quantity of pesticides, but also intended to apply the compounds with low toxicity. They mainly depended on fungicides as their main pest control measures and used few insecticides and herbicides. The high pesticide users had both high quantity and high toxicity features, indicating that they not only used a large quantity of pesticides, but also intended to use the highly toxic compounds. Considering that they had more fields and acreages, the high pesticide users might emphasize more in pest control than in the negative impacts of pesticides on environment.

Since the pesticide use index can be constructed from either additive (PUI) or multiplicative (PUIM) method, comparison of the two methods was done in identifying low and high pesticide users. The results indicate that though both PUI and PUIM were highly

capable, PUI was more conservative or strict than PUIIM in identifying the low and high pesticide users.

Though the data used in the analysis were several years back, the case study could still provide an alternative to identify the on-farm innovation of growers for reducing pesticide environmental risk. Therefore, it can be concluded that the proposed method is useful for analyzing pesticide use at the grower level, and identifying low and high pesticide users for further investigation of searching ways to reduce pesticide environmental risk. The low pesticide users could be further analyzed to identify their alternative farm management strategies relating to pest controls for some models worthy of extension. The extension of models for reducing pesticide risk should be focused on high pesticide users who usually own large acreages of farming. Therefore, the proposed approach is expected to be helpful for improving pesticide risk management and reducing pesticide environmental risk.

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## Appendix

**Table A1 Names of pesticide chemicals and their corresponding orders used in winegrape farming in Madera County of California from the PUR database**

Order	Chemical code	Chemical name	Order	Chemical code	Chemical name
1	81	Dicloran	9	158	Copper oxychloride sulfate
2	86	<i>Bacillus thuringiensis</i> (Berliner)	10	162	Copper sulfate (basic)
3	89	2-Butoxyethanol	11	173	Cryolite
4	99	Calcium hydroxide	12	175	Copper oxide (ous)
5	104	Captan	13	198	Diazinon
6	105	Carbaryl	14	211	Mancozeb
7	142	Citric acid	15	216	Dimethoate
8	151	Copper hydroxide	16	225	Diphacinone

To be continued

Table A1

Order	Chemical code	Chemical name	Order	Chemical code	Chemical name
17	231	Diuron	65	1218	Alkyl benzene sulfonic acid
18	238	Dinoseb	66	1244	Octylphenoxy polyethoxy ethanol
19	253	Chlorpyrifos	67	1306	Potassium hydroxide
20	310	Gibberellins	68	1314	Poly- <i>i</i> -para-menthene
21	335	Phosmet	69	1329	Benzoic acid
22	342	Isopropyl alcohol	70	1339	Magnesium sulfate
23	346	Dicofol	71	1363	Ammonium sulfate
24	358	Lime-sulfur	72	1376	Alkyl polyethylene glycol ether
25	367	Malathion	73	1389	Tall oil acids
26	369	Maneb	74	1399	Bentonite
27	383	Methomyl	75	1400	Lactose
28	445	Propargite	76	1444	Polyoxyethylene mixed fatty acid ester
29	473	Petroleum hydrocarbons	77	1482	Butyl alcohol
30	484	Aluminum phosphide	78	1552	Benomyl
31	505	Propionic acid	79	1579	Trisodium phosphate
32	507	Propylene glycol	80	1596	Potash soap
33	510	Pyrethrins	81	1598	Coconut diethanolamide
34	531	Simazine	82	1601	Paraquat dichloride
35	554	Strychnine	83	1698	Polyoxyethylene polypropoxy propanol
36	560	Sulfur	84	1728	Napropamide
37	597	Trifluralin	85	1743	Chem1743
38	616	Metam-sodium	86	1757	Edta, sodium salt
39	626	Zinc phosphide	87	1766	Ethoxylated linear alcohols
40	629	Ziram	88	1788	Chem1788
41	654	Diammonium phosphate	89	1821	Starch
42	662	Urea	90	1855	Glyphosate, isopropylamine salt
43	667	Zinc sulfate	91	1857	Fenamiphos
44	714	Copper	92	1861	Dimethyl polysiloxane
45	726	Potassium nitrate	93	1868	Oryzalin
46	748	Alkylaryl polyoxyethylene glycol	94	1874	Chem1874
47	759	Edta, tetrasodium salt	95	1876	Fenbutatin oxide
48	763	Petroleum distillates	96	1882	Soybean fatty acids, dimethylamine salt
49	765	Petroleum oil, unclassified	97	1884	Chem1884
50	806	2,4-D, dimethylamine salt	98	1917	Silicone defoamer
51	871	Phosphoric acid	99	1918	Tetrapotassium pyrophosphate
52	878	Alkylaryl polyether alcohol	100	1929	Pendimethalin
53	881	Alkylaryl polyoxyethylene ether	101	1973	Oxyfluorfen
54	909	Sodium xylene sulfonate	102	1980	Fenarimol
55	941	Dodecylbenzene sulfonic acid	103	1986	Chem1986
56	979	Limonene	104	2018	Polyoxyethylene polymer
57	1006	Triethanolamine	105	2019	Norflurazon
58	1015	Cottonseed oil	106	2023	Oxyalkylated alcohol
59	1066	Diethylamine salt of coconut fatty acid	107	2024	Chem2024
60	1156	Oleic acid	108	2045	Chem2045
61	1159	Modified phthalic glycerol alkyd resin	109	2048	Alkyl oxy polyethoxy ethanol
62	1173	Alkylphenoxy polyethoxy ethanol	110	2052	Chem2052
63	1198	Free fatty acids and/or amine salts	111	2068	Dicapryl sodium sulfosuccinate
64	1210	Glycol ethers	112	2071	Kerosene

To be continued

Table A1

Order	Chemical code	Chemical name	Order	Chemical code	Chemical name
113	2073	Nonylphenoxy hydroxypoly(oxyethylene)	150	3744	Polyoxyethylene dioleate
114	2081	Iprodione	151	3841	Silicone-polyether copolymer
115	2106	Petroleum distillates, refined	152	3849	Imidacloprid
116	2111	Polyacrylamide polymer	153	3850	Tebuconazole
117	2123	Alkyl polyoxy alkylene ether	154	3858	Chem3858
118	2124	Compounded silicone	155	3859	Chem3859
119	2136	Chem2136	156	3862	Chem3862
120	2158	Chem2158	157	3946	Glufosinate-ammonium
121	2177	Sethoxydim	158	3957	Tebufenozide
122	2198	Alkylaryl polyethylene glycol ether	159	3959	Pyridaben
123	2234	Fenpropathrin	160	3970	Chem3970
124	2245	Myclobutanil	161	3984	Thiazopyr
125	2254	Avermectin	162	3988	Chem3988
126	2260	Triflumizole	163	3998	$\beta$ -Pinene polymer
127	2266	Oleic acid, methyl ester	164	3999	Nonylphenol polyethylene glycol ether
128	2268	Nerolidol	165	4000	Cyprodinil
129	2269	Farnesol	166	4009	Heptamethyltrisiloxane ethoxylated (8 EO)
130	2270	Urea dihydrogen sulfate	167	4015	Alkyl (C8,C10) polyglycoside
131	2273	Sodium tetrathiocarbonate	168	4023	Chem4023
132	2277	Cinnamaldehyde	169	4037	Azoxystrobin
133	2301	Glyphosate, monoammonium salt	170	5015	Ammonium propionate
134	2327	Glyphosate-trimesium	171	5016	Chem5016
135	2334	Diethylene glycol	172	5022	E-11-tetradecen-1-yl acetate
136	2337	Chem2337	173	5023	Z-11-tetradecen-1-yl acetate
137	2360	Chem2360	174	5037	Potassium bicarbonate
138	2610	Chem2610	175	5231	Chem5231
139	2629	Kaolin	176	5321	Trifloxystrobin
140	2775	Phosphatidylcholine	177	5324	Lauric acid
141	2912	Tall oil	178	5325	Chem5325
142	2997	Glyphosate	179	5399	Styrene butadiene polymer
143	3052	Ammonium nitrate	180	5447	QST 713 strain of dried <i>Bacillus subtilis</i>
144	3247	Isopropylamine dodecylbenzene sulfonate	181	5451	Kresoxim-methyl
145	3519	Methyl soyate	182	5557	Forchlorfenuron
146	3520	Chem3520	183	5599	Chem5599
147	3689	Methyl silicone resins	184	5740	Chem5740
148	3738	Polymerized acrylic acid	185	5815	Fluazifop- <i>p</i> -butyl
149	3743	Polyoxyethylene dinonyl phenol	186	90104	Captan, other related

Chem1743: nonylphenoxy polyethyleneoxy ethanol; Chem1788: poly(methylene para-nonylphenoxy)-poly(oxypropylene) propanol; Chem1874:  $\alpha$ -alkyl- $\omega$ -hydroxypoly(oxyethylene) ethanol; Chem1884:  $\alpha$ -alkyl- $\omega$ -hydroxypoly(oxyethylene) poly(oxyethylene); Chem1986: *N,N*-bis-(2-( $\omega$ -hydroxypoly(oxyethylene) ethyl) alkylamine, alkyl derived from coconut oil fatty acids; Chem2024: alkylaryl polyoxyethylene glycol phosphate ester; Chem2045: petroleum oil, paraffin based, see chemical code 401; Chem2052:  $\alpha$ -(*p*-nonylphenyl)- $\omega$ -hydroxypoly(oxyethylene) with an average of 9–10 mol of ethylene oxide; Chem2136: alkyl oxy-polyoxyethylene and alkyl phenyloxy-polyoxyethylene; Chem2158: alkyl polyoxyethylene ethers, polymerized resins and fatty acids; Chem2337: encapsulated  $\delta$ -endotoxin of *Bacillus thuringiensis* var. *kurstaki* in killed pseudomonas fluorescens; Chem2360: proprietary blend of linear secondary alcohols reacted with ethylene oxide; Chem2610: 2-(3-hydroxypropyl)-hepta-methyl trisiloxane, ethoxylated, acetate; Chem3520: polyalkene oxide modified heptamethyl trisiloxane; Chem3858: *Bacillus thuringiensis* (Berliner), subsp. *kurstaki*, serotype 3a,3b; Chem3859: *Bacillus thuringiensis* (Berliner), subsp. *kurstaki*, strain EG2348; Chem3862: *Bacillus thuringiensis* (Berliner), subsp. *kurstaki*, strain SA-11; Chem3970: *Bacillus thuringiensis* (Berliner), subsp. *kurstaki*, strain SA-12; Chem3988: *Bacillus thuringiensis* (Berliner), subsp. *kurstaki*, genetically engineered strain EG7841 lepidopteran active toxin; Chem4023: *Bacillus thuringiensis* (Berliner), subsp. *kurstaki*, strain HD-1; Chem5016: *p*-nonylphenyl polyoxyethylene (4–14 mol) dihydrogen phosphate ester; Chem5231: organosilicone, polyoxyalkylene ether copolymer; Chem5325: *Bacillus thuringiensis* var. *kurstaki*, genetically engineered strain EG7826; Chem5599: 2,6,8-trimethyl-4-nonyloxy polyethylene oxyethanol; Chem5740:  $\alpha$ -alkyl (C12–C15)  $\omega$ -hydroxypoly(oxyethylene), sodium salt