Aquatic Life Water Quality Criteria Derived via the UC Davis Method: III. Diuron

Tessa L. Fojut, Amanda J. Palumbo, and Ronald S. Tjeerdema

1 Introduction

Diuron is a phenylurea herbicide that has been frequently detected in surface waters (the US Environmental Protection Agency, USEPA 2003), including periods when relatively low amounts were used, because it is moderately persistent in the water column (Ensminger et al. 2008). Diuron poses a risk to aquatic life because it, and other herbicides, can cause adverse effects on algae and vascular plants, which are the foundation of the aquatic food chain. Water quality standards are used to regulate pesticides in surface waters, and these standards are typically based on water quality criteria for the protection of aquatic life. When pesticide concentrations do not exceed water quality criteria, no adverse effects on aquatic life are expected. The derivation of acute and chronic water quality criteria for diuron using a new methodology developed by the University of California, Davis (TenBrook et al. 2010), is described in this chapter. The UC Davis methodology (UCDM) was designed to be more flexible than the USEPA method (1985) for deriving water quality criteria, although many aspects of the methods are similar.

2 Data Collection and Evaluation

Diuron (*N′*-(3,4-dichlorophenyl)-*N*, *N*-dimethylurea) is a phenylurea herbicide that is moderately soluble in water. Based on its physical–chemical properties, the herbicide is not likely to partition to sediments or to volatilize (Table 1), and it is considered to be moderately persistent because it is stable to hydrolysis (Table 2).

T.L. Fojut (✉) • A.J. Palumbo • R.S. Tjeerdema
Department of Environmental Toxicology, College of Agricultural and Environmental Sciences, University of California, Davis, CA 95616-8588, USA
e-mail: tlfojut@ucdavis.edu

R.S. Tjeerdema (ed.), *Aquatic Life Water Quality Criteria for Selected Pesticides*, Reviews of Environmental Contamination and Toxicology 216,
DOI 10.1007/978-1-4614-2260-0_3,

Table 1 Physical–chemical properties of diuron

Molecular weight	233.10
Density	1.4 g/mL (IUPAC 2008)
Water solubility	38 mg/L (geomean, $n = 2$; Tomlin 2003; IUPAC 2008)
Melting point	158°C (Lide 2003)
Vapor pressure	1.15×10^{-3} mPa (IUPAC 2008)
Henry's constant (K_H)	173,205 Pa m^3 mol^{-1} (geomean, $n = 2$; Mackay et al. 2006; IUPAC 2008)
Log K_{oc} [a]	2.61 (geomean, $n = 20$; Mackay et al. 2006)
Log K_{ow} [b]	2.78 (geomean, $n = 3$; Hansch et al. 1995; Sangster Research Laboratories 2008; IUPAC 2008)

[a] Log-normalized organic carbon–water partition coefficient
[b] Log-normalized octanol–water partition coefficient

Table 2 Environmental fate of diuron

	Half-life	Water	Temp (°C)	pH	Reference
Hydrolysis	>4 months	Phosphate buffer	20	5–9	Mackay et al. (2006)
	Stable	Sterile buffer	25	5, 7, 9	USEPA (2003)
Aqueous photolysis	2.25 h	Distilled	NR	NR	Mackay et al. (2006)
	43 days	NR	NR	NR	USEPA (2003)
Biodegradation (aerobic)	~20 days	Filtered sewage water	20	NR	Mackay et al. (2006)

NR not reported

Approximately 86 original studies on the effects of diuron on aquatic life were identified and reviewed. These studies are available in the open literature or may be requested from the USEPA or the California Department of Pesticide Regulation (CDPR). Studies that fell into three categories were evaluated according to the UCDM: (1) single-species effects, (2) ecosystem-level studies, and (3) terrestrial wildlife studies.

According to the UCDM scheme, single-species effect studies were rated for relevance and reliability, in a manner which was summarized by Palumbo et al. (2012). Studies that were rated as relevant (R) or less relevant (L) were also rated for reliability, whereas those that were rated as not relevant (N) were not further rated. There were three categories of study reliability: reliable (R), less reliable (L), or not reliable (N). The reliability ratings were determined by how many test parameters (e.g., nominal concentrations, source of dilution water, etc.) were reported, and if they were acceptable according to standard methods. Studies were then assigned a two-letter code in which their degree of relevance and reliability were rated. Studies that were rated not relevant (N) or not reliable (RN or LN) were not used for criteria derivation. All data rated as acceptable (RR) or supplemental (RL, LR, LL) for criteria derivation are summarized in Tables 3–7. Acceptable data rated as relevant and reliable (RR) were used for numeric criteria derivation. Supplemental data that were rated as less relevant and/or less reliable (RL, LR, or LL) for particularly sensitive, threatened, or endangered species were compared to the criteria to ensure protection of these species. Data summary records

Table 3 Final acute toxicity data set for diuron

Species	Test type	Meas/ Nom	Chemical grade (%)	Duration (h)	Temp (°C)	End point	Age/size	LC/EC_{50} (μg/L) (95% CI)	Reference
Daphnia magna	S	Nom	80.0	48	19.9	Mortality/ immobility	<24 h	12,000 (10,000–13,000)	Baer (1991)
Daphnia pulex	SR	Meas	99.8	96	22	Mortality	5 days	17,900 (14,200–22,600)	Nebeker and Schuytema (1998)
Hyalella azteca	SR	Meas	99.8	96	22	Mortality	<11 days	19,400 (17,700–21,300)	Nebeker and Schuytema (1998)

All studies were rated RR (data rated as acceptable)
S Static, *SR* static renewal, *FT* flow through

Table 4 Final chronic plant toxicity data set for diuron

Species	Test type	Meas/ Nom	Chemical grade (%)	Duration	Temp (°C)	End point	Age/size	NOEC[a] (μg/L)	LOEC[b] (μg/L)	MATC[c] (μg/L)	EC_{50} (μg/L) (95% CI)	Reference
Lemna gibba G3	S	Meas	99.1	7 days	24.7	Growth inhibition (biomass yield), relative growth rate (biomass)	Plant with 4 fronds	2.47	8.11	**4.48**	14.4 (9.26–19.6)[d]	Ferrell (2006)
Navicula pelliculosa	S	Nom	99.1	72 h	22–24	Growth inhibition (biomass)	Cells	11	33	19.1	22 (9–56)	Dengler (2006b)
N. pelliculosa	S	Nom	99.1	72 h	22–24	Growth inhibition (growth rate)	Cells	11	33	19.1	65 (33–160)	Dengler (2006b)
N. pelliculosa						Growth inhibition				**19.1**		Geomean
Pseudokirchneriella subcapitata (formerly *Selenastrum capricornutum* Printz)	S	Meas	96.8	120 h	24	Growth inhibition	2-day-old algal cells	1.3	2.5	**1.8**	2.9 (2.5–3.5)	Blasberg et al. (1991)
Scenedesmus obliquus	S	Nom	Technical	24 h	21	Growth inhibition	Algal cells	NR	NR	NR	10	Geoffroy et al. (2002)
Synechococcus leopoliensis	S	Nom	99.1	72 h	22–25	Growth inhibition (biomass)	Algal cells	3.7	11	**6.4**	26 (4–100)	Dengler (2006a)

All studies were rated RR

S Static, *SR* static renewal, *FT* flow through, *NR* not reported, *n/a* not applicable

Species mean chronic value is in bold

[a] No-observed effect concentration

[b] Lowest-observed effect concentration

[c] Maximum acceptable toxicant concentration

[d] EC_{50} based on biomass yield end point

Table 5 Final chronic animal toxicity data set for diuron

Species	Test type	Meas/ Nom	Chemical grade (%)	Duration (days)	Temp (°C)	End point	Age/size	NOEC (µg/L)	LOEC (µg/L)	MATC (µg/L)	Reference
Chironomus tentans	SR	Meas	99.8	10	24	Mortality	2 days, first instar	1,900	3,400	2,540	Nebeker and Schuytema (1998)
Daphnia pulex	S	Meas	99.8	7	NR	Reduced number of young/mortality	5 days	4,000.0	7,700	5,550	Nebeker and Schuytema (1998)
Hyalella azteca	SR	Meas	99.8	10	22	Mortality/reduced weight	<11 days	7,900	15,700	11,140	Nebeker and Schuytema (1998)
Lumbriculus variegatus	SR	Meas	99.8	10	23	Reduced weight	Small, short adults	1,800	3,500	2,510	Nebeker and Schuytema (1998)
Physa gyrina	SR	Meas	99.8	10	24	Reduced weight	2 days, first instar	13,400	22,800	17,480	Nebeker and Schuytema (1998)
Pimephales promelas	FT	Meas	98.6	64	25	Deformity, mortality	Eggs <24 h, hatched fry	33.4	78	51	Call et al. (1983, 1987)
Pseudacris regilla	SR	Meas	99.8	14	20		Tadpole	14,500	21,100	17,490	

(continued)

Table 5 (continued)

Species	Test type	Meas/ Nom	Chemical grade (%)	Duration (days)	Temp (°C)	End point	Age/size	NOEC (µg/L)	LOEC (µg/L)	MATC (µg/L)	Reference
						Growth inhibition (length)					Schuytema and Nebeker (1998)
Rana aurora	SR	Meas	99.8	7	20	Growth inhibition (wet weight)	Tadpole	7,600	14,500	10,500	Schuytema and Nebeker (1998)
Rana catesbeiana	SR	Meas	99.8	21	24	Growth inhibition (dry weight)	Tadpole	11,690[a]	16,430[a]	12,450[a]	Schuytema and Nebeker (1998)
Xenopus laevis	SR	Meas	99.8	4 days	24	Growth inhibition (length)	Embryo	10,490[b]	20,540[b]	14,680[b]	Schuytema and Nebeker (1998)

All studies were rated RR

S static, *SR* static renewal, *FT* flow through, *NR* not reported

[a] SMCV calculated from three values

[b] SMCV calculated from two values

Table 6 Acceptable excluded data rated RR with given reason for exclusion

Species	Test type	Meas/ Nom	Chemical grade (%)	Duration	Temp (°C)	End point	Age/size	LC/EC_{50} (μg/L) (95% CI)	MATC (μg/L)	Reference	Reason for exclusion
Chironomus tentans	SR	Meas	99.8	10 days	24	Reduced weight	2 days, first instar	–	4,910	Nebeker and Schuytema (1998)	A
Daphnia magna	S	Nom	80.0	24 h	19.9	Mortality/ immobility	<24 h	68,000 (55,000–86,000)	–	Baer (1991)	D
Lemna gibba G3	S	Meas	99.1	7 days	24.7	Growth inhibition (biomass)	Plant with 4 fronds	15.7 (10.06–20.8)	4.48	Ferrell (2006)	A
L. gibba G3	S	Meas	99.1	7 days	24.7	Growth inhibition (frond count)	Plant with 4 fronds	19.1 (13.4–24.8)	14.47	Ferrell (2006)	A
L. gibba G3	S	Meas	99.1	7 days	24.7	Growth inhibition (frond count yield)	Plant with 4 fronds	17.5 (11.8–23.2)	14.47	Ferrell (2006)	A
L. gibba G3	S	Meas	99.1	7 days	24.7	Relative growth rate (frond count)	Plant with 4 fronds	–	14.5	Ferrell (2006)	A
P. promelas	SR	Meas	99.8	7 days	25	Reduced weight	2.5 days embryo	–	5,900	Nebeker and Schuytema (1998)	C
P. promelas	SR	Meas	99.8	10 days	24	Mortality	1.5 months juvenile	–	23,280	Nebeker and Schuytema (1998)	B
Pseudacris regilla	SR	Meas	99.8	10 days	20	Increased deformity	Embryo	–	20,540	Schuytema and Nebeker (1998)	A

(continued)

Table 6 (continued)

Species	Test type	Meas/ Nom	Chemical grade (%)	Duration	Temp (°C)	End point	Age/size	LC/EC$_{50}$ (µg/L) (95% CI)	MATC (µg/L)	Reference	Reason for exclusion
P. regilla	SR	Meas	99.8	14 days	20	Growth inhibition (wet weight)	Tadpole	–	24,720	Schuytema and Nebeker (1998)	A
P. regilla	SR	Meas	99.8	14 days	20	Growth inhibition (dry weight)	Tadpole	–	24,750[a]	Schuytema and Nebeker (1998)	A
Rana catesbeiana	SR	Meas	99.8	21 days	24	Growth inhibition (length)	Tadpole	–	18,950[a]	Schuytema and Nebeker (1998)	A
R. catesbeiana	SR	Meas	99.8	21 days	24	Growth inhibition (wet weight)	Tadpole	–	22,560[a]	Schuytema and Nebeker (1998)	A
Synechococcus leopoliensis	S	Nom	99.1	72 h	22–25	Growth inhibition (growth rate)	Algal cells	–	19.1	Dengler (2006a)	A
Xenopus laevis	SR	Meas	99.8	4 days	24	Deformity	Embryo	–	22,560	Schuytema and Nebeker (1998)	A

Reasons for exclusion
A. Less-sensitive end point
B. Less-sensitive life stage
C. Test type not preferred (static vs. flow through)
D. Not the most sensitive or appropriate duration
[a]SMCV calculated from two values

Table 7 Supplemental diuron data rated RL, LR, LL with given reason for rating and exclusion (listed at the end of table)

Species	Test type	Meas/ Nom	Chemical grade (%)	Duration	Temp (°C)	End point	Age/size	LC/EC_{50} (µg/L) (95% CI)	MATC (µg/L)	Reference	Rating/ reason
Achnanthes brevipes	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	24 (SE = 1.0)	–	Hollister and Walsh (1973)	LL/1, 2, 6
Americamysis bahia	FT	Meas	96.8	28 days	25.3	Number of young surviving	<24 h juvenile	–	1,400	Ward and Boeri (1992b)	RL/2
Amphora exigua	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	31 (SE = 4)	–	Hollister and Walsh (1973)	LL/1, 2, 6
Apium nodiflorum	S	Nom	>99	14 days	NR	Relative growth rate	Single stem node with leaf	2.808	NOEC = 0.05	Lambert et al. (2006)	LL/1, 5, 6
A. nodiflorum	S	Nom	>99	14 days	NR	Growth inhibition (roots)[b]	Single stem node with leaf	0.00026	NOEC < 0.0005	Lambert et al. (2006)	LL/1, 5, 6, 7
A. nodiflorum	S	Nom	>99	14 days	NR	Change in chlorophyll fluorescence ratio	Single stem node with leaf	>5.0	NOEC = 5	Lambert et al. (2006)	LL/1, 5, 6
Artemia salina	S	NR	NR	24 h	25	Mortality	Instar II–III larvae	12,010 (11,420 –12,100)	–	Koutsaftis and Aoyama (2007)	LL/2, 5
Asellus brevicaudus	S	Nom	95.0	96 h	15	Mortality	Mature	15,500 (7,200–33,400)	–	Johnson and Finley (1980)	LL/5, 6
Chara vulgaris	S	Nom	>99	14 days	NR	Relative growth rate	Terminal lengths of shoots with 3 nodes	0.35	NOEC = 0.0005	Lambert et al. (2006)	LL/1, 5, 6

(continued)

Table 7 (continued)

Species	Test type	Meas/ Nom	Chemical grade (%)	Duration	Temp (°C)	End point	Age/size	LC/EC_{50} (µg/L) (95% CI)	MATC (µg/L)	Reference	Rating/ reason
C. vulgaris	S	Nom	>99	14 days	NR	Change in chlorophyll fluorescence ratio	Terminal lengths of shoots with 3 nodes	4.033	NOEC = 0.5	Lambert et al. (2006)	LL/1, 5, 6
Chlamydomonas moewusii Gerloff	S	Nom	80.0	7 days	21	Growth inhibition	7-day-old algal cell stock	559.44	–	Cain and Cain (1983)	RL/1, 6
Chlamydomonas sp.	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	37 (SE = 3)	–	Hollister and Walsh (1973)	LL/1, 2, 6
Chlamydomonas sp.	S	Nom	99.8	20 min	21.5	Change in chlorophyll fluorescence ratio	2–4-week-old algal cells	10.8 (8.5–13.6)	0.22	Podola and Melkonian (2005)	RL/1, 5, 8
Chlorella pyrenoidosa	S	Nom	95.0	4 days	25	Growth inhibition	Algal cells	25	–	Maule and Wright (1984)	LR/1, 6
C. pyrenoidosa	S	Nom	50.0	96 h	25	Growth inhibition	Algal cells	1.3	–	Ma et al. (2001), Ma (2002)	LL/1, 3, 6
Chlorella sp.	S	Nom	Technical	10 days	20.5	Growth inhibition	Algal cells	$EC_{66} = 4$	–	Ukeles (1962)	LL/1, 2, 6
Chlorella sp.	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	19 (SE = 2)	–	Hollister and Walsh (1973)	LL/1, 2, 6

Chlorella vulgaris	S	Nom	50.0	96 h	25	Growth inhibition	Algal cells	4.3	–	Ma (2002)	LL/1, 3, 6
C. vulgaris SAG211-11b	S	Nom	99.8	20 min	21.5	Change in chlorophyll fluorescence ratio	2–4-week-old algal cells	27.4 (21.1–35.5)	0.22	Podola and Melkonian (2005)	RL/1, 8
Chlorococcum sp.	S	Nom	Technical	7 days	20	Growth inhibition	Algal cells	$EC_{62} = 10$	NOEC < 1.0	Walsh and Grow (1971)	RL/1, 2
Chlorococcum sp.	S	Nom	Technical	10 days	20	Growth inhibition	Algal cells	10	–	Walsh (1972)	RL/1, 2
Chlorococcum sp.	S	Nom	Technical	90 min	20	Reduced oxygen evolution	Algal cells	20	–	Walsh (1972)	RL/1, 2
Chlorococcum sp.	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	20 (SE = 4)	–	Hollister and Walsh (1973)	LL/1, 2, 6
Crassostrea virginica	FT	Meas	96.8	96 h	23	Shell deposition	Neonates, <24 h	4,800 (4,400–5,200)	NOEC = 2,400	Ward and Boeri (1991)	RL/2
Cryptomonas sp.	S	Nom	99.8	20 min	21.5	Change in chlorophyll fluorescence ratio	2–4-week-old algal cells	6.4 (5.3–7.8)	0.22	Podola and Melkonian (2005)	RL/1, 5, 8
Ctenopharyngodon idella	FT	NR	100.0	96 h	13	Mortality	1+ year, 15.8 g, 9.5 cm	31,000 (28,000–34,000)	–	Tooby et al. (1980)	LL/1, 5, 6
Cyclotella nana	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	39 (SE = 7)	–	Hollister and Walsh (1973)	LL/1, 2, 6
Cyprinodon variegates	FT	Meas	96.8	32 days	30	Mortality	<24 h	–	2,500	Ward and Boeri (1992a)	RL/2

(continued)

Table 7 (continued)

Species	Test type	Meas/ Nom	Chemical grade (%)	Duration	Temp (°C)	End point	Age/size	LC/EC_{50} (µg/L) (95% CI)	MATC (µg/L)	Reference	Rating/ reason
Daphnia magna	S	Nom	Technical	26 h	21.1	Mortality/ immobility	First instar	47,000 (41,600 –53,100)	–	Crosby and Tucker (1966)	LL/1, 5, 6
Daphnia pulex	S	Nom	95.0	48 h	15	Mortality/ immobility	First instar	1,400 (1,000–1,900)	–	Johnson and Finley (1980)	LL/5, 6
Dunaliella euchlora Lerche	S	Nom	Technical	10 days	20.5	Growth inhibition	Algal cells	EC_{56} = 0.4	–	Ukeles (1962)	LL/1, 2, 6
Dunaliella tertiolecta	S	Nom	99.0	96 h	20	Growth inhibition	Algal cells	5.9	–	Gatidou and Thomaidis (2007)	LL/2, 5
D. tertiolecta	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	10 (SE = 3)	–	Hollister and Walsh (1973)	LL/1, 2, 6
D. tertiolecta Butcher	S	Nom	Technical	10 days	20	Growth inhibition	Algal cells	20	–	Walsh (1972)	RL/1, 2
D. tertiolecta Butcher	S	Nom	Technical	90 min	20	Reduced oxygen evolution	Algal cells	10	–	Walsh (1972)	RL/2, 6, 8
Eudorina elegans	S	Nom	99.8	20 min	21.5	Change in chlorophyll fluorescence ratio	2–4-week-old algal cells	13.2 (10.4–16.9)	0.22	Podola and Melkonian (2005)	RL/1, 5, 8
Gammarus fasciatus	S	Nom	Technical	24 h	15.5	Mortality	Early instar	2,500 (1,000–5,500)	–	Sanders (1970)	LL/1, 5, 6
G. fasciatus	S	Nom	Technical	48 h	15.5	Mortality	Early instar	1,800 (800–5,200)	–	Sanders (1970)	LL/1, 5, 6
G. fasciatus	S	Nom	Technical	96 h	15.5	Mortality	Early instar	700 (190–8,200)	–	Sanders (1970)	LL/1, 5, 6

Gammarus lacustris	S	Nom	Technical	24 h	21.1	Mortality	2 months	700 (590–8,300)	–	Sanders (1969)	LL/1, 5, 6
G. lacustris	S	Nom	Technical	48 h	21.1	Mortality	2 months	380 (290–500)	–	Sanders (1969)	LL/1, 5, 6
G. lacustris	S	Nom	Technical	96 h	21.1	Mortality	2 months	160 (130–190)	–	Sanders (1969)	LL/1, 5, 6
Isochrysis galbana	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	10 (SE = 3)	–	Hollister and Walsh (1973)	LL/1, 2, 6
I. galbana Parke	S	Nom	Technical	90 min	20	Reduced oxygen evolution	Algal cells	10	–	Walsh (1972)	RL/1, 2, 8
I. galbana Parke	S	Nom	Technical	10 days	20	Growth inhibition	Algal cells	10	–	Walsh (1972)	RL/1, 2
Lemna gibba G3	S	Nom	98.0	7 days	25	Growth inhibition	NR	29 (27–31)	–	Okamura et al. (2003)	LR/6
Lemna minor	S	Nom	98.0	48 h	21	Reduced oxygen evolution	Plant fronds	–	LOEC = 5	Eullaffroy et al. (2007)	LL/1, 6, 7
L. minor 1769	S	Nom	98.0	7 days	25	Growth inhibition	NR	30 (28–31)	–	Okamura et al. (2003)	LR/6
L. minor	S	Nom	98.0	7 days	25	Growth inhibition	Plant fronds	25	LOEC = 5	Teisseire et al. (1999)	RL/1, 6
Lepomis macrochirus	S	Nom	Technical	96 h	12.7	Mortality	0.6–1.5 g	8,900 (8,200–9,600)	–	Macek et al. (1969)	LL/1, 5, 6
L. macrochirus	S	Nom	Technical	96 h	18.3	Mortality	0.6–1.5 g	7,600 (7,000–8,200)	–	Macek et al. (1969)	LL/1, 5, 6
L. macrochirus	S	Nom	Technical	96 h	23.8	Mortality	0.6–1.5 g	5,900 (5,300–6,500)	–	Macek et al. (1969)	LL/1, 5, 6

(continued)

Table 7 (continued)

Species	Test type	Meas/ Nom	Chemical grade (%)	Duration	Temp (°C)	End point	Age/size	LC/EC_{50} (μg/L) (95% CI)	MATC (μg/L)	Reference	Rating/ reason
Lymnaea spp.	S	Nom	NR	96 h	NR	Mortality	Adult	15,300	–	Christian and Tate (1983)	LL/1, 3, 6
Monochrysis lutheri	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	18 (SE = 3)	–	Hollister and Walsh (1973)	LL/1, 2, 6
M. lutheri Droop	S	Nom	Technical	10 days	20.5	Growth inhibition	Algal cells	EC_{100} = 0.02	–	Ukeles (1962)	LL/1, 2, 6
M. lutheri Droop	S	Nom	Technical	10 days	20.5	Mortality	Early instar	2,500 (1,000–5,500)	–	Sanders (1970)	LL/1, 5, 6
Myriophyllum spicatum	S	Nom	>99	14 days	NR	Relative growth rate	Terminal lengths of shoots with 3 nodes	5	NOEC = 0.0005	Lambert et al. (2006)	LL/1, 5, 6
M. spicatum	S	Nom	>99	14 days	NR	Change in chlorophyll fluorescence ratio	Terminal lengths of shoots with 3 nodes	>5	NOEC = 5	Lambert et al. (2006)	LL/1, 5, 6
Navicula forcipata	S	Nom	99.0	96 h	20	Growth inhibition	Algal cells	27	–	Gatidou and Thomaidis (2007)	LL/2, 5
Navicula inserta	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	93(SE = 12)	–	Hollister and Walsh (1973)	LL/1, 2, 6
Neochloris sp.	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	28 (SE = 5)	–	Hollister and Walsh (1973)	LL/1, 2, 6
Nitzschia (Ind. 684)	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	169 (SE = 17)	–	Hollister and Walsh (1973)	LL/1, 2, 6

Nitzschia closterium	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	50 (SE = 6)	–	Hollister and Walsh (1973)	LL/1, 2, 6
Oscillatoria cf. chalybea	S	Nom	80.0	96 h	25	Growth inhibition	Algal cells	28	LOEC = 280	Schrader et al. (1998)	LR/1, 6
Oncorhynchus clarki (*Salmo clarki*)	S	Nom	95.0	96 h	10.0	Mortality	3.00 g	1,400 (1,100–1,900)	–	Johnson and Finley (1980)	LL/5, 6
Oncorhynchus mykiss (*Salmo gairdneri*)	S	Nom	95.0	96 h	13	Mortality	0.8 g	4,900 (4,100–5,900)	–	Johnson and Finley (1980)	LL/5, 6
O. mykiss (*Salmo gairdneri*)	S	Nom	80.0	96 h	13	Mortality	1.2 g	16,000 (11,300–22,700)	–	Johnson and Finley (1980)	LL/5, 6
O. mykiss	S	Nom	95	7 days	10	Mortality	Juveniles, hatched <24 h ago	74,000 (29,000–3,681,000)	–	Okamura et al. (2002)	LR/1, 6
O. mykiss	S	Nom	95	14 days	10	Mortality	Juveniles, hatched <24 h ago	15,000 (11,000–29,000)	–	Okamura et al. (2002)	LR/1, 6
O. mykiss	S	Nom	95	21 days	10	Mortality	Juveniles, hatched <24 h ago	5,900 (4,700–7,700)	–	Okamura et al. (2002)	LR/1, 6
O. mykiss	S	Nom	95	28 days	10	Mortality	Juveniles, hatched <24 h ago	230 (8.9–590)	–	Okamura et al. (2002)	LR/1, 6
Phaeodactylum tricornutum	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	10 (SE = 3)	–	Hollister and Walsh (1973)	LL/1, 2, 6
P. tricornutum Bohlin	S	Nom	Technical	90 min	20	Reduced oxygen evolution	Algal cells	10	–	Walsh (1972)	RL/1, 2, 8

(continued)

Table 7 (continued)

Species	Test type	Meas/ Nom	Chemical grade (%)	Duration	Temp (°C)	End point	Age/size	LC/EC_{50} (µg/L) (95% CI)	MATC (µg/L)	Reference	Rating/ reason
P. tricornutum Bohlin	S	Nom	Technical	10 days	20	Growth inhibition	Algal cells	10	–	Walsh (1972)	RL/1, 2
P. tricornutum Bohlin	S	Nom	Technical	10 days	20.5	Growth inhibition	Algal cells	$EC_{21} = 0.4$	–	Ukeles (1962)	LL/1, 2, 6
Pimephales promelas	FT	Meas	98.6	96 h	24.3	Mortality	30 days	14,200 (13,400–15,000)	–	Call et al. (1983, 1987)	RL/1, 5
Platymonas sp.	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	7 (SE = 3)	–	Hollister and Walsh (1973)	LL/1, 2, 6
Porphyridium cruentum	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	24 (SE = 3)	–	Hollister and Walsh (1973)	LL/1, 2, 6
Protcoccus sp.	S	Nom	Technical	10 days	20.5	Growth inhibition	Algal cells	$EC_{48} = 0.02$	–	Ukeles (1962)	LL/1, 2, 6
Pseudokirchneriella subcapitata (*Selenastrum capricornutum*)	S	Nom	80.0	96 h	25	Growth inhibition	Algal cells	36.4	LOEC = 280	Schrader et al. (1998)	LR/1, 6
P. subcapitata (*S. capricornutum*)	S	Nom	98.0	3 days	25	Growth inhibition	Algal cells	6.6 (5.9–7.2)	–	Okamura et al. (2003)	LL/5, 6
P. subcapitata (*S. capricornutum*)	S	Nom	99.8	20 min	21.5	Change in chlorophyll fluorescence ratio	2–4-week-old algal cells	13.8 (9.3–20.4)	0.22	Podola and Melkonian (2005)	RL/1, 8

P. subcapitata (*S. capricornutum*)	S	Nom	98	120 h	24	Growth inhibition	Algal cells	22	NOEC = 10	Douglas and Handley (1988)	RL/6
P. subcapitata (*S. capricornutum*)	S	Nom	98	72 h	24	Growth inhibition	Algal cells	18	–	Douglas and Handley (1988)	RL 6
Pteronarcys californica	S	Nom	95.0	96 h	15	Mortality	Second year class	1,200 (900–1,700)	–	Johnson and Finley (1980)	LL/5, 6
P. californica	S	Nom	Technical	24 h	15.5	Mortality	30–35 mm	3,600 (2,800–4,700)	–	Sanders and Cope (1968)	LL/1, 5, 6
P. californica	S	Nom	Technical	48 h	15.5	Mortality	30–35 mm	2,800 (2,100–3,800)	–	Sanders and Cope (1968)	LL/1, 5, 6
P. californica	S	Nom	Technical	96 h	15.5	Mortality	30–35 mm	1,200 (870–1,700)	–	Sanders and Cope (1968)	LL 1, 5, 6
Raphidocelis subcapitata	S	Nom	50.0	96 h	25	Growth inhibition	Algal cells	0.7	–	Ma et al. (2006)	LL/3, 5, 6
Salvelinus namaycush	S	Nom	95.0	96 h	10	Mortality	1.5 g	2,700 (2,400–3,000)	–	Johnson and Finley (1980)	LL/5, 6
Scenedesmus obliquus	S	Nom	50.0	96 h	25	Growth inhibition	Algal cells	4.09	–	Ma (2002)	LL/1, 3, 6
S. obliquus	S	Nom	98.0	1 min	22	Change in chlorophyll fluorescence ratio	Algal cells	1[a]	–	Eullaffroy and Vernet (2003)	LL/1, 4, 6, 8

(continued)

Table 7 (continued)

Species	Test type	Meas/ Nom	Chemical grade (%)	Duration	Temp (°C)	End point	Age/size	LC/EC_{50} (μg/L) (95% CI)	MATC (μg/L)	Reference	Rating/ reason
Scenedesmus quadricauda	S	Nom	50.0	96 h	25	Growth inhibition	Algal cells	2.7	–	Ma (2003)	LL/1, 3, 6
Scenedesmus subspicatus	S	Nom	Technical	24 h	20	Growth inhibition	Algal cells, 3-day old	NR	NOEC = 4	Schafer et al. (1994)	LR/5, 6
S. subspicatus	S	Nom	Technical	72 h	20	Growth inhibition	Algal cells, 3-day old	36	NOEC = 10	Schafer et al. (1994)	LR/5, 6
Scherffelia dubia	S	Nom	99.8	20 min	21.5	Change in chlorophyll fluorescence ratio	2–4-week-old algal cells	3.9 (2.5–6.2)	0.22	Podola and Melkonian (2005)	RL/1, 8
Simocephalus serrulatus	S	Nom	95.0	48 h	15	Mortality	First instar	2,000 (1,400–2,800)	–	Johnson and Finley (1980)	LL/5, 6
Staurodesmus convergens	S	Nom	99.8	20 min	21.5	Change in chlorophyll fluorescence ratio	2–4-week-old algal cells	4.1 (2.5–6.9)	0.22	Podola and Melkonian (2005)	RL/1, 5, 8
Stauroneis amphoroides	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	31 (SE = 2)	–	Hollister and Walsh (1973)	LL/1, 2, 6
Synechocystis sp.	S	Nom	99.8	20 min	21.5	Change in chlorophyll fluorescence ratio	2–4-week-old algal cells	7.6 (5.5–10.5)	0.22	Podola and Melkonian (2005)	RL/1, 5, 8
Tetraselmis elegans	S	Nom	99.8	20 min	21.5	Change in chlorophyll fluorescence ratio	2–4-week-old algal cells	3.0 (2.3–3.8)	0.22	Podola and Melkonian (2005)	RL/1, 8

Thalassiosira fluviatilis	S	Nom	Technical	3 days	20	Reduced oxygen evolution	Algal cells	95 (SE = 10)	–	Hollister and Walsh (1973)	LL/1, 2, 6
Ulothrix fimbriata	S	Nom	95.0	7 days	25	Growth inhibition	Algal cells	540	–	Maule and Wright (1984)	LR/1, 6

S Static, *SR* static renewal, *FT* flow through, *NR* not reported, *95% CI* 95% confidence interval, *SE* standard error

Reasons for ratings

1. Not a standard method
2. Saltwater
3. Low chemical purity or purity not reported
4. Toxicity value not calculable
5. Control not described and/or response not reported
6. Low reliability score
7. End point not linked to growth, reproduction, or survival
8. Inappropriate test duration

[a] Value reported as toxicity threshold, which is conceptually very similar to an MATC, but calculated differently than an MATC or an EC_x

[b] Growth inhibition of roots is not a standard end point

including the rationale for the scores and ratings were created for each study, all of which are included in the Supporting Material (http://extras.springer.com/).

Because diuron is a herbicide, many of the single-species studies were plant toxicity tests. Plant data are more difficult to interpret than animal data because a variety of end points may be used, but the significance of each one is not clear. According to the UCDM, all plant studies were considered as chronic because the typical end points of growth or reproduction are inherently chronic. Only end points of growth or reproduction (measured by biomass) and tests lasting at least 24 h had the potential to be rated highly, and to be used for criteria calculation, which is in accordance with standard methods (ASTM 2007a, 2007b, USEPA 1996). The four main end points identified in plant toxicity tests are described below, including whether the end point is clearly linked to survival, growth, or reproduction.

2.1 Growth Inhibition

All of these end points are evaluated relative to a control growth measurement. Depending on the plant, the endpoint measurement may have been assessed by direct cell counts with a hemacytometer, cell counts with a spectrophotometer, cell counts with an electronic particle counter, chlorophyll concentration measured by absorbance, turbidity measured by absorbance, or number of fronds (*Lemna* spp.). In all cases, growth of exposed samples was compared statistically to controls.

2.2 Relative Growth Rate

The biomass of macrophytes was measured before and after exposure to calculate a growth rate as (final mass–initial mass)/initial mass $\times$ 100. This end point is very similar to growth inhibition, except that it is expressed as a positive effect while growth inhibition is expressed as a negative effect. In all cases, the growth rate of exposed samples was compared statistically to controls.

2.3 Change in Chlorophyll Fluorescence Ratio

Chlorophyll fluorescence was measured at a maximal fluorescence and either a variable or steady-state fluorescence and a ratio were computed. An increase in the ratio indicates a disruption of photosystem II (PSII), which may lead to a decrease in carbohydrate production and thus decreased growth. With this end point, one measures physiological stress in plants (Lambert et al. 2006). This ratio is a valid measurement that is related to algal growth according to ASTM Standard Method E1218-04 (ASTM 2004), but is described as being less definitive than measuring

chlorophyll *a* content, and is therefore not a preferred end point if one more directly related to growth is available.

2.4 Reduced Oxygen Evolution

Plants evolve oxygen during photosynthesis, and reduced photosynthesis has been shown by Walsh (1972) to correlate well with the concentrations that inhibit growth, but it is not clear that this end point is a good predictor of growth inhibition across all plant species. The value for this end point is always calculated as being relative to controls.

To ensure that the derived criteria are protective of ecosystems and used all available data, all multispecies mesocosm, microcosm, and ecosystem (field and laboratory) studies that were rated as being acceptable and reliable (R) or less reliable (L) were compared to the criteria. Studies on the effects of diuron on mallard ducks were rated for reliability using the terrestrial wildlife evaluation table. Mallard studies that were rated as being reliable (R) or less reliable (L) were used to evaluate the bioaccumulation of diuron.

3 Data Reduction

The data reduction procedure is described by Palumbo et al. (2012). Multiple toxicity values for diuron for the same species were reduced down to a species mean acute value (SMAV) or a species mean chronic value (SMCV). Acceptable (RR) data were excluded from the final data sets that were employed for criteria calculations for the following reasons: more appropriate exposure durations were available, flow-through tests are preferred over static tests, a test with a more sensitive life stage of the same species was available, and tests with more sensitive end points were available. Excluded data are given in Table 6. The final acute data set contains three animal SMAVs (Table 3), the final chronic plant data set contains three SMCVs (Table 4), and the final chronic animal data set contains ten SMCVs (Table 5).

4 Acute Criterion Calculation

Although plants are more sensitive to diuron, the acute criterion was calculated from acute animal toxicity data because plant toxicity tests are considered as being chronic. Three SMAVs from two different taxa were available: planktonic crustaceans (*Daphnia magna* and *Daphnia pulex*) and a benthic invertebrate (*Hyalella azteca*). Because there were so few data, the acute criterion was not

calculated using a species sensitivity distribution (SSD). At least five data values are required to fit an SSD to a data set, and the data must fulfill five different taxa requirements (planktonic crustacean, benthic invertebrate, fish from the family Salmonidae, warm water fish, and insect). Instead, the acute criterion was calculated using the assessment factor (AF) procedure (TenBrook et al. 2010). The AFs in the UCDM were derived by randomly sampling 12 organic pesticide data sets to give estimates of the median fifth percentile of a distribution (TenBrook et al. 2010). AFs are recognized as a conservative approach for dealing with uncertainty in assessing risks posed by chemicals and are widely used in other methods for deriving criteria.

The acute criterion was calculated by dividing the lowest SMAV (12 mg/L for *D. magna*) from the acceptable (RR) data set by an AF. The magnitude of the AF was determined by the number of taxa available in the data set. The acute data set fulfilled two of the five taxa requirements, corresponding to an AF of 36 (TenBrook et al. 2010). The acute value calculated using the AF represents an estimate of the median fifth percentile of the SSD, which is the recommended acute value. The recommended acute value is divided by a factor of 2 to calculate the acute criterion. Because the toxicity datum used to calculate the criterion was presented in only two significant figures, the criterion is rounded to two significant figures.

$$\begin{aligned} \text{Acute value} &= \frac{\text{LowestSMAV}}{\text{Assessment factor}}, \\ &= 0.33 \text{ mg/L}. \end{aligned} \tag{1}$$

$$\begin{aligned} \text{Acute criterion} &= \frac{\text{Acutevalue}}{2}, \\ &= 0.17 \text{ mg/L } (170 \ \ \mu\text{g/L}). \end{aligned} \tag{2}$$

5 Chronic Criterion Calculation

The chronic data demonstrate that plants are more sensitive to diuron than animals. Because diuron is a herbicide and the data demonstrates that plants are the most sensitive taxon, only plant data were used to derive the chronic criterion. The chronic criterion is likely to also be protective of animals because they are less sensitive to diuron. Four acceptable maximum acceptable toxicant concentrations (MATCs) and five acceptable EC_{50}s were available for vascular plants or alga. MATCs are recommended for derivation of the chronic criterion because they approximate a no-effect concentration (unlike EC_{50}s). EC_x toxicity values are not recommended for chronic criteria derivation unless there is data for the relevant species indicating what level of x corresponds to a no-effect level, which was not available for the diuron data set. Since there were too few MATCs to fit a distribution to the data, the chronic criterion was derived by setting the chronic criterion equal to the lowest

NOEC from an important alga or vascular aquatic plant species that has measured concentrations and a biologically relevant end point (TenBrook et al. 2010). In this scheme, the NOEC of 1.3 μg/L for the green algae *Pseudokirchneriella subcapitata* (formerly *Selenastrum capricornutum*) serves as the chronic criterion.

6 Water Quality Effects and Bioavailability

Temperature and pH do not appear to have a significant effect on the toxicity of diuron, as it is only a very weak base and no such effects have been documented in the literature. Because diuron has a moderate octanol–water partition coefficient ($\log K_{ow} = 2.78$), decreased bioavailability due to surface sorption is possible. Knauer et al. (2007) demonstrated that the addition of black carbon (BC) in its native form to water only slightly decreased the toxicity of diuron to the freshwater green algae *P. subcapitata* (formerly *S. capricornutum*). BC is ubiquitous in the environment because it is a product of incomplete combustion and can act as a supersorbent for some organic contaminants as a result of its large surface area, but it represents only a small fraction of total organic carbon, which is usually responsible for the majority of sorption to solids. Studies in which the sorption of diuron to dissolved organic carbon and clays were investigated are not currently available in the literature, but sorption to these materials is also likely to inhibit bioavailability in a similar manner as sorption to BC. Because there is little information regarding which phases of diuron (freely dissolved, sorbed to dissolved organic carbon, or sorbed to suspended solids) are bioavailable, it is recommended that criteria compliance is based on whole water concentrations.

7 Chemical Mixtures

Diuron is a PSII inhibitor, as are all phenylurea herbicides. Other widely used herbicides, such as the triazines, are also PSII inhibitors, but have different binding sites than the phenylurea herbicides. The concentration addition model is recommended because it has been tested and shown to successfully predict the toxicity of compound mixtures that possess the same mode of action (Mount 2003). It has been confirmed in several studies that the toxicity of a mixture of PSII-inhibitor herbicides, including diuron, can be predicted by the concentration addition method (Arrhenius et al. 2004; Backhaus et al. 2004; Knauert et al. 2008). When diuron is detected with other PSII-inhibitor herbicides, the toxicity of the mixture should be predicted by the concentration addition model and used to determine criteria compliance. If numeric water quality criteria are not available for other PSII-inhibitor herbicides, the model cannot be used and diuron should be considered alone.

The toxicity of diuron in mixtures with other chemicals that work by different modes of action has been reported (e.g., Hernando et al. 2003; Walker 1965), but interaction coefficients for multiple species have not been calculated. Therefore, nonadditive mixture toxicity cannot yet be incorporated into criteria compliance. Lydy and Austin (2005) demonstrated a nonadditive form of toxicity when mixtures of diuron and organophosphate insecticides were tested; these authors found that some acted as synergists with diuron. Teisseire et al. (1999) examined the phytotoxicity of the herbicide combined with two fungicides (copper and folpet) on duckweed (*Lemna minor*) because these pesticides are often used in combination in vineyards. They found that growth inhibition from the combination of diuron and copper depended on the concentrations of both chemicals used, whereas it only depended on the herbicide's concentration when combined with folpet. Diuron is widely used as an antifouling biocide in paint for ship hulls and is often used in combination with other antifouling agents. Several articles were found in which researchers studied the toxicity of mixtures of diuron or diuron metabolites and other antifouling agents, including Irgarol (cybutryne), Sea nine 211 (4, 5-dichloro-2-*n*-octyl-3(2H)-isothiazolone), copper, chlorothalonil, copper pyrithione, zinc pyrithione, and tri-*n*-butyltin (Chesworth et al. 2004; Fernandez-Alba et al. 2002; Gatidou and Thomaidis 2007; Koutsaftis and Aoyama 2007; Manzo et al. 2008; Molander et al. 1992). Resulting toxicities were synergistic, additive, or antagonistic for different mixtures, and were sometimes dependent on concentration ratios and how many compounds were in the mixture.

8 Sensitive Species

The derived criteria were compared to the most sensitive toxicity values in both the acceptable (RR) and supplemental (RL, LR, LL) data sets to ensure that these species are adequately protected. The lowest acute value in the data sets is 160 μg/L for the amphipod *Gammarus lacustris* (Sanders 1969), which is below the derived acute criterion of 170 μg/L. This study was rated LL because the control response was not reported, many other study details were not documented, and the test concentrations were not measured. Additionally, data for another amphipod, *Gammarus fasciatus*, is the next lowest acute value in the data set (700 μg/L), indicating that *Gammarus* species are particularly sensitive to diuron. Because the *G. lacustris* toxicity value is based on nominal, instead of measured, concentrations, the acute criterion was not adjusted downward. If measured data that is highly rated becomes available for *Gammarus* species in the future, it should be examined to determine if the acute criterion is protective of this sensitive genus.

Although there are several supplemental chronic data values that are below the derived chronic criterion (1.3 μg/L), the criterion was not adjusted because the lower toxicity values were lacking at least one of the following critical parameters: (1) the use of an end point that directly related to survival, growth, or reproduction; (2) the use of an exposure duration of $\geq$24 h (ASTM 2007a, 2007b; USEPA 1996);

(3) proper design of hypothesis tests and reporting of parameters used to evaluate the reasonableness of the resulting toxicity values; (4) the use of diuron ≥80% purity; and (5) the use of freshwater species. These studies are discussed in detail below.

The lowest measured chronic value in the data sets is an EC_{50} of 0.00026 µg/L for the rooted macrophyte *Apium nodiflorum*—for a nonstandard end point of root growth (Lambert et al. 2006). This value was calculated by extrapolation, not interpolation, is lower than the NOEC reported for this test, and is below the lowest concentration tested; thus, it was not used for criterion adjustment. There are several other NOECs reported in this study for an appropriate end point (relative growth rate) that are below the proposed chronic criterion (0.0005–0.05 µg/L), but it was not possible to evaluate the reasonableness of these NOECs because the control responses were not reported, the *p*-value selected was not reported, and a minimum significant difference was not calculated.

Podola and Melkonian (2005) report NOEC and LOEC values of 0.1 and 0.5 µg/L, respectively, for nine different algae. These values are below the proposed criteria, but this study used a less preferred end point, change in chlorophyll fluorescence, and a nonstandard exposure duration of 20 min. The authors proposed the use of a biosensor to detect and identify herbicides in the environment, and do not discuss the link between the effects they quantify and survival, growth, or reproduction of the algal strains. Similarly, Eullaffroy and Vernet (2003) reported a toxicity threshold of 1 µg/L for green algae, which is slightly below the chronic criterion. The exposure duration was only 1 min, and its purpose was to rapidly detect herbicides in the environment. This study did not follow a standard method, used extremely short exposure durations, and did not include an acceptable toxicity value (e.g., NOEC, LOEC, MATC, or EC_x). Values from these studies cannot be directly related to survival, growth, or reproduction, and probably only demonstrate exposure to diuron, not adverse effects. Therefore, the chronic criterion was not adjusted downward based on these data.

Ma et al. (2001) and Ma (2002) performed studies that contained the same data for the alga *Chlorella pyrenoidosa*, an EC_{50} equal to the derived criterion. These studies used diuron with a purity of 50% and did not report a control response. In another study by Ma et al. (2006), an EC_{50} below the derived criterion (0.7 µg/L) was reported, but also used diuron of 50% purity. The low-purity compound used in these tests precludes the use of them for criterion adjustment. One study that used saltwater organisms (Ukeles 1962) reported toxicity values below the derived chronic criterion (0.02 and 0.4 µg/L), but such organisms are suspected to have different sensitivities than freshwater species; therefore, they are not used to derive or adjust freshwater criteria.

9 Ecosystem-Level Studies

The chronic criterion was compared to multispecies studies to ensure that the results from single-species studies are protective of multispecies systems. Ten mesocosm, microcosm, or ecosystem (field and laboratory) studies were identified (Table 10),

which were almost all indoor or laboratory studies mimicking small river or pond natural environments and in which microbial, phytoplanktonic, or bacterial communities were examined. An initial drop in phytoplankton biomass was noted in most of these studies, which led to a decrease in dissolved oxygen from the decay of the phytoplankton.

Planktonic communities have displayed varying degrees of response to diuron, depending on, among other things, the concentrations applied. Hartgers et al. (1998) set up microcosms containing phyto-, peri-, bacterio-, and zoo-plankton and monitored them for a 28-day exposure to a mixture of diuron, atrazine, and metolachlor, followed by a 28-day recovery period. An NOEC for the mixture based on phytoplankton was determined to be 1.5 μg/L diuron; thus, the criterion of 1.3 μg/L would likely be protective of phytoplankton based solely on diuron. Flum and Shannon (1987) reported a 96-h EC_{50} of 2,205 μg/L (1,630–3,075 μg/L 95% CI) for an artificial microecosystem containing zooplankton, amphipods, ostracods, unicellular and filamentous algae, protozoans, and microbes, which is much higher than the derived chronic criterion. The EC_{50} was based on monitoring the redox potential, pH, and dissolved oxygen as a measure of toxicity.

Planktonic and algal communities exposed to diuron have been studied in regard to the aquaculture industry because some algae give fish an "off" flavor, yet plankton is necessary for healthy ponds. Zimba et al. (2002) assessed the effect of 9 weeks of diuron application (10 μg/L) on catfish pond ecology. The only significant effect from the exposure was a change in the phytoplankton composition; its biomass was not altered. Perschbacher and Ludwig (2004) also studied plankton communities in outdoor pool mesocosms simulating aquaculture ponds. Three diuron concentrations were tested and monitored for 4-weeks post application. Diuron depressed primary production and biomass of phytoplankton for at least 4-weeks post application, which in turn caused a decrease in dissolved oxygen to levels that are potentially lethal to fish. The concentrations were not measured, and were reported as field rate (1.4 kg a.i./ha), 1/10 field rate, and 1/100 field rate of Direx without adjuvants.

Tlili et al. (2008) studied biofilm communities in a small river with chronic exposure to 1 μg/L diuron, as well as 3-h pulses of 7 or 14 μg/L diuron with and without prior exposure. The results indicate that photosynthesis was never significantly inhibited by any of the treatments, but the pulses did alter the community structure of the microalgae. The pulses affected the eukaryotic community structure in microcosms that did not have prior chronic diuron exposure, but had no significant impact on those that did have prior exposure. Dorigo et al. (2007) assessed prokaryotic and eukaryotic communities and microalgae exposed to vineyard runoff water in a small stream containing diuron concentrations of 0.09 and 0.43 μg/L. The diuron tolerance in these communities increased in the downstream direction and the pristine control site had the lowest tolerance, following the concept that contaminant exposure increases the tolerance of biofilms either by adaptation or species changes. The end points in these studies are not clearly linked to survival, growth, and reproduction and do not exhibit a clear dose–response relationship, so it is not clear if diuron exposure at these levels impacted the

diversity of species in biofilm communities. Community restructuring may have long-term effects on an ecosystem; however, the studies available only provide preliminary data on this subject. The authors of two other studies also reported adverse effects on microbes from diuron exposure (Pesce et al. 2006; Sumpono et al. 2003), but the concentrations tested were well-above the derived criteria and do not provide information regarding protection at levels near the criterion.

The literature shows that herbicides in aquatic ecosystems may have detrimental effects on the bottom trophic levels of the food chain, which may indirectly impact species up the food chain via changes in water quality or decreased food supply. However, many of these studies only tested a single concentration, and no dose–response relationship can be inferred and no-effect concentrations are not available. Considering the available studies, it appears that the derived acute and chronic criteria could be protective of these types of negative effects because most studies used much higher exposure concentrations. The only studies that reported effects at concentrations lower than the derived chronic criterion examined biofilm community restructuring, and provided preliminary data that cannot be incorporated into criteria derivation until more in-depth studies are available.

10 Threatened and Endangered Species

Threatened and endangered species (TES) may be more sensitive than standard test species, and their protection is considered by comparing toxicity values for TES to the derived criteria. Several listed animal species are represented in the data set (CDFG 2010a, 2010b; USFWS 2010). There is an RR study for *Rana aurora*, which has a related subspecies that is endangered (California red-legged frog, *R. a. draytonii*). The *R. aurora* 14-day LC_{50} is 22.2 mg/L, which is well above the acute criterion of 0.17 mg/L. The supplemental data set includes acute toxicity values for the listed salmonids *Oncorhynchus mykiss* and *Oncorhynchus clarki* (listed subspecies is *Oncorhynchus clarki henshawi*). There are two 96-h LC_{50}s for *O. mykiss* of 4.9 (4.1–5.9) mg/L and 16 (11.3–22.7) mg/L, and an LC_{50} of 1.4 (1.1–1.9) mg/L for cutthroat trout (*O. clarki*), which are both well above the acute criterion of 0.17 mg/L.

The USEPA interspecies correlation estimation (Web-ICE v. 3.1; Raimondo et al. 2010) software was used to estimate toxicity values for the listed animals represented in the acute data set by members of the same family or genus. The estimated toxicity values (Table 8) range from 0.729 to 4.491 mg/L for various salmonids.

No plant studies used in the criteria derivation were performed on state or federal endangered, threatened, or rare species. Plants are particularly sensitive to diuron because it is a herbicide, but there are no aquatic plants listed as state or federal endangered, threatened, or rare species; so they could not be considered in this section.

Table 8 Threatened, endangered, or rare species predicted values by Web-ICE (v. 3.1; Raimondo et al. 2010)

Surrogate		Predicted	
Species	LC_{50} (mg/L)	Species	LC_{50} (95% confidence interval) (mg/L)
Rainbow trout (*Oncorhynchus mykiss*)	4.9	*Oncorhynchus aguabonita whitei*	4.491 (3.613–5.581)
		Oncorhynchus gilae apache	4.491 (3.613–5.581)
		Oncorhynchus gilae	4.491 (3.613–5.581)
		Oncorhynchus nerka	5.983 (3.225–11.097)
		Oncorhynchus tshawytscha	8.086 (6.104–4.016)
		Oncorhynchus kisutch	4.758 (3.545–6.387)
		Oncorhynchus clarki henshawi	
Cutthroat trout (*O. clarki*)	1.4	*Oncorhynchus clarkii henshawi*	1.206 (0.967–1.504)
			1.206 (0.967–1.504)
		Oncorhynchus clarkii seleniris	1.206 (0.967–1.504)
		Oncorhynchus clarkii stomias	0.729 (0.290–1.832)
		O. gilae apache	0.729 (0.290–1.832)
		O. gilae	1.673 (1.156–2.421)
		O. kisutch	1.206 (0.967–1.504)
		O. nerka	1.206 (0.967–1.504)
		O. tshawytscha	

11 Bioaccumulation and Partitioning to Air and Sediment

Diuron has a log K_{ow} of 2.78 (Sangster Research Laboratories 2008), and a molecular weight of 233.1, which indicates a low bioaccumulative potential. There is a USEPA pesticide tolerance established for farm-raised freshwater finfish tissue of 2.0 mg/kg (USEPA 2007), but there are no FDA food tolerances for diuron (USFDA 2000). The bioconcentration of diuron has been measured in various species (Table 9) and these bioconcentration factors (BCFs) indicate that it has a low potential for bioaccumulation in the environment. Because diuron has a low potential to bioaccumulate and low toxicity to mallard ducks (lowest dietary $LC_{50} = 1{,}730$ mg/kg feed; USEPA 2003), the protection of terrestrial wildlife from bioaccumulation was not assessed further. Because diuron has a low vapor pressure and a moderate log K_{ow}, it is also not likely to partition to the air or sediment, and currently there were no state or federal air quality or sediment quality standards identified for diuron (CARB 2008; CDWR 1995; NOAA 1999).

Table 9 Bioconcentration factors (BCFs) for diuron

Species	BCF	Exposure	Reference
Gambusia affinis	290	S	Isensee (1976)
Physa sp.	40	S	Isensee (1976)
Daphnia magna	260	S	Isensee (1976)
Oedogonium cardiacum	90	S	Isensee (1976)
Pimephales promelas	2.00	FT	Call et al. (1983, 1987)

FT flow through, *S* static
Values are on a wet weight basis and are not lipid normalized

Table 10 Acceptable multispecies field, semifield, laboratory, microcosm, mesocosm studies

Reference	Habitat	Rating
Devilla et al. (2005)	Laboratory model ecosystem	L
Dorigo et al. (2007)	Lotic outdoor stream	L
Flum and Shannon (1987)	Laboratory microcosm	L
Hartgers et al. (1998)	Laboratory microcosm	R
Molander and Blanck (1992)	Laboratory microcosm	L
Perschbacher and Ludwig (2004)	Outdoor pond	L
Pesce et al. (2006)	Laboratory microcosm	L
Sumpono et al. (2003)	Indoor pond	R
Tlili et al. (2008)	Laboratory microcosm	R
Zimba et al. (2002)	Outdoor pond	L

R reliable, *L* less reliable

12 Assumptions, Limitations, and Uncertainties

Environmental managers have the discretion to choose how to use water quality criteria, as such, they should be aware of the assumptions, limitations, and uncertainties involved in the calculations, and the accuracy and confidence in criteria. The UCDM (TenBrook et al. 2010) identifies these points for the various recommended procedures, and this section summarizes any specific data limitations that affected the procedure used to determine the final diuron criteria.

One major limitation was the lack of highly rated acute toxicity data for diuron, which prevented the use of an SSD for acute criterion derivation. Only two of the five taxa required for use of an SSD were available; the three missing taxa were a warm water fish, a fish from the family Salmonidae, and an insect. Because of this lack of data, an AF was used to calculate the acute criterion. Uncertainty cannot be quantified using the AF procedure, as it is based on only one toxicity value. There were no highly rated amphipod data available, which is an important data gap, as this taxon appears to be the most sensitive animal taxa.

The most important limitation is the lack of acceptable plant data because plants are much more sensitive to diuron than animals. Plant and algal data can be difficult to interpret and do not use consistent end points. The chronic data set contained five EC_{50}s and four MATCs, which are the preferred toxicity values for chronic tests.

The methodology requires that MATCs are used to derive chronic criteria by the SSD procedure, unless studies are available with EC_x values that show what level of x is appropriate to represent a no-effect level. Thus, the chronic criterion was calculated as the lowest NOEC in the data set. In this approach, the chronic criterion was derived with the absolute minimum amount of data, and uncertainty cannot be quantified because it is based on only one toxicity value.

Other limitations include the lack of information about diuron and mixture toxicity and ecosystem-level effects. There is evidence that diuron exhibits synergism with some other chemicals, including organophosphate pesticides, but there is a lack of multispecies interaction coefficients available to incorporate the presence of chemical mixtures into criteria compliance. Biofilms displayed sublethal effects to low-level diuron exposures, but these effects need to be further investigated to determine if the exposures are linked to survival, growth, or reproduction of organisms in biofilms. Another issue to consider is the averaging periods of the acute and chronic criteria. The chronic 4-day averaging period should be protective based on available data. However, the acute criterion is very high when compared to plant data, and it may allow for a pulse that could kill off a large amount of algae, resulting in increased biological demand and potential fish kills due to low dissolved oxygen, as discussed in Sect. 9. Clear data on the timing and concentrations that could cause this effect are not currently available, but should be considered when more data is available.

13 Comparison to Existing Criteria

The European Union has derived an environmental quality standard for diuron of 20 μg/L as a maximum allowable concentration and 2 μg/L as the annual average (Killeen 1997), which are analogous to the acute and chronic criterion, respectively. The maximum allowable concentration is lower than the UCDM acute criterion of 170 μg/L, and the annual average is very similar to the UCDM chronic criterion of 1.3 μg/L. These criteria were derived using safety factors, which are analogous to assessment factors. A safety factor of 10 was applied to the lowest credible lethal concentration, which was an LC_{50} of 160 μg/L for *G. fasciatus*, to calculate the maximum allowable concentration. A safety factor of 100 was applied to this datum to calculate the annual average. The authors noted that while algae demonstrated higher sensitivity to diuron, the effects on algae were algistatic, not algicidal, and that based on the algal data the environmental quality standards derived from the animal data are sufficiently protective of these species.

The Netherlands has derived a maximum permissible concentration (MPC) for diuron of 0.43 μg/L (Crommentuijn et al. 2000), which is analogous to a UCDM chronic criterion. This MPC was derived using a statistical extrapolation on the combined freshwater and marine data set, which included data for algae, crustaceans, insects, plants, and fish (Crommentuijn et al. 1997). The lowest reported NOEC was 0.056 μg/L for *Scenedesmus subspicatus*, which is more sensitive than any data in the acceptable UCDM data set.

14 Comparison to the USEPA 1985 Method

Water quality criteria for diuron were also calculated by using the USEPA (1985) method, which requires a total of eight taxa to use an SSD—three additional taxa beyond the five required by the UCDM. Only two of the eight total acute taxa requirements were fulfilled, a planktonic crustacean (*D. magna* or *D. pulex*) and a benthic invertebrate (*H. azteca*). Because of this lack of data, no diuron acute criterion could be calculated according to the USEPA (1985) methodology.

According to the USEPA (1985) methodology, the chronic criterion is equal to the lowest of the Final Chronic Value, the Final Plant Value, and the Final Residue Value. To calculate the Final Chronic Value, animal data is used and the same taxa requirements must be met as in the calculation of the acute criterion. Seven of the eight taxa requirements are available in the RR chronic animal data set (Table 5). The missing taxon is a fish from the family Salmonidae; the seven available taxa are as follows: (1) planktonic crustacean (*D. pulex*), (2) benthic invertebrate (*H. azteca*), (3) insect (*Chironomus tentans*), (4) warm water fish (*Pimephales promelas*), (5) a third family in the phylum Chordata (*Pseudacris regilla*, *R. aurora*, *Rana catesbeiana*, or *Xenopus laevis*), (6) a family in a phylum other than Arthropoda or Chordata (*Physa* sp.), and (7) a family in any order of insect or any phylum not already represented (*Lumbriculus variegatus*).

The California Department of Fish and Game has derived criteria using the USEPA (1985) SSD method with fewer than the eight required families, using professional judgment to determine that species in the missing categories were relatively insensitive and their addition would not lower the criteria (Menconi and Beckman 1996; Siepmann and Jones 1998). It is not clear that a fish from the family Salmonidae would be relatively insensitive to diuron because the lowest animal chronic toxicity value is for a fish (*P. promelas*). As an example, the data in Table 5 were used to calculate genus mean chronic values from the given SMCVs, and the log-triangular distribution was employed to yield a fifth percentile estimate.

$$\begin{aligned}\text{Final Chronic Value} &= \text{Fifth percentile estimate},\\ &= 23\ \mu\text{g/L}.\end{aligned}$$

The Final Plant Value is calculated as the lowest result from a 96-h test conducted with an important plant species, in which the concentrations of test material were measured and the end point was biologically important. None of the plant toxicity values in the RR data set (Table 4) are for a 96-h test, and two use measured concentrations. The closest test that fits this description is the 120-h NOEC of 1.3 µg/L reported for *P. subcapitata* (Blasberg et al. 1991). This test has an exposure duration that is 24 h longer than the specified duration.

$$\begin{aligned}\text{Final Plant Value} &= \text{Lowest result from a plant test},\\ &= 1.3\ \mu\text{g/L}.\end{aligned}$$

The Final Residue Value is calculated by dividing the maximum permissible tissue concentration by an appropriate BCF or bioaccumulation factor (BAF). A maximum allowable tissue concentration is either (a) an FDA action level for fish oil or for the edible portion of fish or shellfish or (b) a maximum acceptable dietary intake based on observations on survival, growth, or reproduction in a chronic wildlife feeding study or long-term wildlife field study. While no FDA action level exists for fish tissue, there is an EPA pesticide tolerance for farm-raised freshwater finfish tissue of 2.0 mg/kg (USEPA 2007). There is no relevant study that meets the requirement of part (b) above. A BCF of 2.0 for *P. promelas* (Table 9) was used to calculate the Final Residue Value.

$$\begin{aligned}\text{Final Residue Value} &= \frac{\text{Maximum permissible tissue concentration}}{\text{BCF}},\\ &= 1\ \text{mg/L}\ (1,000\ \mu\text{g/L}).\end{aligned}$$

The Final Plant Value is lower than both the Final Chronic Value and the Final Residue Value; therefore, the chronic criterion by the USEPA (1985) methodology would be 1.3 μg/L, and the example USEPA chronic criterion is equivalent to the UCDM chronic criterion.

15 Summary and Final Criteria Statement

Acute and chronic water quality criteria for the protection of aquatic life were derived for diuron using the UCDM. The acute criterion is based only on acute animal data and was derived using an assessment factor because there were insufficient data to use a SSD while the chronic criterion was derived using only plant data, which are more sensitive to diuron. The lowest NOEC of a highly rated plant study was used as the criterion because there were insufficient data for use of an SSD for criterion calculation. Plant toxicity data are essential when considering diuron usage and regulations because plants and algae are the most sensitive taxa; however, plant data are difficult to interpret. The criteria should be updated whenever relevant and reliable new data become available.

Aquatic life in the Sacramento River and San Joaquin River basins should not be affected unacceptably if the 4-day average concentration of diuron does not exceed 1.3 μg/L (1,300 ng/L) more than once every 3 years on the average and if the 1-h average concentration does not exceed 170 μg/L more than once every 3 years on the average. Mixtures of diuron and other PSII-inhibitor herbicides should be considered to be additive (see Sect. 7).

Acknowledgments We thank the following reviewers: D. McClure (CRWQCB-CVR), J. Grover (CRWQCB-CVR), S. McMillan (CDFG), J. P. Knezovich (Lawrence Livermore National Laboratory), and X. Deng (CDPR). This project was funded through a contract with the Central Valley Regional Water Quality Control Board of California. Funding for this project was provided by the

California Regional Water Quality Control Board, Central Valley Region (CRWQCB-CVR). The contents of this document do not necessarily reflect the views and policies of the CRWQCB-CVR, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

References

Arrhenius A, Gronvall F, Scholze M, Backhaus T, Blanck H (2004) Predictability of the mixture toxicity of 12 similarly acting congeneric inhibitors of photosystem II in marine periphyton and epipsammon communities. Aquat Toxicol 68:351–367.

ASTM (2004) Standard Guide for Conducting Static Toxicity Tests with Microalgae. In: ASTM E1218 (Environmental Toxicology Standards). American Society for Testing and Materials.

ASTM (2007a) Standard Guide for Conducting Static Toxicity Tests with Microalgae. Designation: E 1218–07. American Society for Testing and Materials.

ASTM (2007b) Standard Practice for Algal Growth Potential with *Pseudokirchneriella subcapitata*. Designation: D 3978–07. American Society for Testing and Materials.

Backhaus T, Faust M, Scholze M, Gramatica P, Vighi M, Grimme LH (2004) Joint algal toxicity of phenylurea herbicides is equally predictable by concentration addition and independent action. Environ Toxicol Chem 23:258–264.

Baer KN (1991) Static, Acute 48-hour EC50 of DPX-14740-165 (Karmex DF) to *Daphnia magna*. Haskell laboratory report No. 508-91. Unpublished study prepared by E. I. du Pont de Nemours and Company, Newark, DE, submitted to the U. S. Environmental Protection Agency. EPA MRID 42046003.

Blasberg J, Hicks SL, Bucksaath J (1991) Acute Toxicity of Diuron to *Selenastrum capricornutum* Printz. DuPont study number AMR-2046-91. ABC laboratory project ID, final report #39335. Unpublished study prepared by ABC Laboratories, Inc. Columbia, MO, submitted to the U. S. Environmental Protection Agency. EPA MRID 42218401.

Cain JR, Cain RK (1983) The effects of selected herbicides on zygospore germination and growth of *Chlamydomonas moewusii* (Chlorophyceae, Volvocales). J Phycology 19:301–305.

Call DJ, Brooke LT, Kent RJ (1983) Toxicity, Bioconcentration and Metabolism of 5 Herbicides in Freshwater Fish. Environmental Research Laboratory-Duluth. U. S. Environmental Protection Agency report, EPA MRID 00141636/TRID 452601029.

Call DJ, Brooke LT, Kent RJ, Knuth ML, Poirier SH, Huot JM, Lima AR (1987) Bromacil and Diuron Herbicides - Toxicity, Uptake, and Elimination in Freshwater Fish. Arch Environ Contam Toxicol 16:607–613.

CARB (2008) California Ambient Air Quality Standards (CAAQS). California Air Resources Board, Sacramento, CA.

CDFG (2010a) State and federally listed endangered and threatened animals of California. California Natural Diversity Database. California Department of Fish and Game, Sacramento, CA. Available from: http://www.dfg.ca.gov/biogeodata/cnddb/pdfs/TEAnimals.pdf.

CDFG (2010b) State and federally listed endangered, threatened, and rare plants of California. California Natural Diversity Database. California Department of Fish and Game, Sacramento, CA. Available from: http://www.dfg.ca.gov/biogeodata/cnddb/pdfs/TEPlants.pdf.

CDWR (1995) Compilation of Sediment and Soil Standards, Criteria, and Guidelines. California Department of Water Resources, State of California, The Resources Agency, Sacramento, CA.

Chesworth JC, Donkin ME, Brown MT (2004) The interactive effects of the antifouling herbicides Irgarol 1051 and Diuron on the seagrass *Zostera marina* (L.). Aquat Toxicol 66:293–305.

Christian FA, Tate TM (1983) Toxicity of Fluometuron and Diuron on the Intermediate Snail Host (*Lymnaea Spp*) of *Fasciola hepatica*. Bull Environ Contam Toxicol 30:628–631.

Crommentuijn T, Kalf DF, Polder MD, Posthumus R, van de Plassche EJ (1997) Maximum permissible concentrations and negligible concentrations for pesticides. RIVM report number 601501002. National Institute of Public Health and the Environment, Bilthoven, The Netherlands.

Crommentuijn T, Sijm D, de Bruijn J, van Leeuwen K, van de Plassche E (2000) Maximum permissible and negligible concentrations for some organic substances and pesticides. J Environ Manag 58:297–312.

Crosby DG, Tucker RK (1966) Toxicity of Aquatic Herbicides to *Daphnia magna*. Science 154:289–291.

Dengler D (2006a) Testing of toxic effects of diuron technical on the blue-green alga *Synechococcus leopoliensis*. Final report. Unpublished study prepared by GAB Biotechnologie GmbH & GAB Analytik GmbH, Germany, sponsored by DuPont de Nemours France S.A. Crop Protection, submitted to the U.S. Environmental Protection Agency. EPA MRID 47936501.

Dengler D (2006b) Testing of toxic effects of diuron technical on the diatom *Navicula pelliculosa*. Final report. Unpublished study prepared by GAB Biotechnologie GmbH & GAB Analytik GmbH, sponsored by DuPont de Nemours France S.A. Crop Protection, submitted to the U.S. Environmental Protection Agency. EPA MRID 47936502.

Devilla RA, Brown MT, Donkin M, Tarran GA, Aiken J, Readman JW (2005) Impact of antifouling booster biocides on single microalgal species and on a natural marine phytoplankton community. Marine Ecology-Progress Series 286:1–12.

Dorigo U, Leboulanger C, Berard A, Bouchez A, Humbert JF, Montuelle B (2007) Lotic biofilm community structure and pesticide tolerance along a contamination gradient in a vineyard area. Aquat Microbial Ecol 50:91–102.

Douglas MT, Handley JW (1988) The algistatic activity of diuron technical. Unpublished study prepared by Huntingdon Research Centre Ltd., Huntingdon, England, sponsored by Du Pont de Nemours (France) S. A., submitted to the U.S. Environmental Protection Agency. EPA MRID 47936503.

Ensminger MP, Starner K, Kelley K (2008) Simazine, diuron, and atrazine detections in California surface waters. California Department of Pesticide Regulation, Sacramento, CA.

Eullaffroy P, Frankart C, Biagianti S (2007) Toxic effect assessment of pollutant mixtures in *Lemna minor* by using polyphasic fluorescence kinetics. Toxicol Environ Chem 89:683–393.

Eullaffroy P, Vernet G (2003) The F684/F735 chlorophyll fluorescence ratio: a potential tool for rapid detection and determination of herbicide phytotoxicity in algae. Water Res 37:1983–1990.

Fernandez-Alba AR, Hernando MD, Piedra L, Chisti Y (2002) Toxicity evaluation of single and mixed antifouling biocides measured with acute toxicity bioassays. Anal Chim Acta 456:303–312.

Ferrell BD (2006) Diuron (DPX-14740) technical: Static, 7-day growth inhibition toxicity test with *Lemna gibba* G3. Laboratory project ID: DuPont 20775. Unpublished study prepared by E.I. du Pont de Nemours and Company Haskell Laboratory for Health and Environmental Sciences, Newark, DE, submitted to the U.S. Environmental Protection Agency. EPA MRID 46996701.

Flum TF, Shannon LJ (1987) The Effects of 3 Related Amides on Microecosystem Stability. Ecotoxicol Environ Saf 13:239–252.

Gatidou G, Thomaidis NS (2007) Evaluation of single and joint toxic effects of two antifouling biocides, their main metabolites and copper using phytoplankton bioassays. Aquat Toxicol 85:184–191.

Geoffroy L, Teisseire H, Couderchet M, Vernet G (2002) Effect of oxyfluorfen and diuron alone and in mixture on antioxidative enzymes of *Scenedesmus obliquus*. Pestic Biochem Physiol 72:178–185.

Hansch C, Leo A, Hoekman D (1995) Exploring QSAR. Hydrophobic, Electronic, and Steric Constants. American Chemical Society, Washington, DC.

Hartgers EM, Aalderink GH, Van Den Brink PJ, Gylstra R, Wiegman JWF, Brock TCM (1998) Ecotoxicological threshold levels of a mixture of herbicides (Atrazine, diuron and metolachlor) in freshwater microcosms. Aquat Ecol 32:135–152.
Hernando MD, Ejerhoon M, Fernandez-Alba AR, Chisti Y (2003) Combined toxicity effects of MTBE and pesticides measured with *Vibrio fischeri* and *Daphnia magna* bioassays. Water Res 37:4091–4098.
Hollister T, Walsh GE (1973) Differential responses of marine phytoplankton to herbicides - oxygen evolution. Bull Environ Contam Toxicol 9:291–295.
Isensee AR (1976) Variability of Aquatic Model Ecosystem-Derived Data. Int J Environ Studies 10:35–41.
IUPAC (2008) IUPAC Agrochemical Information - Diuron. URL ≤http://sitem.herts.ac.uk/aeru/iupac/260.htm≥.
Johnson WW, Finley MT (1980) Handbook of Acute Toxicity of Chemicals to Fish and Aquatic Invertebrates. Resource Publication 137. United States Fish and Wildlife Service, Washington, DC. EPA MRID 40094602.
Killeen S (1997) Development and use of environmental quality standards (EQS) for priority pesticides. Pestic Sci 49:191–195.
Knauer K, Sobek A, Bucheli TD (2007) Reduced toxicity of diuron to the freshwater green alga *Pseudokirchneriella subcapitata* in the presence of black carbon. Aquat Toxicol 83:143–148.
Knauert S, Escher B, Singer H, Hollender J, Knauer K (2008) Mixture toxicity of three photosystem II inhibitors (atrazine, isoproturon, and diuron) toward photosynthesis of freshwater phytoplankton studied in outdoor mesocosms. Environ Sci Technol 42:6424–6430.
Koutsaftis A, Aoyama I (2007) Toxicity of four antifouling biocides and their mixtures on the brine shrimp *Artemia salina*. Sci Total Environ 387:166–174.
Lambert SJ, Thomas KV, Davy AJ (2006) Assessment of the risk posed by the antifouling booster biocides Irgarol 1051 and diuron to freshwater macrophytes. Chemosphere 63:734–743.
Lide DR (ed) (2003) Handbook of Chemistry and Physics. 84th Edition. CRC Press, Boca Raton, FL.
Lydy MJ, Austin KR (2005) Toxicity assessment of pesticide mixtures typical of the Sacramento-San Joaquin Delta using *Chironomus tentans*. Arch Environ Contam Toxicol 48:49–55.
Ma J, Liang W, Xu L, Wang S, Wei Y, Lu J (2001) Acute toxicity of 33 herbicides to the green alga *Chlorella pyrenoidosa*. Bull Environ Contam Toxicol 66:536–541.
Ma J (2002) Differential sensitivity to 30 herbicides among populations of two green algae *Scenedesmus obliquus* and *Chlorella pyrenoidosa*. Bull Environ Contam Toxicol 68:275–281.
Ma J, Lin F, Wang S, Xu L (2003) Toxicity of 21 herbicides to the green alga *Scenedesmus quadricauda*. Bull Environ Contam Toxicol 71:594–601.
Ma JY, Wang SF, Wang PW, Ma LJ, Chen XL, Xu RF (2006) Toxicity assessment of 40 herbicides to the green alga *Raphidocelis subcapitata*. Ecotoxicol Environ Saf 63:456–462.
Ma JY, Xu LG, Wang SF, Zheng RQ, Jin SH, Huang SQ, Huang YJ (2002) Toxicity of 40 herbicides to the green alga *Chlorella vulgaris*. Ecotoxicol Environ Saf 51:128–132.
Macek KJ, Hutchins C, Cope OB (1969) Effects of Temperature on Susceptibility of Bluegills and Rainbow Trout to Selected Pesticides. Bull Environ Contam Toxicol 4:174–183.
Mackay D, Shiu WY, Ma KC, Lee SC (2006) Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals. 2nd edn. CRC Press, Boca Raton, FL.
Manzo S, Buono S, Cremisini C (2008) Predictability of copper, irgarol, and diuron combined effects on sea urchin *Paracentrotus lividus*. Arch Environ Contam Toxicol 54:57–68.
Maule A, Wright SJL (1984) Herbicide effects on the population-growth of some green-algae and cyanobacteria. J Appl Bacteriol 57:369–379.
Menconi M, Beckman J (1996) Hazard assessment of the insecticide methomyl to aquatic organisms in the San Joaquin river system. Administrative report 96–6. California Department of Fish and Game, Rancho Cordova, CA.
Molander S, Blanck H (1992) Detection of Pollution-Induced Community Tolerance (Pict) in Marine Periphyton Communities Established under Diuron Exposure. Aquat Toxicol 22:129–144.

Molander S, Dahl B, Blanck H, Jonsson J, Sjostrom M (1992) Combined Effects of Tri-Normal-Butyl Tin (Tbt) and Diuron on Marine Periphyton Communities Detected as Pollution-Induced Community Tolerance. Arch Environ Contam Toxicol 22:419–427.

Mount DR, Ankley GT, Brix KV, Clements WH, Dixon DG, Fairbrother A, Hickey CW, Lanno RP, Lee CM, Munns WR, Ringer RK, Staveley JP, Wood CM, Erickson RJ, Hodson PV (2003) Effects assessment: Introduction. In: *Reevaluation of the State of the Science for Water-Quality Criteria Development*, Reiley MC, Stubblefield WA, Adams WJ, Di Toro DM, Hodson PV, Erickson RJ, Keating FJ Jr, eds., SETAC Press, Pensacola, FL.

Nebeker AV, Schuytema GS (1998) Chronic effects of the herbicide diuron on freshwater cladocerans, amphipods, midges, minnows, worms, and snails. Arch Environ Contam Toxicol 35:441–446.

NOAA (1999) Sediment Quality Guidelines Developed for the National Status and Trends Program. National Oceanographic and Atmospheric Agency Office of Response and Restoration, Department of Commerce.

Okamura H, Nishida T, Ono Y, Shim WJ (2003) Phytotoxic effects of antifouling compounds on nontarget plant species. Bull Environ Contam Toxicol 71:881–886.

Okamura H, Watanabe T, Aoyama I, Hasobe M (2002) Toxicity evaluation of new antifouling compounds using suspension-cultured fish cells. Chemosphere 46:945–951.

Palumbo AJ, TenBrook PL, Fojut TL, Faria IR, Tjeerdema RS (2012) Aquatic life water quality criteria derived via the UC Davis method: I. Organophosphate insecticides. Rev Environ Contam Toxicol 216:1–49.

Perschbacher PW, Ludwig GM (2004) Effects of diuron and other aerially applied cotton herbicides and defoliants on the plankton communities of aquaculture ponds. Aquaculture 233:197–203.

Pesce S, Fajon C, Bardot C, Bonnemoy F, Portelli C, Bohatier J (2006) Effects of the phenylurea herbicide diuron on natural riverine microbial communities in an experimental study. Aquat Toxicol 78:303–314.

Podola B, Melkonian M (2005) Selective real-time herbicide monitoring by an array chip biosensor employing diverse microalgae. J Appl Phycol 17:261–271.

Raimondo S, Vivian DN, Barron MG (2010) Web-based Interspecies Correlation Estimation (Web-ICE) for Acute Toxicity: User Manual. Version 3.1. Office of Research and Development, U.S. Environmental Protection Agency, Gulf Breeze, FL. EPA/600/R-10/004.

Sanders HO (1969) 25. Toxicity of Pesticides to the Crustacean *Gammarus lacustris*. Bureau of Sport Fisheries and Wildlife. United States Department of the Interior Fish and Wildlife Service, Washington, DC.

Sanders HO (1970) Toxicities of some herbicides to 6 species of freshwater crustaceans. J Water Pollut Cont Fed 42:1544–1550.

Sanders HO, Cope OB (1968) Relative Toxicities of Several Pesticides to Naiads of 3 Species of Stoneflies. Limnol Oceanogr 13:112–117.

Sangster Research Laboratories (2008) LOGKOW A databank of evaluated octanol-water partition coefficients (Log P). URL <http://logkow.cisti.nrc.ca/logkow/index.jsp>.

Schafer H, Hettler H, Fritsche U, Pitzen G, Roderer G, Wenzel A (1994) Biotests using unicellular algae and ciliates for predicting long-term effects of toxicants. Ecotoxicol Environ Saf 27:64–81.

Schrader KK, de Regt MQ, Tidwell PD, Tucker CS, Duke SO (1998) Compounds with selective toxicity towards the off-flavor metabolite-producing cyanobacterium *Oscillatoria cf. chalybea*. Aquaculture 163:85–99.

Schuytema GS, Nebeker AV (1998) Comparative toxicity of diuron on survival and growth of Pacific treefrog, bullfrog, red-legged frog, and African clawed frog embryos and tadpoles. Arch Environ Contam Toxicol 34:370–376.

Siepmann S, Jones MR (1998) Hazard assessment of the insecticide carbaryl to aquatic organisms in the Sacramento-San Joaquin River system. Administrative report 98–1. California Department of Fish and Game, Office of Spill Prevention and Response, Rancho Cordova, CA.

Sumpono, Perotti P, Belan A, Forestier C, Lavedrine B, Bohatier J (2003) Effect of Diuron on aquatic bacteria in laboratory-scale wastewater treatment ponds with special reference to *Aeromonas* species studied by colony hybridization. Chemosphere 50:445–455.
Teisseire H, Couderchet M, Vernet G (1999) Phytotoxicity of diuron alone and in combination with copper or folpet on duckweed (*Lemna minor*). Environ Pollut 106:39–45.
TenBrook PL, Palumbo AJ, Fojut TL, Hann P, Karkoski J, Tjeerdema RS (2010) The University of California-Davis Methodology for deriving aquatic life pesticide water quality criteria. Rev Environ Contam Toxicol 209:1–155.
Tlili A, Dorigo U, Montuelle B, Margoum C, Carluer N, Gouy V, Bouchez A, Berard A (2008) Responses of chronically contaminated biofilms to short pulses of diuron – An experimental study simulating flooding events in a small river. Aquat Toxicol 87:252–263.
Tomlin C (2003) The Pesticide Manual, A World Compendium. 13th edition. The British Crop Protection Council, Alton, Hampshire, UK.
Tooby TE, Lucey J, Stott B (1980) The tolerance of grass carp, *Ctenopharyngodon idella* val to aquatic herbicides. J Fish Biol 16:591–597.
Ukeles R (1962) Growth of pure cultures of marine phytoplankton in presence of toxicants. Appl Microbiol 10:532–537.
USEPA (1985) Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses, PB-85-227049. United States Environmental Protection Agency, National Technical Information Service, Springfield, VA.
USEPA (1996) Algal Toxicity, Tiers I and II, Ecological Effects Test Guidelines, OPPTS 850.5400, EPA 712/C/96/164. United States Environmental Protection Agency, Washington, DC.
USEPA (2003) Reregistration Eligibility Decision (RED) for Diuron. United States Environmental Protection Agency, Office of Prevention, Pesticides, and Toxic Substances, Washington, DC.
USEPA (2007) Diuron, Pesticide Tolerance. Federal Register, Docket # EPA-HQ-OPP-2006-0559, 72, 32533–32540.
USFDA (2000) Industry Activities Staff Booklet. URL <http://www.cfsan.fda.gov/~lrd/fdaact.html>.
USFWS (2010) Species Reports. Endangered Species Program. U.S. Fish and Wildlife Service. Available from: http://www.fws.gov/endangered/; http://ecos.fws.gov/tess_public/pub/listedAnimals.jsp; http://ecos.fws.gov/tess_public/pub/listedPlants.jsp.
Walker CR (1965) Diuron, fenuron, monuron, neburon, and TCA mixtures as aquatic herbicides in fish habitats. Weeds 13:297–301.
Walsh GE (1972) Effects of Herbicides on Photosynthesis and Growth of Marine Unicellular Algae. Water Hyacinth J 10:45–48.
Walsh GE, Grow TE (1971) Depression of Carbohydrate in Marine Algae by Urea Herbicides. Weed Sci 19:568–570.
Ward T, Boeri R (1991) Acute Flow-through Mollusc Shell Deposition Test with DPX-14740-166 (Diuron). Haskell laboratory outside report No. MR-4581-911. Unpublished study prepared by EnviroSystems Division Resource Analysts, Inc., Hampton, NH, sponsored by E.I. du Pont de Nemours and Company, Newark, DE, submitted to the U. S. Environmental Protection Agency. EPA MRID 42217201.
Ward T, Boeri R (1992a) Early life stage toxicity of DPX-14740-166 (Diuron) to Sheepshead minnow, *Cyprinodon variegatus*. Haskell laboratory outside report No. 866-91. Unpublished study prepared by EnviroSystems Division Resource Analysts, Inc., Hampton, NH, sponsored by E.I. du Pont de Nemours and Company, Newark, DE, submitted to the U. S. Environmental Protection Agency. EPA MRID 42312901.
Ward T, Boeri R (1992b) Life-cycle Toxicity of DPX-14740-166 (Diuron) to the Mysid, *Mysidopsis bahia*. Haskell laboratory outside report No. 203-92. Unpublished study prepared by EnviroSystems Division Resource Analysts, Inc., Hampton, NH, sponsored by E.I. du Pont de Nemours and Company, Newark, DE, submitted to the U. S. Environmental Protection Agency. EPA MRID 42500601.
Zimba PV, Tucker CS, Mischke CC, Grimm CC (2002) Short-term effect of diuron on catfish pond ecology. North Am J Aquacult 64:16–23.