Science of the Total Environment 442 (2013) 437–444

Contents lists available at SciVerse ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Risk assessment of land-applied biosolids-borne triclocarban (TCC)

Elizabeth Hodges Snyder [a,*], George A. O'Connor [b]

[a] Soil and Water Science Department, University of Florida, 408 Newell Hall, Gainesville, FL 32611, United States
[b] Soil and Water Science Department, University of Florida, P.O. Box 110510, Gainesville, FL 32611, United States

HIGHLIGHTS

- ► A 16-pathway human and ecological risk assessment of land-applied biosolids-borne triclocarban (TCC) was performed.
- ► Screening-level hazard quotients (HQs) were <1 for 14 pathways; no HQ values were >1 in human pathways.
- ► Screening-level HQs were >1 for soil organism predators (Pathway 10) and aquatic organisms (Pathway 16).
- ► The calculated HQs for the screening-level "worst-case" and "100-year" scenarios were 11–150 for Pathways 10 and 16.
- ► Adjusted HQs remained >1 for Pathway 10, with the exception of the HQ under a one-time agronomic biosolids application.

ARTICLE INFO

Article history:
Received 11 May 2012
Received in revised form 14 September 2012
Accepted 2 October 2012
Available online 24 November 2012

Keywords:
Triclocarban
Antibacterial
Biosolids
Sludge
Risk

ABSTRACT

Triclocarban (TCC) is monitored under the USEPA High Production Volume (HPV) chemical program and is predominantly used as the active ingredient in select antibacterial bar soaps and other personal care products. The compound commonly occurs at parts-per-million concentrations in processed wastewater treatment residuals (i.e. biosolids), which are frequently land-applied as fertilizers and soil conditioners. Human and ecological risk assessment parameters measured by the authors in previous studies were integrated with existing data to perform a two-tiered human health and ecological risk assessment of land-applied biosolids-borne TCC. The 14 exposure pathways identified in the Part 503 Biosolids Rule were expanded, and conservative screening-level hazard quotients (HQ values) were first calculated to estimate risk to humans and a variety of terrestrial and aquatic organisms (Tier 1). The majority of biosolids-borne TCC exposure pathways resulted in no screening-level HQ values indicative of significant risks to exposed organisms (including humans), even under worst-case land application scenarios. The two pathways for which the conservative screening-level HQ values exceeded one (i.e. Pathway 10: biosolids➔soil➔soil organism➔predator, and Pathway 16: biosolids➔soil➔surface water➔aquatic organism) were then reexamined using modified parameters and scenarios (Tier 2). Adjusted HQ values remained greater than one for Exposure Pathway 10, with the exception of the final adjusted HQ values under a one-time 5 Mg ha^{-1} (agronomic) biosolids loading rate scenario for the American woodcock (*Scolopax minor*) and short-tailed shrew (*Blarina brevicauda*). Results were used to prioritize recommendations for future biosolids-borne TCC research, which include additional measurements of toxicological effects and TCC concentrations in environmental matrices at the field level.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

The antibacterial compound triclocarban (TCC) is classified by the USEPA High Production Volume (HPV) Challenge Program as a "High Priority" chemical (USEPA, 2009a). The risk-based classification was determined by integrating the available data to conduct a screening-level exposure and risk characterization, and led the USEPA to request additional assessment, risk management activities, and source/exposure data from HPV sponsor companies (USEPA, 2009a). Triclocarban was also listed as a high priority biosolids contaminant of concern in a recent Water Environment Research Foundation State-of-the-Science Review (Higgins et al., 2010) and in an assessment of international research priorities for the agricultural use of biosolids (Clarke and Smith, 2011).

The primary use of TCC is as an active ingredient in antibacterial bar soaps, and much of the chemical is expected to enter publicly-owned treatment works (POTWs) as a component of domestic wastewater. Triclocarban is effectively concentrated in the solid fraction during activated sludge treatment (USEPA, 2009b), persists through various biosolids production processes (Snyder et al., 2010a), and can be introduced to the soil environment via biosolids land-application. Triclocarban

* Corresponding author at: Department of Health Sciences, University of Alaska Anchorage, 3211 Providence Drive, DPL 405, Anchorage, AK 99508, United States. Tel.: +1 907 786 6541.
E-mail addresses: ehodges4@uaa.alaska.edu (E.H. Snyder), gao@ufl.edu (G.A. O'Connor).

0048-9697/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.scitotenv.2012.10.007

was one of the most frequently detected analytes in biosolids collected through the USEPA 2001 National Sewage Sludge Survey (McClellan and Halden, 2010).

Quantitative human health and ecological risk assessments for TCC in land-applied biosolids were previously hindered by data gaps including conclusive TCC solubility and partitioning measurements, TCC concentrations in nationally representative biosolids (prior to USEPA, 2009b), and biosolids-borne TCC environmental transport, persistence, and terrestrial organism toxicity measurements. Accordingly, we measured TCC solubility (Snyder et al., 2010a), log K_{ow} (Snyder et al., 2010a), biosolids-borne concentrations (Snyder et al., 2010a), partitioning (see Supplemental Information, S1), leachability (see Supplemental Information, S1), persistence (Snyder et al., 2010b), bioaccumulation (*Paspalum notatum* grass and *Eisenia foetida* worms) (Snyder et al., 2011), and toxicity (soil microbes and *E. foetida* worms) (Snyder et al., 2011). Primary data, with secondary data from the literature, are used herein to perform a two-tiered integrated human and ecological risk assessment of land-applied, biosolids-borne TCC. The integrated risk assessment was used to identify the most susceptible populations and pathways of exposure, and to inform additional research to guide possible future environmental regulation of TCC for the protection of human and environmental health.

1.1. Properties of TCC

Conflicting measured and estimated values for TCC water solubility and octanol–water partitioning are reported in the literature (Halden and Paull, 2005; Sapkota et al., 2007; TCC Consortium, 2002a, 2002b; Ying et al., 2007). Until recently, solubility data were limited to early measurements (0.11 mg L^{-1}; Roman et al., 1957), inadequately described methods (0.11 or 11 mg L^{-1};TCC Consortium, 2002a, 2002b), or estimated using QSAR analysis (0.65–1.55 mg L^{-1}; Halden and Paull, 2005; Sapkota et al., 2007; Ying et al., 2007). Measurement of solubility and octanol–water partitioning according to standardized guidelines (i.e. USEPA OPPTS), however, determined that TCC is sparingly soluble in water (0.045 mg L^{-1}) despite a moderate octanol–water partitioning coefficient (log $K_{ow}=3.5$) (Snyder et al., 2010a). Log K_d and log K_{oc} values for indigenous TCC as measured in multiple biosolids produced under a variety of treatment methods are 3.4 ± 0.2 and 3.9 ± 0.2, respectively (see Supplemental Information, S1). Analyses of spiked TCC distribution in biosolids yielded log K_d estimates of 3.34 ± 0.13 (Agyin-Birikorang et al., 2010) and log K_{oc} estimates of 3.88 ± 0.14 (Agyin-Birikorang et al., 2010). The log K_{oc} measured in biosolids-amended fine sand and silty clay loam soils is 3.82 ± 0.16 (Agyin-Birikorang et al., 2010), although measured log K_{oc} values as high as 4.86 have been reported for biosolids-amended soils (Cha and Cupples, 2010; Wu et al., 2009). The compound is a weak acid (estimated $pK_a=12.77$; Sapkota et al., 2007) and is non-volatile (estimated vapor pressure $=3.61\times10^{-9}$ mm Hg at 25 °C; Ying et al., 2007).

Very few studies examining the TCC mode of action have been performed, and a definitive explanation of how TCC functions as an antimicrobial compound has yet to be determined. Triclocarban is an anilide, a class of compounds shown to induce cell death by adsorbing to, and destroying, the semipermeable nature of the cytoplasmic membrane (McDonnell, 2007). Anilide interference with proteins or the membrane phospholipid bilayer could disrupt the proton motive force across the bacterial surface and/or interrupt active transport and energy metabolism (McDonnell, 2007).

1.2. Environmental concentrations

Snyder et al. (2010a) measured TCC concentrations in 23 U.S. biosolids produced through a variety of treatment processes and report a mean concentration of 20 ± 11 mg TCC kg biosolids^{-1} (range: 6–43 mg TCC kg biosolids^{-1}; 95th percentile = 39 mg TCC kg biosolids^{-1}). The largest study of biosolids-borne TCC concentrations to date was performed as a component of the Targeted National Sewage Sludge Survey (TNSSS) (USEPA, 2009b), in which biosolids and sewage sludge from wastewater treatment plants (WWTPs) in 35 states were analyzed for a host of organic and inorganic contaminants. Triclocarban was detected in each of the 84 samples tested in the TNSSS (range: 0.187–441 mg kg^{-1}), with a mean and 95th percentile concentration of 39 ± 60 mg kg^{-1} and 131 mg kg^{-1}, respectively (USEPA, 2009b). Removing a statistical outlier (i.e. 441 mg kg^{-1}), removing TCC concentrations measured in materials not labeled as final products (i.e. not biosolids), and using the average concentration from duplicate samples, the mean and 95th percentile concentrations of the remaining 69 TNSSS materials were 32 ± 32 mg kg^{-1} and 93 mg kg^{-1}, respectively.

1.3. Environmental fate

1.3.1. Environmental mobility

The low water solubility and moderate K_{ow} and K_{oc} properties of TCC contribute to the limited expected environmental mobility of biosolids-borne TCC in amended soils. Following 33 years of biosolids applications to a calcareous mine spoil at agronomic rates, 72–97% of the compound was retained in the top 30 cm (Xia et al., 2010). Less than 1% (i.e. 0.02–0.18%) of TCC amended as a constituent of multiple biosolids applied (18–52 Mg ha^{-1}) to fine sand soil columns leached over the course of eight leaching events (see Supplemental Information, S1). Tile drain effluent TCC concentrations sampled over 160 days from a silty clay loam field receiving single applications of liquid or dewatered biosolids were below the limit of quantitation (Edwards et al., 2009). The groundwater ubiquity score (GUS), which characterizes leachability based on the Gustafson model, is less than −0.5, thus classifying TCC as "non-leachable" (Cha and Cupples, 2010). Loss of biosolids-borne TCC from amended soils via runoff is also minimal. Approximately 0.001% of TCC applied to a silt loam via broadcast application of biosolids was exported in five precipitation events over 34 days (Sabourin et al., 2009).

1.3.2. Biodegradation

Triclocarban is persistent in biosolids-amended soils (persistence defined as $t_{1/2}\geq60$ d; USEPA, 2009c). Mineralization of ^{14}C-TCC equilibrated with biosolids and amended to fine sand and silty clay loam soils (100:1 soil/biosolids) at environmentally relevant concentrations (~0.65 mg total TCC kg biosolids amended soil^{-1}) under aerobic laboratory conditions was determined by quantifying evolved $^{14}CO_2$. Less than 4% of the ^{14}C-TCC mineralized over 7.5 months, and no metabolites were detected (Snyder et al., 2010b). Estimated first order TCC half-lives varied with soil texture, but the minimum value was estimated as 8 years (see Supplemental Information, S1). Approximately 20% to 50% of applied ^{14}C-TCC was converted to bound residues in the soils as evidenced by solids combustion (Snyder et al., 2010b), suggesting reduced bioavailability with time. Virtually no indigenous biosolids-borne TCC degradation was detected in an amended sandy clay loam (2:1 soil/biosolids; 2.7 mg TCC kg biosolids amended soil^{-1}) that was monitored for 3 years under outdoor conditions (Walters et al., 2010). Al-Rajab et al. (2009) demonstrated that, under laboratory and field conditions, spiked TCC delivered to soil as a constituent of dewatered biosolids dissipates significantly slower than TCC spiked directly to soil alone.

No degradation studies were sufficiently long enough to document 50% disappearance of equilibrated or indigenous biosolids-borne TCC in amended soils, and estimating a half-life ($t_{1/2}$) without reaching the first half-life is problematic. Available measured half-lives of equilibrated or indigenous biosolids-borne TCC are significantly greater than the 120 days predicted by the QSAR analysis software EPA Persistent Bioaccumulative Toxic (PBT) Profiler (USEPA, 2009c) and the "weeks to months" predicted by BIOWIN in EPISuite (USEPA, 2009d).

1.3.3. Organism uptake and bioaccumulation

Biosolids-borne TCC can bioaccumulate in both flora and fauna. Bioaccumulation factors (BAFs) for *E. foetida* earthworms incubated in a fine sand and silty clay loam amended with biosolids (~6.9 mg TCC kg amended soil^{-1}) were 18 ± 3.5 $g_{soil} g_{tissue}^{-1}$ (2.9 $g_{OC} g_{lipid}^{-1}$) and 20 ± 2.1 $g_{soil} g_{tissue}^{-1}$ (10 $g_{OC} g_{lipid}^{-1}$), respectively (Snyder et al., 2011). Bioaccumulation factors were less for *E. foetida* (0.71 ± 0.13 and 0.22 ± 0.12 $g_{OC} g_{lipid}^{-1}$) incubated in fine sands and silty clay loams, respectively, that had received three annual applications of biosolids resulting in amended soil concentrations of 0.9–480 μg TCC kg amended soil^{-1} (Higgins et al., 2011). Bioaccumulation can also occur in aquatic organisms, as evidenced by directly measured biota-sediment accumulation factors (BSAFs) of 1.6 ± 0.6 $g_{OC} g_{lipid}^{-1}$ in the oligochaete *Lumbriculus variegatus* incubated in sediment spiked with TCC to 22.4 ppm (Higgins et al., 2009). Bioaccumulation factors for TCC in snails and algae near WWTP outfall sites can reach ~1600 and ~2700, respectively (Coogan and La Point, 2008; Coogan et al., 2007), and BAF values of ~725 were measured in medaka fish (*Oryzias latipes*) larvae incubated in water containing 20 μg TCC L^{-1} under controlled conditions (Schebb et al., 2011).

Bioaccumulation factors of ~2 $g_{soil} g_{tissue}^{-1}$ were measured in the roots of soybean plants (*Glycine max* (L.) Merr.) grown in biosolids-amended soil columns, but translocation to aboveground biomass (leaves and stems) was minimal (BAF<0.5 $g_{soil} g_{tissue}^{-1}$ at 110 d) (Wu et al., 2010). Concentrations in the soybean itself resulted in BAFs of ~0.03 $g_{soil} g_{tissue}^{-1}$ (Wu et al., 2010). Average bioaccumulation of biosolids-borne TCC by Bahia grass (*P. notatum*) grown in fine sand soil columns amended with a variety of biosolids at N-based rates was ≤0.007 $g_{soil} g_{tissue}^{-1}$, three orders of magnitude below the BAF values predicted by the fugacity-based Biosolids-Amended Soil, Level IV computer model (Snyder et al., 2011). A study characterizing TCC accumulation in the roots, stems, and leaves (but excluding edible fruit) of pumpkin (*C. pepo* cultivar Howden), zucchini (*C. pepo* cultivar Gold Rush), and switch grass (*P. variegatum*) grown in biosolids-amended soil (Aryal and Reinhold, 2011) calculated root to soil BAF values and root to shoot translocation factors, but not BAF values comparing aboveground biomass TCC concentrations to soil TCC concentrations. Some minor inconsistencies in values reported in the text, figures and tables precluded manual calculations of g TCC_{soil} g TCC_{tissue}^{-1} BAF values.

1.4. Toxicity to humans and non-humans

A compilation of TCC toxicity data relevant to humans and terrestrial vertebrates is available in the European Commission Scientific Committee on Consumer Products' "Opinion on Triclocarban for Uses Other than a Preservative" (SCCP, 2004). Human, rodent, and soil organism toxicity data are summarized here and in the Supplemental Information, S2 and S3. Human toxicity data are primarily limited to dermal patch exposures with skin irritation and sensitivity endpoints. The majority of studies revealed no skin irritation or sensitivity to TCC concentrations up to 10% in the delivery medium (i.e. soap or petrolatum). The two most commonly cited outbreaks of TCC-induced methemoglobinemia were attributed to the use of a 3.25% diaper rinse, or the administration of heated soap-sud enemas to adult hospital patients (Johnson et al., 1963; heating likely resulted in a primary aromatic amine, a class of compounds known to be capable of inducing methemoglobinemia). Recent research suggests TCC might act as an endocrine disruptor (see Supplemental Information, S6), but the current data do not support the calculation of endpoints [e.g. no observable effects level (NOEL)] required for a quantitative risk assessment. There is no currently available evidence indicating TCC is a carcinogen, mutagen, or clastogen.

The majority of non-human mammalian toxicity studies were performed on Sprague–Dawley rats (*Rattus norvegicus*) and NMRI (Swiss) mice (*Mus musculus*) (see Supplemental Information, S2, S3). In two acute toxicity studies (SCCP, 2004) mice and rats were administered 5000 or 2000 mg TCC kg bw^{-1} (neat product), respectively. No mortalities occurred over 7–14 days of observation, and there were no other signs of toxicity. The LD_{50} was set to >5000 mg kg bw^{-1} for mice, and >2000 mg kg bw^{-1} for rats. Data are also available for multiple subchronic or chronic dietary feeding studies with rats. The lowest dose at which no observable effects (NOEL) on anemia and body, liver and spleen weights were detected was 25 mg TCC kg bw^{-1} d^{-1}, administered to rats in dietary feed for 2 years (SCCP, 2004).

Biosolids-borne TCC had no significant effect on soil microbial respiration or ammonification up to concentrations representing 100 years of annual applications of biosolids containing typical TCC concentrations at agronomic rates, and effects on nitrification were inconclusive (Snyder et al., 2011). No toxic effects were documented in *E. foetida* earthworms incubated in biosolids-amended soils (≤100 mg TCC kg amended soil^{-1}) (Snyder et al., 2011). Many more toxicity data are available for aquatic species than for terrestrial organisms, and have been assembled elsewhere (TCC Consortium, 2002a, 2002b; Supplemental Information, S2).

2. Methods

2.1. Identification of organisms and exposure pathways

Target organisms and exposure pathways considered herein mirrored those in the biosolids risk assessment for the USEPA Part 503 Rule (i.e. the rule by which biosolids are regulated) (USEPA, 1995). The 14 exposure pathways used in the risk assessment process for the Part 503 Biosolids Rule were included in the biosolids-borne TCC risk assessment (Table 1). The original pathway numbers are unchanged, to allow for easy cross reference to the Part 503 Biosolids Rule documents. Two new pathways (identified as Pathways 15 and 16) are included to incorporate terrestrial animal exposures to contaminated fish, and aquatic organism exposure to contaminated surface water. The exposed organism for each pathway is a highly exposed individual (HEI), and is considered to be representative of the subset of the population with the greatest, but realistic, exposures.

Adverse health impacts associated with chronic exposures to a contaminant typically occur at lower environmental concentrations than adverse health impacts associated with an acute exposure(s). Thus, biosolids-borne TCC regulations based on chronic exposure toxicity data should also be protective of human health impacts from acute biosolids-borne TCC exposures. Accordingly, we used the chronic exposure no-observable-adverse-effect-level (NOAEL) and the lowest-observable-adverse-effect-level (LOAEL) as human and animal response endpoints.

Domesticated and wild animal species data were selected to best represent the exposed animal for each relevant pathway. Beef cattle, pigs, poultry, and fish were selected as components of exposure pathways concluding with human consumption of animal meat, as the animals produce the most commonly consumed meat/fish products in the US (USEPA, 2011). Specific wild animal species were selected based on exposure behaviors relevant to the biosolids-borne TCC risk assessment, and on data availability.

2.2. Estimation of risk for each exposure pathway

Risk was assessed in a two-tiered process. A screening-level hazard quotient (HQ) was calculated in Tier 1 as a first estimate of risk for each exposure pathway. The screening-level HQ values were calculated by dividing the screening-level exposure concentrations by the reference dose (RfD) for the corresponding species. The USEPA (1993a) defines the human reference dose as an estimate of "a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects

Table 1
Human and ecological exposure pathways for land-applied biosolids.

Pathway	Description of HEI	Organism endpoint(s)
1. Biosolids➔soil➔plant➔human	Human (except for home gardener) lifetime ingestion of plants grown in biosolids-amended soil	Human (adult)
2. Biosolids➔soil➔plant➔human	Human (home gardener) lifetime ingestion of plants grown in biosolids-amended soil	Human (adult)
3. Biosolids➔soil➔human	Human ingesting biosolids	Human (adult) Human (child)
4. Biosolids➔soil➔plant➔animal➔human	Human lifetime ingestion of animal products (animals raised on forage grown on biosolids-amended soil)	Human (adult) Human (child)
5. Biosolids➔soil➔animal➔human	Human lifetime ingestion of animal products (animals ingest biosolids directly)	Human (adult) Human (child)
6. Biosolids➔soil➔plant➔animal	Animal lifetime ingestion of plants grown on biosolids-amended soil	Cow (*Bos primigenius*) Eastern cottontail rabbit (*Sylvilagus floridanus*)
7. Biosolids➔soil➔animal	Animal lifetime ingestion of biosolids	Cow (*Bos primigenius*) Short-tailed shrew (*Blarina brevicauda*) American woodcock (*Scolopax minor*)
8. Biosolids➔soil➔plant	Plant toxicity due to taking up biosolids-borne TCC when grown in biosolids-amended soils	Bahia grass (*Papsulum notatum*)
9. Biosolids➔soil➔soil organism	Soil organism ingesting biosolids/soil mixture	Worm (*Eisenia foetida*)
10. Biosolids➔soil➔soil organism➔predator	Predator of soil organisms that have been exposed to biosolids-amended soils	Short-tailed shrew (*Blarina brevicauda*) American woodcock (*Scolopax minor*)
11. Biosolids➔soil➔airborne dust➔human	Human lifetime inhalation of particles (dust)	Human (adult) Human (child)
12. Biosolids➔soil➔surface water➔human	Human lifetime drinking surface water and ingesting fish containing TCC from biosolids	Human (adult) Human (child)
13. Biosolids➔soil➔air➔human	Human lifetime inhalation of volatilized TCC from biosolids-amended soil	Human (adult) Human (child)
14. Biosolids➔soil➔groundwater➔human	Human lifetime drinking well water containing TCC from biosolids that leached from soil to ground water	Human (adult) Human (child)
15. Biosolids➔soil➔surface water➔animal	Animal lifetime drinking surface water and ingesting fish containing TCC from biosolids	Osprey (*Pandion haliaetus*)[a] River otter (*Lutra canadensis*)[a]
16. Biosolids➔soil➔surface water➔aquatic organism	Aquatic organism exposed to water containing TCC from biosolids	Water flea (*Ceriodaphnia* sp.) Fathead minnow (*Pimephales promelas*) Shrimp (*Mysidopsis bahia*)

[a] Osprey and the river otter are good indicators of bioaccumulation potential, given their piscivorous diet and high trophic level (USEPA, 1993b).

during a lifetime", and is typically expressed in units of milligrams per kilogram of bodyweight per day (mg kg $bw^{-1} d^{-1}$). Reference doses can also be calculated for non-human organisms. An HQ > 1 indicates that the environmental exposure concentration is greater than the safe daily exposure and is thus cause for concern.

3. Calculations

3.1. Screening-level exposure concentration calculations

First estimates of TCC exposures were calculated by multiplying the concentration in the relevant environmental medium by the corresponding human/animal intake rate (see Supplemental Information, S4). Whenever possible, TCC exposure concentration calculations used measured environmental data available in the literature, or were generated via laboratory measurements. Structure activity relationships (SARs) developed from studies of multiple organic compounds were used in conjunction with measured TCC solubility and K_{ow} values to estimate bioaccumulation factors when measured environmental concentrations were missing. The screening-level exposure concentrations assumed the same "worst-case" (50 Mg biosolids ha^{-1}, one-time application and incorporation to a depth of 15 cm) and "100-year" (5 Mg biosolids ha^{-1}, annual applications incorporated to a depth of 15 cm for 100 years) biosolids land-application scenarios applied in the Part 503 Biosolids Rule risk assessment (NRC, 2002). Consistent with the Part 503 risk assessment, the 95th percentile biosolids-borne TCC concentration from the TNSSS (131 mg TCC kg $biosolids^{-1}$; USEPA, 2009b) was used in the screening-level biosolids exposure calculations.

3.2. Reference dose (RfD) calculations

Reference doses (RfDs) for humans, animals, and aquatic organisms were calculated or identified from the literature. The RfD is calculated as:

$$RfD = NOAEL/(UF \times MF) \quad (1)$$

where UF is one or more uncertainty factors, and MF is a modifying factor based on professional judgment (default = 1). A chronic (2 year) dietary feeding rat study (SCCP, 2004) that resulted in a NOEL of 25 mg kg $bw^{-1} d^{-1}$ was the most scientifically sound mammal toxicity study identified. The observed effects at greater doses in the study (i.e. anemia, reduced body weight, and increased liver and spleen weights), although not labeled as such in the report, can be reasonably considered "adverse". The resulting RfD for humans (see Supplemental Information, S3) was calculated, incorporating appropriate uncertainty factors, as 0.25 mg kg $bw^{-1} d^{-1}$. The RfD for terrestrial animals (Table 2) was also calculated from the chronic rat study, incorporating appropriate uncertainty factors, and was 0.625 mg kg $bw^{-1} d^{-1}$ (Table 2 and Supplemental Information, S3).

The lowest toxicity endpoints for each category of aquatic organism (i.e. fish, crustaceans, and algae) were selected as RfDs for the surface water component of the biosolids-borne TCC risk assessment (Table 2 and Supplemental Information, S2).

Table 2
Hazard quotient equation variables (and screening-level values) for Pathways 10 and 16 in Tier 1 of the integrated human/ecological risk assessment of biosolids-borne triclocarban (TCC).

Abbreviation	Parameter definition	Value	Assumptions/explanation	Reference
BW	Body weight (live weight)	Shrew: 15 g (short-tailed) American woodcock: 180 g	Mean Mean	USEPA (1993b)
EC_d	TCC concentration in earthworm	63 mg kg^{-1} (worst-case, d.w.) 626 mg kg^{-1} (100 y, d.w.)	$BAF_{dw} * SC$	Snyder et al. (2011)
FI	Food ingestion rate	Short-tailed shrew: 2.2 g d^{-1} (d.w.) American woodcock: 19 g d^{-1} (d.w.)	$FI_{mammals} = 0.235 * BW^{0.82}$	Nagy (1987) in Suter (2007)
RfD	Reference dose: daily intake of chemical that during an entire lifetime appears to be without appreciable risk on the basis of all the known facts at the time (USEPA, 1993a)	Animals: 0.625 mg kg bw^{-1} d^{-1}	Animals: calculated using the NOEL (25 mg kg bw^{-1} d^{-1}) from a 2 year chronic toxicity rat study; adjusted using an interspecies uncertainty factor (5), a sensitivity factor (2), a lab-to-field extrapolation factor (2), and intraspecies variability (2)	Monsanto (1981) in SCCP (2004) and Suter (2007)
		Aquatic indicator organisms:		
		Lepomis macrochirus (fish, fresh water): 0.049 mg L^{-1}	Acute toxicity (96 h) NOEC	Monsanto (1976) in TCC Consortium (2002b)
		Salmos gairdneri (fish, estuary, fresh water): <0.049 mg L^{-1}	Acute toxicity (96 h) NOEC	Monsanto (1976) in TCC Consortium (2002b)
		Ceriodaphnia sp. (crustacean): 0.0019 mg L^{-1}	Acute toxicity (48 h) NOEC	Monsanto (1987) in TCC Consortium (2002b)
		Pseudokirchneriella subcapitata (algae): ≤0.01 mg L^{-1}	Toxicity to aquatic plants (72 h) NOEC	Yang et al. (2008) in Chalew and Halden (2009)
		Microcystis aeruginosa (algae, blue, cyanobacteria): 0.01 mg L^{-1}	Toxicity to aquatic plants (14 d) NOEC	Monsanto (1980) in TCC Consortium (2002b)
		Pimephales promelas (fish, fresh water): 0.005 mg L^{-1}	Chronic toxicity (35 d) NOEC	Monsanto (1992), in TCC Consortium (2002b)
		Mysidopsis bahia (crustacean): 0.00006 mg L^{-1}	Chronic toxicity (28 d)	Monsanto (1992), in TCC Consortium (2002b)
		Potamopyrgus antipodarum (freshwater mudsnail): 0.00005 mg L^{-1}	Chronic toxicity (28 d)	Giudice and Young (2010).
SWC	Surface water concentration of TCC	733 ng L^{-1}	Greatest documented TCC concentration in surface water, as reported in TCC Consortium (2002b); likely contains contamination from sewer overflows; exposures to fish and aquatic organisms taken as 100% of surface water concentration	TCC Consortium (2002b)
Variable definitions for calculation of EC_d				
BAF	Bioaccumulation factor: the quotient of the concentration of an element or compound in an organism divided by the concentration in an environmental medium, when the concentrations are near steady state, and when multiple uptake routes may contribute (Suter, 2007)	$BAF_{dw} = 21$ (worm, d.w.)	Greatest BAF values calculated in authors' study of *Eisenia foetida* earthworms	Snyder et al. (2011)
SC	TCC concentration in soil	2.1 mg kg^{-1} (worst-case, d.w.)	Assuming a one-time application of biosolids containing 131 mg TCC kg^{-1} amended at a 50 Mg ha^{-1} rate to a depth of 15 cm	USEPA (2009b)
		21 mg kg^{-1} (100 y, d.w.)	Assuming 100 annual applications of biosolids containing 131 mg TCC kg^{-1} amended at a 5 Mg ha^{-1} rate to a depth of 15 cm	

3.3. Hazard quotient (HQ) calculations

The screening-level hazard quotient (HQ) for each exposure pathway was calculated by dividing the screening-level exposure concentration by the RfD for the corresponding species in Tier 1 of the risk assessment (see Supplemental Information, S3 and S4). Screening-level HQ values <1 suggested that the corresponding HEIs would not be exposed to problematic concentrations of biosolids-borne TCC over a lifetime. Pathways with screening-level HQ values >1 were subjected to more detailed risk evaluations by revisiting environmental concentration and fate estimate parameters and scenarios in order to produce refined estimates of risk referred to as "adjusted" HQ values (Tier 2).

4. Results and discussion

The screening-level HQ values for the majority of pathways (i.e. Pathways 1–9, 11–15) under both land-application scenarios were <1 (i.e. 9.9×10^{-6}–0.90), suggesting that the corresponding HEIs would not be exposed to problematic concentrations of biosolids-borne TCC

Table 3
Screening-level and final adjusted hazard quotients (HQs) for exposure Pathways 10 and 16.

Pathway	HQ equation [a]	Screening-level "worst-case" HQ	Screening-level "100-year" HQ	Screening-level assumptions	Final adjusted "worst-case" HQ	Final adjusted agronomic HQ	Final adjusted "100-year" HQ	Adjustment assumptions
10. Biosolids➔soil➔soil organism➔predator	(EC_d∗FI/BW)/RfD∗CF	Shrew: 15 American woodcock: 11	Shrew: 150 American woodcock: 110	100% bioavailability No TCC loss with time 100% of diet consists of earthworms growing in biosolids-amended soil	Shrew: 6.1 American woodcock: 7.6	Shrew: 0.61–1.2 American woodcock: 0.76–1.5	Shrew: 9.1 American woodcock: 11	Biosolids-borne TCC concentration = 93 mg kg^{-1} TCC $t_{1/2}$ = 20 y [see Supplemental Information] 0.001% TCC loss by leaching (see Supplemental Information) Agronomic biosolids application rate: 5–10 Mg ha^{-1} (NRC, 2002) Shrew specific: 59% of diet is earthworms (USEPA, 1993b)
Screening-level HQ					Adjusted hazard indices using adjusted surface water concentration (ng L^{-1}) assumptions			
					3.4 (runoff) (Sabourin et al., 2009)	17.3 (runoff) [Giudice and Young, 2011]	13 ("worst-case" and "100-year" scenario sedimentation)	
16. Biosolids➔soil➔surface water➔aquatic organism	SWC/RfD∗CF	*Lepomis macrochirus*: 0.015 *Salmos gairdneri*: 0.015 Ceriodaphnia sp.: 0.39 *Pseudokirchneriella subcapitata*: 0.073 *Microcystis aeruginosa*: 0.073 *Pimephales promelas*: 0.15 *Mysidopsis bahia*: 12		Lifetime exposure to maximum concentration of contaminated surface water (733 ng L^{-1}; (TCC Consortium, 2002b))	*Lepomis macrochirus*: $6.9*10^{-5}$ *Salmos gairdneri*: $6.9*10^{-5}$ Ceriodaphnia sp.: 0.0018 *Pseudokirchneriella subcapitata*: 0.00034 *Microcystis aeruginosa*: 0.00034 *Pimephales promelas*: 0.00068 *Mysidopsis bahia*: 0.057	*Lepomis macrochirus*: 0.00035 *Salmos gairdneri*: 0.00035 Ceriodaphnia sp.: 0.0092 *Pseudokirchneriella subcapitata*: 0.0017 *Microcystis aeruginosa*: 0.0017 *Pimephales promelas*: 0.0035 *Mysidopsis bahia*: 0.29	*Lepomis macrochirus*: 0.00027 *Salmos gairdneri*: 0.00027 Ceriodaphnia sp.: 0.0068 *Pseudokirchneriella subcapitata*: 0.0013 *Microcystis aeruginosa*: 0.0013 *Pimephales promelas*: 0.0026 *Mysidopsis bahia*: 0.22	

[a] Where EC_d = exposure concentration; FI = food intake rate; BW = body weight; SWC = surface water concentration of TCC; CF = conversion factors; and RfD = reference dose.

over a lifetime. No human exposure pathways resulted in an HQ > 1. The two environmental pathways with screening-level HQ values > 1 (i.e. Pathways 10 and 16) (Tables 2 and 3) were subjected to more detailed risk evaluations.

4.1. Tier 1 and Tier 2 HQ values and assumptions for Pathways 10 and 16

4.1.1. Pathway 10: biosolids→soil→soil organism→predator

The HQ equation for Pathway 10 (Tables 2 and 3) is:

$$HQ = (EC_d * FI/BW)/RfD * CF \quad (2)$$

where EC_d is the exposure concentration of TCC in the consumed earthworm (mg kg^{-1} d.w.), FI is the food intake rate (g d^{-1}), BW is the body weight of the soil organism (i.e. earthworm) predator (g), RfD is the soil organism predator reference dose (mg kg bw^{-1} d^{-1}), and CF is the unit conversion factor. Screening-level HQ variables and assumptions for the "worst case" and "100-year" scenarios (Tables 2 and 3) included the expectations that 100% of the earthworm-borne TCC was bioavailable, that there was no TCC loss with time, and that 100% of the soil organism predator [i.e. *Blarina brevicauda* (short-tailed shrew) and *Scolopax minor* (American woodcock)] diet consisted of earthworms living in biosolids-amended soil. The screening-level HQ values for Pathway 10 were all > 1 (range: 11–150), with the "100-year" HQ values being exactly one order of magnitude greater than the "worst-case" HQ values (Table 3).

Screening-level HQ parameter and scenario assumptions were revisited with more realistically conservative values (Table 3; see Supplemental Information, S5). The first recalculation of the HQ values utilized the adjusted 95th percentile biosolids-borne TCC concentration from the TNSSS (93 $^{-1}$), and modestly reduced the "worst case" and "100 year" HQ values (range: 7.6–100). A second recalculation of the HQ values incorporated a conservative reduction in biosolids-borne TCC half-life [20 years; Snyder et al., 2010b and Supplemental Information, S1], loss by leaching (see Supplemental Information, S1), a decrease in the earthworm diet of the short-tailed shrew (USEPA, 1993b), and consideration of a third "agronomic" land-application scenario (i.e. a one-time application at agronomic rates of 5–10 Mg ha^{-1}) (Table 3). However, all Pathway 10 final adjusted "worst-case" and "100-year" HQ values remained > 1 (range: 6.1–11). The final adjusted agronomic (5–10 Mg ha^{-1}) HQ values were 0.61–1.2 for the shrew and 0.76–1.5 for the American woodcock, suggesting that a typical one-time biosolids application can still result in exposure concentrations above expected adverse effect levels. Similar agronomic calculations for the "100-year" application scenario result in HQ values > 1 and suggest that biosolids-borne TCC pollutant limits to guide sustainable long-term land-application should be determined.

4.1.2. Pathway 16: biosolids→soil→surface water→aquatic organism

The HQ equation for Pathway 16 (Tables 2 and 3) is:

$$HQ = SWC/RfD * CF \quad (3)$$

where SWC is the TCC surface water concentration (ng L^{-1}), RfD is the aquatic organism reference dose, and CF is the unit conversion factor. A screening-level HQ of one was exceeded for chronic toxicity to a single aquatic indicator organism, *Mysidopsis bahia* (Table 3). The screening-level HQ values, however, were calculated using the greatest measured TCC concentration in US surface waters reported in the TCC Consortium dataset (733 ng L^{-1}) (TCC Consortium, 2002b), which likely represents contamination from a raw sewage overflow or a measurement at a WWTP outfall site rather than from run-off or sedimentation from biosolids-amended fields. The surface water concentration of 733 ng L^{-1} falls within the range of undiluted TCC concentrations in WWTP effluent (240–12,000 ng L^{-1}; TCC Consortium, 2002b), as opposed to other documented surface water concentrations (0.00001–240 ng L^{-1}; TCC Consortium, 2002b), or maximum concentrations measured in biosolids-amended soil runoff [3.4 ng L^{-1} (Sabourin et al., 2009) and 17.3 ng L^{-1} (Giudice and Young, 2011)].

The biosolids-amended soil runoff concentrations likely provide better approximations of TCC surface water concentrations attributable only to land-applied biosolids, and result in adjusted HQ values well below one for all sensitive organisms (Table 3). The concentration of TCC in soil runoff (and wastewater effluent) will be diluted (USEPA, 1995; Supplemental Information, S6) following entry into surface waters, and equilibrium concentrations will likely be reduced following sorption to sediment, resulting in further reduced HQ values. Clearly, the major potential threats to the health of aquatic organisms by surface water contamination of TCC will be due primarily to wastewater treatment plant effluent, and more importantly, raw sewage overflows and leaking sewer lines (neither of which apply to sustainable and legal land application of biosolids).

4.2. Impacts of solubility and partitioning values on calculations of HQ values

Solubility and partitioning values were utilized in calculating the HQ values for Pathway 4 (biosolids→soil→plant→animal→human), Pathway 5 (biosolids→soil→animal→human), and Pathway 16 (biosolids→soil→surface water→aquatic organism). Both maximum and minimum solubility and partitioning values were used in calculating the HQ values, in recognition of the range of reported measured and estimated values. Pathways 4 and 5 utilize solubility in estimates of BAF values, and, logically, the BAF values decrease as the solubility is increased from our relatively low measurement of 0.045 mg L^{-1}. Decreases in the BAF values in turn result in decreases in the HQ values. Pathway 16 utilizes K_d in the estimation of surface water concentration. As the log K_d value is increased from our relatively low measurement of 3.4, the estimated surface water concentration decreases, and the associated HQ values also decrease. Thus, in this case, the use of alternate solubility and partitioning values from the literature does not change the findings of the risk assessment herein.

5. Conclusions

Literature-derived and recently measured data were used to characterize screening-level "worst case" and "100-year" biosolids application scenarios adapted from the Part 503 Biosolids Rule risk assessment (USEPA, 1995) for 16 human and ecological exposure pathways. No biosolids-borne TCC human exposure pathways resulted in HQ > 1, even under "worst case" and "100-year" land-application scenarios. Environmental pathways for which the screening-level HQ values exceeded one were reevaluated, or adjusted, using modified parameters and an "agronomic" application scenario. Adjusted HQ values remained greater than one for Exposure Pathway 10 (i.e. biosolids→soil→soil organism→predator), with the exception of the final adjusted HQ value under the one-time 5 Mg ha^{-1} (agronomic) biosolids loading rate scenario for the American woodcock and shrew. To our knowledge, the risk assessment herein is one of the first studies to identify an unacceptable risk associated with a pharmaceutical and personal care product (PPCP) compound in land-applied biosolids. Additional work to fill several remaining data deficiencies is needed, however, before current guidelines could be modified to protect the most sensitive species (see Supplemental Information, S6).

The most urgent biosolids-borne TCC research needs include confirmation of TCC concentrations in various environmental matrices at the field level following land-application of various biosolids materials at various application rates. Measurements needed include TCC accumulation in edible plant biomass, TCC concentrations in surface waters receiving field runoff, confirmation of TCC bioavailability to predator organisms, and better characterization of actual environmental effects in terrestrial organisms. Future studies of biosolids-borne TCC accumulation by edible

plants grown in the field are needed to address the variability in measured greenhouse-grown plant BAF values.

Future studies of biosolids-borne TCC bioaccumulation by earthworms in the field are also needed to address variable impacts of environmental processes, the effects of TCC aging, and the ability of worms to migrate to and from contaminated surface soil. The toxicity data used herein to estimate the risks of biosolids-borne TCC to humans and terrestrial vertebrates described such adverse effects as anemia, reduced body weight, and increased liver and spleen weights in rodents. Studies surveying for similar biosolids-borne TCC effects in earthworm predators would be particularly useful for determining whether adverse effects occur at the field level. Confirming earthworm-borne TCC bioavailability and assimilation efficiency could help improve the accuracy of biosolids-borne TCC risk estimates and protective limits for earthworm predators. Further study of the parameters for Pathways 7 [biosolids➔soil➔animal (shrew)] and 9 [biosolids➔soil➔soil organism (i.e. adverse impacts to worms)] also seems prudent, given screening-level HQ values approaching, though not reaching, one (i.e. 0.9 and 0.74, respectively). Five other areas of concern not addressed herein, but requiring additional study, include risks to benthic organisms (and consumers), plant toxicity, additive or synergistic effects with other biosolids-borne compounds, endocrine effects, and antimicrobial resistance development. Information currently available is insufficient to fully estimate potential associated human health or ecological risks (see Supplemental Information, S6).

Acknowledgments

The research was made possible through a grant from the USEPA Office of Wastewater Management (CP-83288701.0) and in collaboration with the Procter & Gamble Company.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2012.10.007.

References

Agyin-Birikorang SA, Miller M, O'Connor GA. Retention-release characteristics of triclocarban and triclosan in biosolids, soils, and biosolids-amended soils. Environ Toxicol Chem 2010;29(9):1925–33.

Al-Rajab AJ, Sabourin L, Scott A, Lapen DR, Topp E. Impact of biosolids on the persistence and dissipation pathways of triclosan and triclocarban in an agricultural soil. Sci Total Environ 2009;407:5978–85.

Aryal N, Reinhold DW. Phytoaccumulation of antimicrobials from biosolids: impacts on environmental fate and relevance to human exposure. Water Res 2011;45:5545–52.

Cha J, Cupples AM. Triclocarban and triclosan biodegradation at field concentrations and the resulting leaching potentials in three agricultural soils. Chemosphere 2010;81:494–9.

Chalew TEA, Halden RU. Environmental exposure of aquatic and terrestrial biota to triclosan and triclocarban. JAWRA J Am Water Res Assoc 2009;45:4-13.

Clarke BO, Smith SR. Review of emerging organic contaminants in biosolids and assessment of international research priorities for the agricultural use of biosolids. Environ Int 2011;37:226–47.

TCC Consortium. US high production volume (HPV) chemical challenge program: robust summary and test plan for triclocarban. http://www.epa.gov/chemrtk/pubs/summaries/tricloca/c14186tc.htm 2002a. (Available from).

TCC Consortium. IUCLID data set. Report No.: 201-14186B; 2002b. (Available from: http://www.epa.gov/hpv/pubs/summaries/tricloca/c14186rs.pdf).

Coogan MA, La Point TW. Snail bioaccumulation of triclocarban, triclosan, and methyltriclosan in a North Texas, USA, stream affected by wastewater treatment plant runoff. Environ Toxicol Chem 2008;27:1788–93.

Coogan MA, Edziyie RE, La Point TW, Venables BJ. Algal bioaccumulation of triclocarban, triclosan, and methyl-triclosan in a North Texas wastewater treatment plant receiving stream. Chemosphere 2007;67:1911–8.

Edwards M, Topp E, Metcalfe CD, Li H, Gottschall N, Bolton P, et al. Pharmaceutical and personal care products in tile drainage following surface spreading and injection of dewatered municipal biosolids to an agricultural field. Sci Total Environ 2009;407:4220–30.

Giudice BD, Young TM. The antimicrobial triclocarban stimulates embryo production in the freshwater mudsnail Potamopyrgus antipodarum. Environ Toxicol Chem 2010;29(4):966–70.

Giudice BD, Young TM. Mobilization of endocrine-disrupting chemicals and estrogenic activity in simulated rainfall runoff from land-applied biosolids. Environ Toxicol Chem 2011;30:2220–8.

Halden RU, Paull DH. Co-occurrence of triclocarban and triclosan in U.S. water resources. Environ Sci Technol 2005;39:1420–6.

Higgins CP, Paesani ZJ, Chalew TEA, Halden RU. Bioaccumulation of triclocarban in *Lumbriculus variegates*. Environ Toxicol Chem 2009;28(12):2580–6.

Higgins CP, Sharp JO, Sepulvado JG, Littrell BJ, O'Connor GA, Snyder E, et al. Trace organic chemicals in biosolids-amended soils: state-of-the-science review. WERF Report SRSK5T09. IWA Publishing; 2010.

Higgins CP, Paesani ZJ, Abbott Chalew TE, Halden RU, Hundal LS. Persistence of triclocarban and triclosan in soils after land application of biosolids and bioaccumulation in *Eisenia foetida*. Environ Toxicol Chem 2011;30(3):556–63.

Johnson RR, Navone R, Larson BS. An unusual epidemic of methemoglobinemia. Pediatrics 1963;31:222–5.

McClellan K, Halden RU. Pharmaceuticals and personal care products in archived U.S. biosolids from the 2001 EPA National Sewage Sludge Survey. Water Res 2010;44(2):658–68.

McDonnell GE. Antisepsis, disinfection, and sterilization. Hoboken, New Jersey: Wiley-Blackwell; 2007.

National Research Council (NRC). Biosolids applied to land: advancing standards and practices. Washington, DC: United States Environmental Protection Agency, Committee on Toxicants and Pathogens in Biosolids Applied to Land. National Academies Press; 2002.

Roman D, Barnett E, Balske R. Cutaneous antiseptic activity of 3, 4, 4′-trichlorocarbanilide. 592 Toilet Good Assoc 1957;28:3-12.

Sabourin L, Beck A, Duenk PW, Kleywegt S, Lapen DR, Hongxia L, et al. Runoff of pharmaceuticals and personal care products following application of dewatered municipal biosolids to an agricultural field. Sci Total Environ 2009;407:4596–604.

Sapkota A, Heidler J, Halden R. Detection of triclocarban and two co-contaminating chlorocarbanilides in US aquatic environments using isotope dilution liquid chromatography tandem mass spectrometry. Environ Res 2007;103(1):21–9.

SCCP European Commission. Opinion on triclocarban for other uses than as a preservative. Scientific Committee on Consumer Products. Report No.: SCCP/0851/04; 2004.. (Available from: http://ec.europa.eu/health/ph_risk/committees/04_sccp/docs/sccp_o_016.pdf).

Schebb NH, Flores I, Kurobe T, Fanze B, Ranganathan A, Hammock BD, Teh SJ. Bioconcentration, metabolism and excretion of triclocarban in larval Qurt medaka (*Oryzias latipes*). Aquat Toxicol 2011;105(3–4):448–54.

Snyder EH, O'Connor G, McAvoy D. Measured physicochemical characteristics and biosolids-borne concentrations of the antimicrobial triclocarban. Sci Total Environ 2010a;408(13):2667–73.

Snyder EH, O'Connor G, McAvoy D. Fate of ^{14}C-triclocarban in biosolids-amended soils. Sci Total Environ 2010b;408(13):2726–32.

Snyder EH, O'Connor G, McAvoy D. Bioaccumulation and toxicity of biosolids-borne triclocarban. Chemosphere 2011;82(3):460–7.

Suter GW. Ecological Risk Assessment. CRC Press, Boca Raton, Florida; 2007.

United States Environmental Protection Agency (USEPA). Reference dose (RfD): description and use in health risk assessments. Washington, DC: USEPA; 1993a. (Available from: http://www.epa.gov/IRIS/rfd.htm).

United States Environmental Protection Agency (USEPA). Wildlife exposure factors handbook, EPA/600/R-93/187. Washington, DC: USEPA; 1993b.

United States Environmental Protection Agency (USEPA). A guide to the biosolids risk assessments for the EPA part 503 rule, EPA/832-B-93-005. Washington, DC: USEPA; 1995.

United States Environmental Protection Agency (USEPA). Initial risk-based prioritization of high production volume (HPV) chemicals. Washington, DC: USEPA; 2009a. (Available from: http://www.epa.gov/hpvis/rbp/101-20-2_Triclocarban_Web_April%202009.pdf).

United States Environmental Protection Agency (USEPA). Targeted national sewage sludge survey sampling and analysis technical report ("Technical Report", EPA-822-R-08-016). Washington, DC: USEPA; 2009b.

United States Environmental Protection Agency (USEPA). Persistent bioaccumulative toxic (PBT) profiler, v 1.203. Washington, DC: USEPA; 2009c.

United States Environmental Protection Agency (USEPA). Estimation programs interface suite™ for Microsoft® Windows, v 3.20. Washington, DC: USEPA; 2009d.

United States Environmental Protection Agency (USEPA). Exposure factors handbook. Washington, DC: National Center for Environmental Assessment, Office of Research and Development; 2011.

Walters E, McClellan K, Halden RU. Occurrence and loss over three years of 72 pharmaceuticals and personal care products from biosolids–soil mixtures in outdoor mesocosms. Water Res 2010;44:6011–20.

Wu C, Spongberg A, Witter J. Adsorption and degradation of triclosan and triclocarban in soils and biosolids-amended soils. J Agric Food Chem 2009;57(11):4900–5.

Wu C, Spongbeg AL, Witter JD, Fang Czajkowski K. Uptake of pharmaceuticals and personal care products by soybean plants from soils applied with biosolids and irrigated with contaminated water. Environ Sci Technol 2010;44(16):6157–61.

Xia K, Hundal LS, Kumar K, Armbrust K, Cox AE, Granato TC. Triclocarban, triclosan, polybrominated diphenyl ethers, and 4-nonylphenol in biosolids and in soil receiving 33-year biosolids application. Environ Toxicol Chem 2010;29(3):597–605.

Ying G, Yu X, Kookana R. Biological degradation of triclocarban and triclosan in a soil under aerobic and anaerobic conditions and comparison with environmental fate modeling. Environ Pollut 2007;150:300–5.