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Row Crop Herbicide Drift Effects on Water Bodies and Aquaculture

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1. Introduction

Aquatic ecosystems produce substantial amounts of aquatic products; including all new sources of seafood, from aquaculture. Level land with clay soils and the availability of water supplies makes riverine alluvial plains favorable areas for row crops and aquaculture. Aquaculture ponds are susceptible to impacts from row crop production through drift of herbicides. To assess these impacts we have conducted field research in replicated mesocosms filled with water and associated naturally-occurring communities from various pond ecosystems and subjected to expected levels of drift from all major aerially-applied herbicides currently in use. Rather than an organismal approach and LC_{50}'s, data indicates community-level approaches better approximate ecosystem impacts. Herbicide drift that affects phytoplankton adversely or in a stimulatory manner will similarly impact the ecosystem, as phytoplankton produce oxygen, take up ammonia and nitrite and provide food for zooplankton. Drift levels are below toxic levels to most other aquatic organisms, including fish (Spradley, 1991). Drift amounts reaching water bodies and ponds, including fish ponds, depend on many factors, but the cumulative range is most affected by the size of the water body. Thus, other than in direct overflight, larger catfish ponds (6-8 ha) have a drift range of 1-10% and smaller more recent designs of 4 ha, 5-20%. Even smaller ponds, used for fingerling production and baitfish production (0.8-2 ha), may receive drift amounts of up to 30% of the field rate.Herbicide drift may be expected to impact small water bodies through death or reduction in the photosynthetic rats of phytoplankton, which could reduce the supply of dissolved oxygen, inhibit removal of toxic nitrogenous wastes, and reduce production of zooplankton by reducing their food supply. These conditions could also result in death, disease, or lower growth rates of managed or cultured fishes. Triazine herbicides (atrazine and simazine), as well as amides (propanil), phenylureas (diuron), triazones, uraciles and phenolics, act through inhibition of photosystem II (PSII) of photosynthesis (Cobb, 1992). They are widely used in agriculture, since they provide a low-cost basal weed control (Jay et al., 1997). Using mesocosms and naturally-occurring plankton communities in a multi-day study provides better extrapolations to real environments than laboratory studies on a single species (Juettner et al., 1995), and possibly prevent overestimate of impacts (Macinnis-Ng and Ralph, 2002). The major drift source is aerial application, with an estimated 20 X higher drift deposition compared to application by ground spray booms (Hill et al., 1994).

2. Evaluation of 40 aerially-applied row crop herbicide effects on water bodies

Recent studies at the University of Arkansas at Pine Bluff (UAPB) have assessed the effects of herbicide drift from 40 herbicides used on adjacent soybean, rice, cotton, corn and winter wheat row crops to plankton and water quality in adjacent flood plain ponds (Perschbacher et al., 1997, 2002, 2008; Perschbacher and Ludwig, 2004). Herbicide drift may be expected to impact ponds through death or a reduction in the photosynthetic rate of phytoplankton, which could reduce the supply of dissolved oxygen, inhibit removal of toxic nitrogenous wastes, and reduce production of zooplankton by reducing the food supply (Waiser and Robarts, 1997). Aerial application has drift deposition 20 times higher compared to application by ground spray booms (Hill et al., 1994).%). The mode of action of herbicides impacting phytoplankton, is reversable inhibition of photosynthesis at photosystem II (PSII) and should not be species specific (Cobb, 1992; Solomon et al., 1996). Photosystem II inhibitors are widely used in agriculture, since they provide a low-cost basal weed control (Solomon et al., 1997; Jay et al., 1997).

2.1 Methods and materials

These studies were conducted to determine if aerially-applied herbicides would cause measurable plankton and water quality changes in outdoor pool mesocosms filled with water from a fish pond. Rates used encompassed the estimated range of drift and a field rate (full) equivalent to direct application. The studies were conducted at the UAPB Aquaculture Research Station at the approximate time of the year when the respective herbicides are applied. The experimental plankton mesocosms used were above ground, circular 500-L fiberglass tanks arranged in four rows on a cement pad. When filled, water depth of tanks was 0.7 m (slightly less than the average depth of most fish ponds) and there was no mud substrate. Water surface area of each tank was 0.78 m^2 and diameter was 1.0 m, similar to those used in a prior study of atrazine effects on plankton and water quality (Juettner et al., 1995). Tanks were filled immediately prior to herbicide application with water pumped from an adjacent 0.1-ha pond.

Herbicides were applied over the tank surfaces at one of three levels: field rates (equal to overspray) and high and low drift rates of 1/10 and 1/100th of this level, respectively (Perschbacher et al., 1997). A control, without herbicide addition, was the fourth treatment. Each herbicide was tested at the recommended application rate (Baldwin et al., 2000). Commercial formulations were used without addition of adjuvants or wetting agents. Approximately 30 ml of distilled water was used to dissolve the herbicide. Each treatment was replicated three times in randomly- assigned tanks. Tanks were flushed and air-dried between trials.

Each herbicide was added to the tanks at approximately 0900. A set of measurements was taken immediately prior to application and again 24, 48 and 72 hours after application. If effects were noted, sampling was continued approximately weekly until morning oxygen (DO) levels of drift treatments did not significantly different from the control (ie. recovery). Dissolved oxygen is the water quality parameter most sensitive to herbicide effects (Juettner et al., 1995) and most critical to fish culture. Water temperature, dissolved oxygen and pH were measured with a multiprobe meter (OI Analytical, College Station, TX). Total ammonia nitrogen (TAN) and nitrite-nitrogen were measured by Nessler and diazotization methods (Hach Co., Loveland, CO), respectively. Unionized ammonia (UIA) levels were calculated from measured temperature, TAN and pH. Chlorophyll *a,* corrected for pheophytin *a,* and a 2-h light and dark bottle estimation of phytoplankton net primary productivity (NPP) by the oxygen method followed APHA (2005), except for use of ethanol as the solvent for chlorophyll (Nusch, 1980). Major zooplankton group concentrations were also determined in each replicate in the following manner. Three, 1-l samples were obtained with a tube sampler that encompassed the entire water column. The samples were concentrated by being strained through a 70-um Wisconsin plankton net and then preserved in 70% isopropyl alcohol. Samples were identified and quantified by using a Sedgwick-Rafter cell and a microscope (Ludwig, 1993). Statistical analysis was by SAS statistical software package. ANOVA (after pretesting for normality) and LSD were used to test for significant differences ($P \leq 0.05$) among treatments for each day during each trial.

2.2 Results and discussion

Atrazine lowered NPP on d 2; and effects on ecosystems from field studies have been summarized as short-lived, with quick recovery at concentrations less than 50 ug/l (Solomon et al., 1996). Solomon et al. (1996) observed stimulation of chlorophyll *a* on d 7 post-application of 50 ug/L atrazine. This was also found by us at d 7 with propanil (Perschbacher et al. 1997, 2002). Edziyie (2004) noted drift from propanil affected fry ponds with ≤10 ug/l chlorophyll *a* less than culture ponds with levels of 50-85 ug/l of chlorophyll *a*, such as were present in this study. This may explain the reduced effects of atrazine, but is in need of further study. Carfentrazone drift rates resulted in significantly lower rotifer and nauplii numbers compared to control levels the day after application, but not on the second day. Reductions ranged from 5-30% of control numbers and could not be explained from chlorophyll *a* data or net primary productivity. Zooplankton from diuron and atrazine were noted greatly impacted (Table 2). Propanil at 1 and 10% drift rates did not result in significant effects, although full field rates did (Perschbacher et al., 2002). Further evaluation of propanil is considered in the section 3.

These studies indicate that drift effects from 40 common aerially-applied herbicide applications on plankton and water quality were limited to atrazine, diuron and carfentrazone (Table 1). Of the 40 herbicides, diuron presents the greater risk for reduced water quality and for a longer time period, of at least 4 weeks (Table 2).

3. Evaluation of drift levels to small alluvial plain water bodies: atrazine, propanil and diuron

Small water bodies, equal to or less than 1.2 ha, in alluvial plains may be subjected to greater drift concentrations from adjacent row crops, due to reduced surface areas and volumes (Perschbacher and Ludwig 2007). These small ponds may be used for growing early and vulnerable stages of commercial aquaculture crops, and for fish consumption by farm pond owners. The three herbicides causing appreciable impacts, atrazine, propanil and diuron, were further tested at maximum drift rates expected of 30% of field rates.

Common Name	Trade Name	Date Applied	A.I (kg/ha)	Chl. α (ug/l)
Soybean				
Bentazon	Basagran	8/23	0.57	200
Imazaquin	Image	8/2	0.14	240
Fomesafen	Flexstar	8/16	0.43	250
Aciflourfen	Blazer	8/9	0.43	270
Fluzifop	Fusilade	8/16	0.10	240
Clethodim	Prism	7/26	0.07	300
Chlorimuron	Canopy	8/9	0.004	125
Glyphosphate	Roundup	8/2	0.43	500
Flumiclorac	Resource	6/8	0.045	135
Sethoxydim	Vantage	6/1	0.45	239
Carfentrazone*	Aim	3/2	0.03	400
Rice				
Clomazone	Command	5/23	0.60	280
Thiobencarb	Bolero	5/29	3.40	400
Pendamethalin	Prowl	6/5	1.10	250
Propanil	Stam	6/12	4.50	160
Quinclorac	Facet	6/20	0.60	450
Halosulfuron	Permit	6/27	0.07	475
Bensulfuron methyl	Londax	7/5	0.07	240
2.4-D-amine	2,4-D	7/5	1.70	45
Molinate	Ordram	7/25	5.60	450
Triclopyr	Grandstand	7/11	0.40	115
Fenoxyprop-ethyl	Acclaim	6/15	0.13	114
Cyhalofop	Clincher	7/5	0.30	65
Bispyribac-sodium	Regiment	7/12	0.036	114
Cotton				
Diuron (burndown)*	Direx	3/5	1.40	390
Diuron (defoliant)	Direx	9/23	0.165	850
Paraquat	Gramaxone	4/10	0.83	160
Quizalofop	Assure	6/18	0.05	300
Dimethipin	Harvade	9/16	0.15	750
Tribufos	Def	10/7	1.00	1075
Ethephon	Finish	10/14	1.76	1000
Sodium chlorate	Defol	10/21	5.30	520
Glufosinate	Liberty	3/13	0.55	344
Flumioxazin	Valor	4/6	0.03	334
Corn				
Mesotrione	Callisto	5/30	1.80	150
Metolachlor	Dual	3/8	0.10	350
Atrazine*	AAtrex	5/6	0.90	30
Rimsulfuron	TranXit	5/3	0.90	40
Nicosulfuron	Steadfast	4/29	0.90	105
Winter Wheat				
Thifensulfuron + Tribenuron	Harmony Extra	3/25	0.028	189
* significant effects noted				

Table 1. Summary of mesocosm tests of drift from aerially-applied herbicides by major crop, common name, trade name, date applied, recommended active ingredient (A.I.) field rate and approximate levels of pond plankton.

Days Post-Application	Diuron 1/100	Diuron 1/10	Atrazine 1/100	Atrazine 1/10
DO				
1	92*	92*	80	102
2	93*	81*	100	104
7	83*	71*	102	111*
Recovery (days)	21	>28	0	0
NPP				
1	49*	21*	124	105
2	37*	25*	82*	79*
7	41*	22*	84	82
Chlorophyll *a*				
1	97	95	110	102
2	99	96	89	93
7	83*	58*	96	115
pH				
1	96*	95*	100	100
2	98*	91*	100	100
7	89*	87*	100	100
TAN				
1	194*	122*	94	101
2	120	80	92	85
7	243*	356*	133	94
UIA				
1	100	50*	100	100
2	84	12*	80	87
7	35*	37*	150*	125
Nitrite-N				
1	100	100	112	93
2	120	20	141	151*
7	100	133	25	150
Rotifers				
1	67	78	200	150
2	126	226	128	57
7	115	96	22*	67
Copepod nauplii				
1	238	163	74	76
2	66	92	104	95
7	100	100	199	300
Copepod adults				
1	100	160	173	110
2	75	150	110	113
7	64	21*	120	94
Cladocerans*				
1	NA	NA	120	94
2	NA	NA	73	127
7	NA	NA	100	82
*no cladocerans observed in diuron trials				

DO = 0900 Dissolved Oxygen; Recovery = return of morning DO to control levels;
NPP = Net Primary Productivity; TAN = Total Ammonia Nitrogen; UIA = Unionized Ammonia

Table 2. Comparison of mean low (1/100 direct application rate) and high (1/10 direct application rate) drift effects of diuron and atrazine, expressed as percentage of control levels. Means significantly different ($P \leq 0.05$) from control means, indicated by *.

3.1 Methods and materials

The study was conducted at the University of Arkansas at Pine Bluff (UAPB) Aquaculture Research Station The experimental mesocosms were 500-l, above ground, circular fiberglass tanks arranged in four rows on a cement pad. When filled, water depth of the tanks was 0.7 m (slightly less than the average depth of most fish ponds) and there was no soil substrate. Surface area of each tank was 0.78 m^2 and diameter was 1.0 m, similar to those used by Juettner et al.(1995). Tanks were filled immediately prior to herbicide application with water pumped from an adjacent 0.1-ha Aquaculture Research Station experimental pond. Total dissolved solids were 290 mg/l, hardness 185 mg/l and alkalinity 197 mg/l as calcium carbonate.

Commercial formulations, without adjuvants or wetting agents, were applied over the tank surfaces at 30% of field rates (Baldwin et al., 2000) in four randomly selected pools each. Four additional pools received no herbicide and served as controls. The level used was equivalent to highest potential cumulative drift concentrations based on graphs in Hill et al. (1994) to water bodies of 1.2 ha surface area. The experimental dose was added to 30 ml of distilled water for more uniform application over the tank surface.

Immediately following filling, the first set of measurements were taken. The suite of measurements was subsequently taken 24, 48 and 72 h after application. If impacts were noted, sampling was continued approximately weekly until morning oxygen levels of drift treatments did not significantly differ from the control. Dissolved oxygen is the water quality parameter most sensitive to herbicide effects (Juettner et al., 1995) and most critical to aquatic life. Water temperature, dissolved oxygen, total dissolved solids (TDS), and pH were measured with a multiprobe meter (YSI, Yellow Springs, OH). Total ammonia nitrogen and nitrite-nitrogen were measured by Nessler and diazotization methods (Hach Co., Loveland, CO), respectively. Unionized ammonia levels were obtained from water temperature, TDS, TAN and pH. Chlorophyll *a,* corrected for pheophytin *a* and using ethanol as a solvent (Nusch, 1980), and a 2-h light and dark bottle estimation of net phytoplankton primary productivity by the oxygen method followed Standard Methods (APHA, 2005). Concentrations of the major zooplankton groups (rotifers, copepod nauplii, adult copepods and cladocerans) were also determined in each replicate in the following manner. Six, 1-L samples were obtained with a tube sampler that encompassed the entire water column. The samples were concentrated by being strained through a 70-um Wisconsin plankton net and then preserved in 70% isopropyl alcohol. Samples were identified and quantified by using a Sedgwick-Rafter cell and a microscope. Phytoplankton were enumerated and identified to genus (Prescott, 1962) in Sedgwick-Rafter cells with Whipple grid at 150X (APHA, 2005) from 20 ml unconcentrated samples obtained with a 0.9-m polyvinyl chloride (PVC) column sampler and preserved with 1 ml of formalin. Cyanobacteria were further identified to species using Cocke (1967). A randomized block design was used. Means from each sample date were tested for significant differences ($P \leq 0.05$) with controls by paired, single tail Student's t-tests.

3.2 Results

Propanil levels were 58 ug/l and atrazine levels were 19.5 ug/l. Significant changes from control treatment values were found for several parameters in all three herbicide treatments (Perschbacher and Ludwig, 2007). Following application on 20 June, net primary productivity was significantly depressed on d 1 in the propanil treatments, but increased on d 2 and 3. Morning dissolved oxygen was lower on d 1-3, but not to critical levels. Also, in the presence of propanil, pH and consequently UIA were lower from d 1-3. Atrazine reduced morning DO on d 2 and 3, but not net primary productivity. Nitrite-N, however, was significantly higher on d 1. Phytoplankton total numbers, and the cyanobacterium *Chroococcus* sp. which dominated, were reduced by propanil on d 1-3; similarly affected by atrazine on d 2 and 3. Numbers of green algae, *Scenedesmus* sp. and *Coelastrum* sp., and diatoms were however stimulated by propanil and diatoms by atrazine. Zooplankton were little affected by either herbicide.

Due to the greater impacts of diuron (at levels equivalent to 30 ug/l), response of important environmental metrics to diuron drift are presented in Tables 3-5. No significant differences in pre-application sampling were found. Following application of diuron, net primary productivity was reduced by 97%, and recovered on d 7 (Table 1). Morning oxygen concentration also declined on day 1 by 32%, and was at stressful levels from d 2-3. Recovery was attained on d 14. Chlorophyll *a* and pheophytin *a* levels were significantly higher on d 2-14. Levels of pH were reduced by diuron addition from d 1-14. With lower pH values, unionized ammonia was significantly less from d 2-14. Plankton were also significantly impacted. Cyanobacteria, with the exception of *Chroococcus* spp., were reduced from d 1 and green algae, especially *Scenedesmus* spp. were stimulated (Table 4, 5). The other major group of phytoplankton, pinnate diatoms, were unchanged with the exception of a decline on d 7. In terms of percentage composition of the phytoplankton community, in diuron-treated mesocosms cyanobacteria declined from 24 to 20%, while green algae increased from 45 to 72%. Diatoms also declined from 26 to 8% (Table 5).

Zooplankton groups with significantly reduced mean abundances included: nauplii-616/l compared to control level of 1750/l on d 7, and cladocerans-0/l treatment level compared to 33/l on d 2. Copepod numbers however increased: from 1483/l control level to treatment level of 2133/l on d 3, and from 1150/l control level to the 2133/l treatment level on d 4. Rotifers were not impacted, in contrast to the findings of Zimba et al. (2002) who found an increase in rotifers.

3.3 Discussion

Diuron is a urea herbicide, that is 4-6 times more potent in photosynthesis inhibition than simazine herbicide (Ashton and Crafts, 1981). The concentration used in this study and representing the highest drift level of diuron (Direx) was 30 ug/l. Cyanobacteria were most susceptible to diuron, found previously with diuron (Zimba et al. 2002) and propanil and atrazine (Voronova and Pushkar 1985, Leboulanger et al. 2001, Perschbacher and Ludwig 2007). An increase in chlorophyll *a* was also noted by Ricart et al. (2009) in biofilms exposed to 0.07-9.0 ug/L diuron. This was attributed to a so-called “shade-adaptation” response to reduced photosynthetic efficiency from diuron. Zimba et al. (2002) observed no decrease in phytoplankton biomass, as measured by chlorophyll *a*, during 9 weekly treatments of 10 ug/l diuron each, but found the phytoplankton composition was altered. Numbers of filamentous cyanobacteria decreased, while ultraplankton coccoid cyanobacteria, diatoms and chlorophytes increased and chlorophyll *b* indicative of chlorophytes was significantly higher on one sample date.

Although drift levels of diuron in the present study were 3 times higher than in the Perschbacher and Ludwig (2004) study, which evaluated maximum drift effects to water bodies over 7 ha, inhibition of photosynthesis was longer lasting in the 2004 study. The dominance of cyanobacteria which formed surface scums and were thus unstable in the former study may have been responsible for the greater impacts, as found for propanil (Edziyie, 2004).

The present study found that in small eutrophic ponds, typical in agricultural environments and with relatively high chlorophyll *a* levels, short-term negative impacts would be expected on morning DO from atrazine, propanil and diuron. However, they may also benefit water quality by reducing pH, a major concern in eutrophic ponds utilized for recreational fish production and commercial fish culture (Barkoh et al., 2005; Ludwig et al., 2007) and which in turn resulted in lowered unionized ammonia levels.

Parameters	Treatment			Time	(d)		
		0	1	2	3	7	14
DO (mg/l)	C	16.13	14.83*	11.23*	8.63*	6.73*	8.73
	D	16.07	11.02	3.10	2.50	4.63	7.87
NPP (mg O_2/l/h)	C	1.28	0.63*	0.51*	ND	0.13	0.35
	D	1.47	0.05	0.07	ND	0.22	0.32
Chlorophyll *a* (ug/l)	C	202.4	113.0	81.0*	70.8*	37.1*	ND
	D	209.2	131.6	126.5	108.0	118.1	ND
Pheophytin *a* (ug/l)	C	31.4*	41.7	19.4*	23.6	4.2*	ND
	D	45.9	47.9	38.7	33.7	21.2	ND
pH	C	8.57	8.73*	8.63*	8.42*	8.20*	8.47*
	D	8.60	8.60	8.07	7.73	7.75	8.17
UIA (mg/l)	C	0.01	0.02	0.02*	0.01*	0.01*	0.10*
	D	0.02	0.02	0.01	0.00	0.00	0.00

DO = 0900 Dissolved Oxygen; NPP = Net Primary Productivity; UIA = Unionized Ammonia; ND = No Data

Table 3. Mean (SE) water quality differences in diuron (D) and control (C) treatments. Column means significantly different have different letters ($P \leq 0.05$).

Species/Genera	Treatment		Time	(d)	
		0	2	7	14
Scenedesmus spp.	C	30.6	19.3	10.0	0.3*
	D	19.0	32.7	20.9	12.7
Ankistrodesmus spp.	C	1.4	2.3	1.5	0.5*
	D	2.1	2.5	1.5	2.5
Coelastrum spp.	C	1.1	0.8	0.1*	0.0*
	D	1.2	1.1	1.1	0.3
Anabaena levanderi	C	0.3	0.3	1.3*	12.3*
	D	0.2	0.1	0.0	0.0
Anabaena circinalis	C	0.1	0.2	0.5*	3.5*
	D	0.1	0.1	0.0	0.1
Oscillatoria angustissma	C	7.1	11.3*	27.3*	27.9*
	D	3.9	5.6	18.7	0.1
Chroococcus dispersus	C	3.3	2.7	6.7	0.2
	D	8.0	1.3	3.9	4.5
Pinnate diatoms	C	10.7	8.8	16.5*	1.0
	D	10.4	6.8	4.7	1.8

Table 4. Mean phytoplankton (10^3 cells/ml) in diuron (D) and control (C) treatments. Column means significantly different have * ($P \leq 0.05$).

Groups	Treatment		Time	(d)	
		0	2	7	14
Cyanobacteria	C	23.1	31.8*	55.7*	95.6*
	D	24.1	12.5	14.3	20.0
Green	C	51.6	47.4*	18.8*	2.0*
	D	45.4	71.8	68.1	72.0
Diatom	C	22.5	20.6	25.5	20.0*
	D	25.7	15.7	17.5	7.8

Table 5. Mean % composition of major phytoplankton groups by natural units, with and without diuron addition, over time. Column means significantly different are * ($P \leq 0.05$).

4. Modifiying factors due to algal state from *in situ* mesocosm testing

Aquaculture ponds often have surface floating scums predominately composed of cyanobacteria. These scum-forming algae are common in eutrophic ponds, including aquaculture ponds, especially during the growing season with warm temperatures and high nutrient loadings. Cyanobacteria in a suface scum state are unstable and prone to sudden die-offs (Boyd et al., 1975). The objective of this study was to test the effect of propanil on a pond with algal scums.

4.1 Methods and materials

The experiment was conducted at the University of Arkansas at Pine Bluff mesocosm facility. A completely randomized design was used, with three replicates for each treatment in 12 mesocosms and with water of approximately 400 ug/l chlorophyll *a* from a goldfish pond. The treatments used were: a control with no propanil, 1%, 10% and 100% of the recommended field rates (0.45 kg/ha). Variables measured included: morning dissolved oxygen, pH, nitrite-nitrogen, total ammonia nitrogen, unionized ammonia , net primary productivity, chlorophyll *a* and phytoplankton composition. Methods followed Standard Methods (APHA 2005). Samples were taken before and after treatments were added.

4.2 Results and discussion

Microsystis and *Anabaena* dominated the phytoplankton and formed the surface scum. Significantly lower DO and net primary productivity resulted after application in the 10% and full treatment. However, recovery was noted after 48 h. Also lower was pH following application. Tan and UIA were higher on d 2.

In the earlier trials (Perschbacher et al., 1997, 2002) without surface scum algae, propanil at 10% drift resulted only in elevated chlorophyll *a*, but no significant differences were noted in chlorophyll *a* and phytoplankton composition in the present study. Thus, the significant negative impacts found in the present study were not expressed in previous studies, and the difference is attributed to the algal state.

Effects of propanil drift depended on the level of chlorophyll *a* found in the systems, in the study by Edziyie (2005). The greatest impact was on water quality in ponds with chlorophyll *a* levels 50-200 ug/l and lesser impacts below 20 and above 300 ug/l. Phytoplankton at high levels have been proposed to modify pesticide effects by sorption to the algae (Day and Kaushik, 1987; Waiser and Robarts, 1997; Stampfli et al., 2011).

5. Conclusions

5.1 Large pond (7 ha and larger) simulations

Of the 40 herbicide applications tested, significant effects from drift levels of 1 and 10% (the range possible in ponds equal to and larger than 7 ha) were noted for diuron (used for burndown) and atrazine. Diuron presents the greater risk for reduced water quality and for a longer time period (in excess of 4 wks). Atrazine effects are short-lived . Carfentrazone resulted in brief zooplankton reductions.

5.2 Surface scum algal populations simulations

Algal populations forming scums appear more susceptible to these drift levels. Propanil levels which did not result in reductions in water quality in mixed water column populations, resulted in adverse reactions equal to the direct overspray. The concentration of algae at the surface and the propensity for algae in this stage to be unstable (crash) are judged responsible.

5.3 Differing chlorophyll *a* level simulations

Effects of propanil and atrazine drift, and perhaps of other herbicides, depend on the level of chlorophyll *a* found in the systems. The greatest impact of propanil was on water quality in ponds with chlorophyll *a* levels 50-200 ug/l and lesser impacts below 20 and above 300 ug/l. Absorption by algae, and other factors, may be responsible.

5.4 Small pond (1.2 ha and smaller) simulations

Simulations in small ponds, equal to or less than 1.2 ha, used drift rates up to 30%. Although atrazine and propanil did not cause concern, diuron caused DO drops that were below 3 mg/l for several days and recovery was not noted until 14 days.

5.5 Beneficial aspects of herbicide drift

Beneficial effects of atrazine, propanil and diuron included reduction or elimination of cyanobacteria, and reduced pH (Ludwig et al., 2007) and thus reduced UIA. Clorophyll *a* levels were stimulated by propanil and atrazine.

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