Learned Discourses: Timely Scientific Opinions

Timely Scientific Opinions

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Rules. All submissions must be succinct: no longer than 1000 words, no more than 6 references, and at most one table or figure. Reference format must follow the journal requirement found on the Internet at http:\\www.setacjournals.org. Topics must fall within *IEAM*'s sphere of interest.

Submissions. All manuscripts should be sent via email as Word attachments to Peter M Chapman (peter_chapman@golder.com).

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In a Nutshell…

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TOO LITTLE WATER IN TOO MANY CITIES

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URBANIZATION AND WATER SCARCITY

Cities are home to many. There are currently more than 400 cities with more than 1 million inhabitants and 23 megacities (metropolitan areas with a population of more than 10 million), mainly in Asia (United Nations 2012). According to the United Nations (UN), 50% of people live in cities and, by 2050, 67% of all humans will be living in cities. In developed countries this percentage is even higher (more than 86%).

The speed at which global urbanization is taking place is unparalleled. In 1970, for example, there were just 2 megacities (Tokyo and New York), in 1990 there were 10, in 2011, 23, and by 2025 there will be 37 megacities. Just how impressive this urbanization is becomes apparent when you look at the growth forecasts. The UN estimates that, between 2011 and 2050, the world population will grow from 7 to 9.3 billion and that the population in cities will increase from 3.6 to 6.3 billion, whereas the number of people living in rural areas will decline.

This means that future growth in the world's population will be absorbed by cities. Together with the migration from rural areas to cities, during this period more than 200,000 people—a day—will need to find a new place to live in an urban environment. This will be accompanied by strong growth in urban water demands, especially in fast growing urban regions in East and West Africa, South America, and Asia (Dobbs et al. 2012).

The availability of sufficient clean and fresh water is a prerequisite for the health, economic development, and social

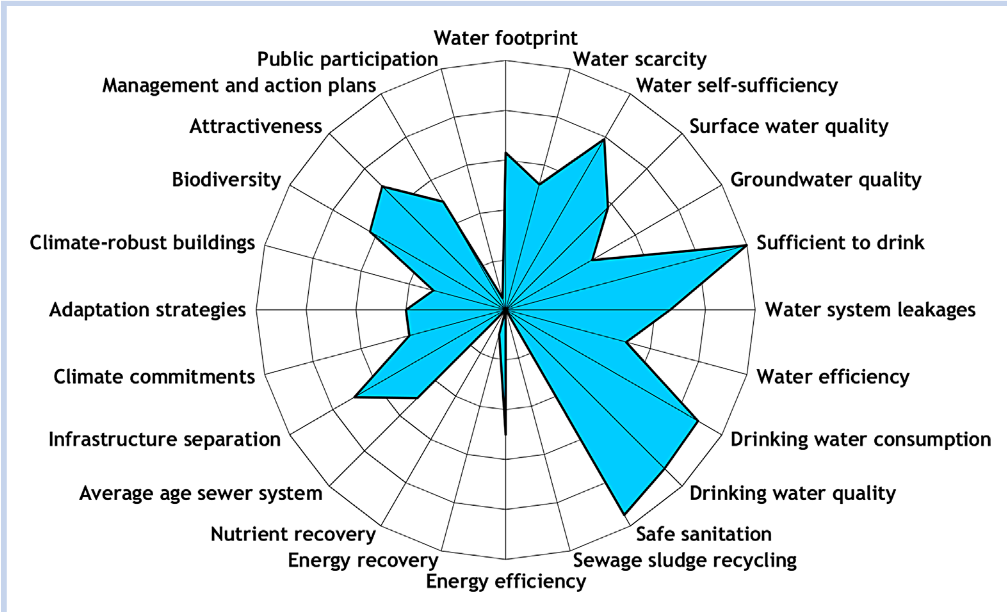

Figure 1. The baseline assessment (City Blueprint) of the megacity Istanbul based on 24 indicator scores. The indicators are scored on a scale between 0 (center of the circle; very poor performance) to 10 (periphery of the circle; excellent performance).

well-being of any society. The world's water resources are threatened, however, by increasing demand from growing urban populations leading to groundwater depletion, saltwater intrusion, and the deterioration of water quality from pollution and climate change (Van Leeuwen 2013; Hoekstra and Wiedman 2014). These threats are placing water increasingly higher on the international agenda. The United Nations estimates that in 2025 approximately 2 billion people will have an absolute water shortage, and that two-thirds of the world population will be affected by water scarcity. Because of the rapid urbanization, the challenges and solutions regarding sustainable water use will predominantly reside in cities.

NOT ONLY TOO LITTLE

Water scarcity is certainly not the only challenge in cities. Extreme weather events have also led to casualties and great economic damage. Recent examples include the extreme rainfall that took place in Copenhagen in 2011. The city center was flooded when over 150 mm of rain fell during a 2 hour period. Insurance damages alone were estimated at approximately 1 billion euros. The effects of Hurricane Sandy in New York in 2012 were also significant. Economic losses across New York were estimated to be at least $18 billion. Recently, the World Economic Forum produced a report on global risks in which the Forum ranked the 10 global risks of highest concern. Three of them are related to water: the greater incidence of extreme weather events (rank 6); failure of climate change mitigation and adaptation (rank 5); and, the water crisis (rank 3).

SUSTAINABLE TRANSITIONS IN CITIES

Water governance encompasses the political, economic, and social processes and institutions by which governments, civil society, and the private sector make decisions about how best to use, develop, and manage water resources. The transformation of cities toward "water wise cities" is a process that encompasses a variety of steps such as a baseline assessment, visioning and defining objectives, scenario building and strategy development, action planning and implementation, and finally, monitoring and evaluation (Van Leeuwen 2013).

From the baseline assessments (Figure 1) we have carried out for 30 cities in 22 countries (CBAG 2014), we have learned that various gaps or obstacles exist. In fact, 7 governance gaps have been defined (OECD 2011): the policy gap (overlapping, unclear allocation of roles and responsibilities), the administrative gap (mismatch between hydrological and administrative boundaries), the information gap (asymmetries of information between central and subnational governments), the capacity gap (lack of technical capacity, staff, time, knowledge, and infrastructure), the funding gap (unstable or insufficient revenues of subnational governments to effectively implement water policies), the objective gap (intensive competition between different ministries), and the accountability gap (lack of citizen concern regarding water policy and low involvement of water users' associations).

The challenge is to overcome these gaps and this can be done (Van Leeuwen 2013), but doing so requires a long term vision and action plan, collaboration between cities and sharing best practices in cities around the world. The longer political leaders wait, the more expensive adaptation will become, and the danger to citizens and the economy as a result of water scarcity and floods will increase. This is the basic philosophy of the City Blueprint Action Group of the European Innovation Partnership on Water of the European Commission (CBAG 2014). This group adheres to the principles that: cities are the major problem holders; active civil societies including the private sector with visionary local government can cope with these water challenges; and, the solution to the global water governance crisis requires a bottom-up approach and collaboration among cities and regions by sharing best practices.

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EFFECTIVE ENVIRONMENTAL RISK COMMUNICATION—SUCCESS STORIES OR URBAN LEGENDS?

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We take part in different risk discourses every day both willingly and in passing. Thanks to social media, we not only share, but also create risk information. However, it seems that increased knowledge does not equal peace of mind; the more we learn, the more we worry about risks. These growing concerns have a direct impact on regulatory affairs and risk management, and that is where risk communication should come into play. Do risk communication studies keep up with this viral information flow? What makes risk communication successful? How do we define success—by the size of the audience, the number of people we manage to convince, the effect of the intervention, or the number of tweets and retweets?

Despite over 30 years of studies, there is still little agreement among risk researchers about the questions above. For a start, research on risk communication can take 3 different avenues: the content of communication (risk information); the process (how this information is shared); and, the reasons for communication (why the information is shared). We have been investigating these issues in relation to environmental risks. Our goal was to establish a set of criteria for risk communication success and to find common features of successful risk communication campaigns. We focused on environmental risk interventions, but included different communication formats (e.g., spatial maps), as long as there was a clear environmental or ecological risk or threat being communicated. Another important criterion was to include only studies in which the effect of communication was measured and assessed (e.g., in randomized controlled trials). Success in risk communication was defined as a measurable effect such as behavioral change, raised awareness, or change of attitudes.

Literature in the area is voluminous. Using the query "environmental risk communication," we searched the most popular scientific databases within the timespan from 1945 to March 2014, to find 2372 publications in the Web of Science alone. Table 1 illustrates our search for studies meeting our predefined criteria.

Table 1. Studies found in the Web of Science database[a]

Search term: "Environmental risk communication"	Number of articles found
Excluded: no empirical research/not accessible	1740
Excluded: occupational/health risk domain	505
Excluded: not matching full criteria set	110
Included: empirical risk communication studies	17
Total	2372

[a]We found 1740 articles related to "environmental risk communication" but only included empirical studies that were accessible.

Our preliminary review took into account the 2372 articles found in the Web of Science. The majority was related to risk communication but did not contain empirical data matching our predefined criteria. A popular area of study is stakeholder analyses, identifying stakeholders in risk communication, and stakeholder networks. Leading topics in environmental risk communication were climate change skepticism, followed by nuclear risks, pesticides, flood, and other water-related risks, and genetic modifications.

WHAT WORKS?

One of the better studied areas in risk communication, also vitally relevant for risk managers and other risk communication practitioners is information framing effects. Framing effects refer to tailoring and adapting the format or the source of the message to a given audience.

The format

Environmental risk managers often face the challenge of communicating uncertainty and probabilities to the general public. Studies into numeracy show that verbal descriptions and graphical representations of probabilities work better in getting an accurate understanding of probability than their numerical equivalents (Dieckmann et al. 2012). Another tried and tested risk communication trick is negative and positive framing of uncertainty. Positive framing (e.g., "95% saved" in comparison to "only 5% lost") generally evokes better support for the message. Studies also show that natural frequencies (e.g., 1 in 10) result in a more accurate understanding of risk than probabilities (Liberali et al. 2012; Hart 2013). On the other hand, a classical experiment by Slovic and Peters (2006) showed that participants preferred a safety measure saving 98% of 150 lives over a safety measure that saved 150 lives, which shows that proportions are easier to assess and understand than absolute numbers without context.

The source

The source of risk information is another important element affecting risk communication success. Trust in the information source is one of the most vital factors. Obviously, expertise and knowledge about the subject are the easiest criteria to assess credibility of the information source, but risk information is not targeted exclusively at experts. A classical framing effect study shows that different attributes help to build the perception of trust and credibility, depending on where the information comes from (Peters et al. 1997). For instance, industry representatives were assessed as trustworthy if they were perceived as concerned and caring; trust in governmental agencies was related to their perceived commitment, and for non-governmental organizations (NGOs) perceived expertise affected their credibility.

The audience

It is easy and intuitive to agree with people who think like us and who share the same sets of values and beliefs. Risk communication is no exception here, and the cultural cognition approach shows that people tend to believe in risk information which is in accordance with their world views. A study by Kahan et al. (2010) showed that environmental risk messages (on climate change and nuclear waste) conveyed by experts "framed" to fit the world view of the audience were more successful in convincing the audience than messages from experts coming from a different cultural background. In other words, if risk managers wish to convince the public, they would do better finding an expert who shares many similarities with the audience.

IMPLICATIONS FOR ENVIRONMENTAL RISK MANAGEMENT

Communication of environmental risks, in comparison with human health risks, remains an understudied area. This is rather surprising, if we take into account the fact that, in our literature review, articles calling for future research were more frequent than actual studies into different communication strategies. However, it is important to remember that environmental risk is different from personal risk. Consequences of environmental threats are often impersonal, delayed in time and space, and responsible actors are often impossible to determine. Hence, environmental beliefs are often driven by personal values and resources, whereas in the health risk domain, fear (for one's own well-being) is a strong driving factor. Effective environmental risk management depends on effective risk communication. There are lessons to be learned from studying health and personal risk communication strategies, and there is clearly a need for additional research linking these areas to the environmental risk domain.

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THREE PROPOSITIONS FOR IMPROVED SCIENCE COMMUNICATION FROM ENVIRONMENTAL RESEARCH

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When talking with colleague Magnus Engwall of Örebro University during the Society of Environmental Toxicology and Chemistry (SETAC) Europe Annual Meeting 2011 in Milan about the impact of environmental research on the public and on policy, we thought that it might be a valuable activity to systematically review how our science is communicated, and whether we could improve the situation. Subsequently, we organized three sessions at the SETAC Europe Annual Meetings in Berlin 2012, Glasgow 2013, and Basel 2014, with a total of 16 platforms and 27 posters, including a panel discussion in Glasgow (Table 1A). A fourth session has been successfully proposed for the Barcelona meeting in 2015. In parallel, we started an open access article series on science and risk communication in *Environmental Sciences Europe*, inviting the community to contribute their views, expertise, and ideas on the topic (Table 1B).

From what we have learned so far, it is obvious that there is a strong interest in science communication among environmental scientists. We invited everyone in the SETAC membership directory who had indicated risk communication as a field of expertise to attend the 3 above-noted sessions. All 3 sessions were well attended with very lively discussions. Response outside the meetings was also strong and fostered interesting conversations. We found that pure communication experts were not sufficiently familiar with scientific issues to be helpful, and within the environmental community, communication experience and knowledge were largely scattered among individual scientists.

Science communication is not a field of expertise or even research for many researchers. However, we postulate that many colleagues have experienced valuable lessons—including failures—regarding communicating their work to target groups or the broader public.

Our first proposition is that this body of knowledge should be structured to be available for strengthening communication of environmental sciences to any type of stakeholder, including the general public. The network of people with communication expertise established through the 3 sessions builds the initial basis for this process.

Science communication is of course nothing new. It is also not new to environmental research. It is represented in press releases, in popular newspaper articles, in science slams, and at science nights, to name but a few. Compared to many other disciplines, however, environmental sciences are crucial to public health, and hence are at the heart of what people need and that affect their daily lives: good environmental quality, safe food, clean air, and clean drinking water. Environmental

Table 1. Overview of activities since 2012 to strengthen science communication of environmental research

Session	Platforms
1[a]	
Berlin 2012	F. Schwab: The gap between scientific publication and the press—A case example A. Hunka: Discourse of risk communication—Taking the risk of communicating risks P. Garrigues: Reach Regulation: Communication behind the information needs V. Castellani: Research findings and decision making: The case of renewable energy T. Hinton: Challenges of integrating science and people within a network of excellence R. Berghahn: Keep your boots muddy
Glasgow 2013	S. Wieck: The necessity of disinfected toilet brushes—Information policy of companies on disinfectants in private I. Stresius: Experience with risk communication in different estuaries and lagoons A. Hunka: How does the public react when scientists disagree? Scientific consensus and risk communication F. Lafaye: Discussing environmental issues from different disciplinary perspectives. The first step for public communication on science Panel discussion: Valery Forbes, Agnieszka Hunka, Ursula Klaschka, Stewart Owen, John Redshaw, Thomas-Benjamin Seiler, Birgit Sokull-Klüttgen, Andrew Thompson
Basel 2014	S. Bowman: Bridging the gap: A case for the use of social media in environmental science J. Bozich: Blogging: A tool for informal communication of scientific research and technology I. Heidmann: Uncertainties in environmental nanoparticle research: What is communicated in scientific literature and mass media? A. Hunka: Effective environmental risk communication—Success stories or urban legends? T. Gocht: Science communication in the field of innovative human safety assessment: The SEURAT-1 dissemination strategy M. Dreyer: Pharmaceutical residues in the water cycle: Challenges of communicating an "uncertain risk" to the public
1[b]	
Article series	Seiler T-B, Engwall M, Hollert H. 2013. Lost in translation? Ways for environmental sciences to communicate about risk and research. Environ Sci Europe 25:8–12. Rinn A, Kivelitz C, Berghahn R. 2013. See it with my eyes: Artificial stream research communicated by an artist. Environ Sci Europe 25:13–21. Castellani V, Piazzalunga A, Sala S. 2013. Research findings and decision making: The case of renewable energy. Environ Sci Europe 25:22–25. Heidmann I, Milde J. 2013. Communication about scientific uncertainty: How scientists and science journalists deal with uncertainties in nanoparticle research. Environ Sci Europe 25:25–29. Klaschka U, Rother H-A. 2013. 'Read this and be safe!' Comparison of regulatory processes for communicating risks of personal care products to European and South African consumers. Environ Sci Europe 25:30–36.

[a]Platform presentations in the past 3 sessions organized at SETAC Europe Annual Meetings 2012, 2013, and 2014.
[b]Current content of the article series on science and risk communication in *Environmental Sciences Europe*.

sciences thus have a "traditional" link to the general public and the media.

Balancing science and the general public's comprehension, however, is a very fine line, and pitfalls are numerous. The fact that there is uncertainty in scientific findings is a main driver for misunderstanding, distrust, and consequently lack of interest or even opposition to such findings. In the environmental sciences any uncertainty, e.g., regarding nanoparticle toxicity or genetically modified organisms, can easily affect communication with the general public and result in misunderstandings and overreaction (e.g., general bans on genetically modified organisms). In contrast, uncertainty about the Higgs boson in the physical sciences has minimal emotional impact. It is the emotional response to perceived impact on daily life that shifts disconnect between the environmental sciences and the general public from academic concern to a complete failure of the fundamental motivation for environmental research.

The session at the SETAC Europe Annual Meeting 2014 in Basel, and also other sessions and initiatives at that meeting, gave a broad overview of the different available tools and concepts, including the first ever SETAC science slam and gamification (the use of game thinking and game mechanics in nongame contexts to engage users in solving problems). Platform presentations emphasized the use of social media in science communication. Some student presenters aimed their presentations at established older colleagues; communication expertise can be a matter of age (i.e., younger scientists are more comfortable with social media than older scientists). Other presenters reported on research about uncertainty and success stories in science communication from both theoretical and practical points of view.

Communication should convey meaningful information and create shared understanding. If messages from environmental sciences are not readily understood by the general public, we remain in our "Ivory Tower." We must provide easily comprehensible communications and confirm they have been understood appropriately. Consequently, our 2nd proposition: it is not sufficient for environmental science to merely contact the general public. We must also effectively and sustainably distribute research findings.

We see the need for tailored communication concepts taking into account the particularities of environmental research, which leads to our third proposition. Environmental sciences should be thoroughly reviewed and analyzed regarding: their key features; their current perception by the general public and impact on policy; and, their potential for a participatory role of the public in conducting scientific research, thus strengthening the impact on societal development as well as policy decisions. The three propositions should be worked on by a SETAC Europe advisory group on science and risk communication, which we will propose in 2015.

OVERVIEW OF SCIENTIFIC EVIDENCE FOR CHOCOLATE HEALTH BENEFITS

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The potential health benefits of consuming chocolate have only recently been discovered. Laboratory studies and observational and small scale experimental studies on humans have found that chocolate consumption lowers blood pressure and may also have other positive health effects. There are several bioactive compounds in chocolate that may promote alertness and may affect stress levels by prompting serotonin production, which is a calming neurotransmitter. The number of publications concerning cocoa and chocolate is increasing steadily. Of such publications, an increasing proportion concerns the effects of polyphenols and, in particular, flavonoids on human biology and health. Studies that link chocolate consumption with health outcomes (instead of intermediate outcomes like blood pressure) are less common. There appears to be some scientific evidence to justify eating a moderate amount of dark chocolate daily.

Figure 1. In the special session discussion on sustainable chocolate production not all participants were aware that they can choose to buy more sustainable chocolate. The fact that chocolate is a luxury product seemed an additional motive to strive for sustainable production. At the end of the session participants were able to taste and compare 4 different types of cocoa beans and the chocolate that was made from them.

INTRODUCTION

A Special Session at the 24th Annual Meeting of the Society of Environmental Toxicology and Chemistry (SETAC) Europe in Basel in 2014, entitled Sustainability of Swiss Chocolate Production, considered sustainable chocolate production and human health issues associated with societal costs and benefits (Figure 1). Chocolate consumption is often described as a "guilty pleasure" by the many media that deal with healthy food: eating chocolate gives pleasure and comfort, although at the same time it makes one feel guilty because chocolate is mainly fat (and sugar) without much beneficial nutrition. Over the past decade this image problem of chocolate has shifted positively: claims that chocolate consumption has health benefits have been substantiated by scientific articles, and in the media chocolate has been given the status of "super food" or "brain food."

BENEFITS AND RISKS

In a review article on chocolate and cocoa and human health, Latif (2013) reported potential beneficial health effects: prevention of cardiovascular diseases (reduction of oxidative stress, lowering of blood pressure, increased vasodilatation, increased platelet activity, antidiabetic effects, and antistress effects); effects on neurons; possible antitumor effects; anti-inflammatory effects; anti-obesity effects; and, better exercise recovery. Compounds held responsible for these benefits are antioxidants such as flavanoids that provide defense against free radicals. Chocolate also contains theobromine and caffeine, which are central nervous system stimulants, diuretics and smooth muscle relaxants, and valeric acid, which is a stress reducer.

Health risks from chocolate include contribution to weight gain, heartburn, and allergies. Dark chocolate contains 513 kcal (2152 kJ)/100 g, which needs at least 1.5 hours cycling or walking to burn the energy (for comparison, avocado, another "super" food, contains 188 kcal [790 kJ]/100 g).

RESEARCH

The potential beneficial effects of chocolate are supported by epidemiological and human intervention studies. The latter are mostly randomized, blind, and placebo-controlled studies in which the effects of a daily consumption of a certain amount of chocolate or ingredients of chocolate are being studied. The first epidemiological "evidence" for beneficial health effects of chocolate were found in the Kuna Indian population of the islands of Panama. This population is characterized by a low prevalence of atherosclerosis, type 2 diabetes, and hypertension. The "secret" behind this is the daily intake of a homemade cocoa drink by the indigenous Kuna Indians. These traits disappear after migration to urban areas on mainland Panama and subsequent changes in diet (Latif 2013).

The European Food Safety Authority (EFSA) is an authority in deciding whether commercially used health claims for food items are substantiated by scientific evidence. The health claim "cocoa flavonols help maintain endothelium-dependent vasodilatation, which contributes to normal blood flow" was supported by 6 studies with randomized controlled trials pertinent to the claim and approximately 10 additional studies. EFSA (2012) concluded that: normal blood flow is a beneficial physiological effect; there is a dose–effect relationship between flavonols and blood flow; 200 mg of cocoa flavonols should be consumed daily; and, the target population is the general population.

A typical example of an epidemiological study is one on the influence of flavonoids from chocolate, wine, and tea on cognitive performance. Elderly Norwegian participants were asked to perform cognitive tests and to fill in a questionnaire on habitual food intake. A dose–dependent association was found between intake of chocolate, wine, and tea and cognition, with maximum effects at 10 g/day for chocolate, 100 mL/day for wine, and a linear effect for tea (Nurk et al. 2009).

ECONOMICAL IMPORTANCE AND CONFLICTS OF INTEREST

In reviewing beneficial chocolate health effects, Latif (2013) warns that the majority of the studies claiming benefits of chocolate are small-scale, and sponsored or carried out by chocolate manufacturers whose interests cannot be ignored. The worth of the global chocolate market is growing and estimated at 98.3 billion US$ by 2016 (MarketsandMarkets

2014). On the other hand, high costs are associated with the diseases that might be reduced by chocolate consumption. For instance, it is estimated that cardiovascular diseases cause an economic cost of 169 billion euro per year in Europe (Leal et al. 2006).

Based on presumed health benefit effects, annual sales of food supplements containing resveratrol, a compound also present in chocolate and thought to be responsible for the "French health paradox" (the apparently paradoxical epidemiological observation that French people have a relatively low incidence of coronary heart disease, while having a diet relatively rich in saturated fats), amount up to 30 million US$ in the United States alone. However, a recently published and much talked about, large, long-term epidemiological study showed that resveratrol in red wine, chocolate, and grapes was not associated with improved health in elderly Italians (Semba et al. 2014).

Latif (2013) also mentions that most products used in studies contain more polyphenols than commercially available products. Furthermore, milk and white chocolate contain more sugar and (far) less beneficial compounds.

DOSAGE

In the studies mentioned in this article, different daily dark chocolate doses are mentioned that might lead to health benefits. EFSA (2012) mentions 10 g high-flavanol dark chocolate, the study with elderly Norwegians states 10 g, and Latif (2013) reports approximately 60 g.

CONCLUSIONS

There is scientific evidence for both physical and mental health positive effects of (dark) chocolate, although there remains much uncertainty. Dose–effect relationships are needed, as well as more focus on the negative health effects of chocolate consumption. The results of chocolate health studies may have considerable economic implications, for both chocolate manufacturers and for general health care. There seems some consensus about a beneficial dosage of 10 g dark chocolate per day (>70% cocoa).

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MULTIMEDIA MASS-BALANCE MODELS FOR CHEMICALS IN THE ENVIRONMENT: RELIABLE TOOLS OR BOLD OVERSIMPLIFICATIONS?

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Models are essential tools for our understanding of the fate of chemicals in the environment (MacLeod et al. 2010). Models allow us to interpolate between concentration data measured in the field (and to extrapolate beyond measured data), to establish a mechanistically based interpretation of measured concentrations, and to run scenarios under a range of different conditions, for example for a world with a warmer climate.

There are many different types of models for chemicals in the environment, such as models for chemicals in plumes released from smokestacks or other point sources, hydrological models for transport of chemicals in groundwater, atmospheric transport models, models for chemical uptake by plants, and many more. The focus of this Learned Discourse is on multicompartment or multimedia mass-balance models. Models of this type have been used since the late 1970s in a wide range of applications (Mackay 1979). To illustrate how these models work, we first consider the simplest possible case of one chemical in one environmental compartment (called by modelers a box): carbon tetrachloride (CCl_4) in the troposphere. If we assume that emissions and losses are equal (steady state) and that the troposphere is a well-mixed reservoir of CCl_4, the mass-balance equation is $E = k \cdot c \cdot V$. Here E (t/y) is the continuous emission of CCl_4 into the troposphere, k (1/y) is the first-order loss rate constant of CCl_4 in the troposphere, V (m^3) is the volume of the troposphere, and c is the concentration of CCl_4 in tropospheric air. Approximate values for the three parameters are $E = 80$ kt/y (in the 1990s), $k = 0.0333$ 1/y, and $V = 5 \cdot 10^{18}$ m^3 (k is the inverse of the tropospheric lifetime of CCl_4, which is approximately 30 years). Solving for c yields $c = 3.11 \cdot 10^{-9}$ mol/m^3, which is equivalent to 76 ppt. Measured concentrations of CCl_4 in the troposphere are approximately 90 ppt, and for such a simple model the agreement between modeled and measured concentrations is good.

Next, the CCl_4 case above can be expanded to include a second environmental compartment or box, in this case seawater. The mass-balance equation then reads, $E = k_a \cdot c_a \cdot V_a + k_w \cdot c_w \cdot V_w$, with the subscripts "a" and "w" denoting air and water, respectively. Now also the volume of the water compartment, V_w, and the rate constant for CCl_4 loss from water, k_w, have to be known, and in addition to the mass-balance equation a second equation is needed to calculate the two unknowns, c_a and c_w. This equation defines the ratio of the CCl_4 concentrations in air and water as is prescribed by the chemical's air–water partition coefficient, K_{aw}: $K_{aw} = c_a/c_w$. The K_{aw} is a chemical-specific property that needs to be known in addition to V_w and k_w before the two-box model can be solved.

In general, we can now see that four pieces of information are needed for a reliable estimate of a chemical's concentration in an environmental system: the emission source strength, the volumes of the compartments that the chemical enters, the main loss process or processes removing the chemical from the system, and the partitioning properties of the chemical.

On this basis, the box-model concept has been extended from simple unit-world models, which represent the global troposphere, seawater, and topsoil by one box each, to complex models including many boxes and processes. Examples are Globo-POP (Wania and Mackay 1999) and CliMoChem (by Scheringer and coworkers; ETH Zurich) as two global models consisting of latitudinal zones, and BETR-Global (MacLeod et al. 2010) as a global model with 288 grid cells. Although these models capture many different aspects of the global environmental fate of organic chemicals, their performance strongly depends on the quality of only four types of data. These are, as mentioned above, the emission rate, compartment volumes, main loss processes, and partitioning properties for the important compartments. In the models, these data are integrated with the additional knowledge that is contained in the models: the law of mass conservation, the laws of chemical kinetics, Fick's laws of diffusion, and extensive empirical data sets on the composition of the environment (temperature, precipitation rates, organic carbon concentration in soil, concentration of OH radicals and aerosol particles in air, etc.). Generally, these latter components of the models are available with relatively low uncertainty, and this makes the models a valid platform for the assessment of the environmental fate of organic chemicals. If there is a substantial discrepancy between model results and measured concentrations, it is in most cases caused by inaccurate data for emissions and/or main loss process or processes and phase partitioning.

Over the last 15 years, multimedia mass balance models have been used to investigate the fate of a wide range of organic chemicals in the global environment, including comparison to concentrations measured in the field. In most cases, the agreement between modeled and measured concentrations is fully satisfactory (Wania and Mackay 1999; Becker et al. 2011). In many studies, the long-term fate of long-lived chemicals such as persistent organic pollutants (POPs) was investigated. However, it is also possible to set up multimedia mass-balance models for less persistent chemicals and highly dynamic local or regional systems. This is illustrated by a modeling study into the fate of the herbicide, diuron, in a catchment in the coastal plains of Queensland, Australia (Camenzuli et al. 2012). Diuron is used in this region mainly on sugarcane, and a mass-balance model was used to estimate the amounts of diuron that are flushed from the agricultural soil into the water of the Great Barrier Reef lagoon. This is a source of concern because the region has extremely high rainfall in the wet season (up to 200 mm per day) and diuron washed out from the soils and transferred to seawater may affect the wildlife in the lagoon. The model for this case consisted of agricultural and nonagricultural soil, seawater, sediment underneath the water, and air. It was parameterized with actual precipitation, temperature, and wind speed data from the region. The diuron emissions were assumed to enter the agricultural soil and were derived from actual application rates reported for sugarcane in the region.

Figure 1 shows the model results (line) in combination with diuron concentrations measured in seawater of the lagoon (dots). Shown are results for the years 2008 to 2011; wet seasons are indicated in gray. The model results include uncertainty ranges (dashed lines), which were derived from the uncertainties of individual model parameters by means of error propagation.

The results show higher concentrations in the wet seasons, when runoff of diuron is higher because of strong rainfall, and

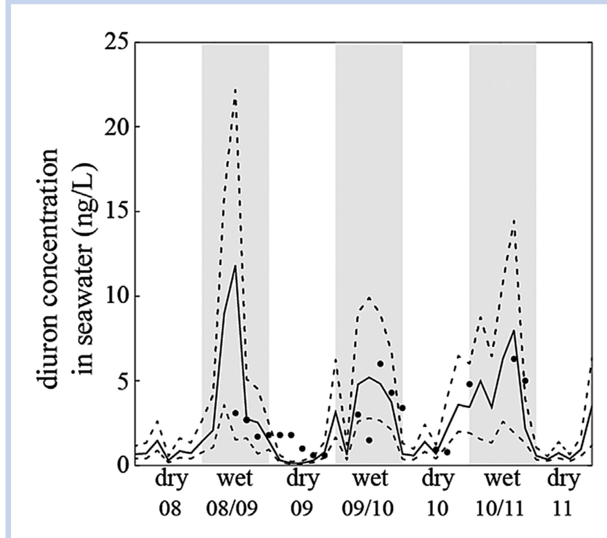

Figure 1. Modeled (full black line) and measured (dots) concentrations of diuron in seawater in the Great Barrier Reef lagoon, Queensland, Australia. The dashed lines indicate uncertainty ranges of the modeled concentrations. Reprinted from The Science of the Total Environment, 440, L. Camenzuli et al., Describing the environmental fate of diuron in a tropical river catchment, pp. 178–185, Copyright (2012), with permission from Elsevier.

demonstrate that the model can reproduce the pronounced seasonal pattern that is visible in the measured data. The model also makes it possible to quantify the amounts of diuron present in each compartment of the system at any time point in a model run, to determine the diuron fluxes to seawater, and to evaluate how diuron concentration in seawater respond if the use of diuron in the region is restricted. For all these aspects, see Camenzuli et al. (2012).

In conclusion, multimedia mass-balance models provide highly useful tools for estimating concentrations of chemicals in the environment, checking the consistency of emission data, chemical property data, and concentrations measured in the field, and evaluating scenarios of different environmental conditions or chemical use. Because of their flexible structure, it is always possible to "update" these models; current multimedia mass-balance models accommodate many new findings for individual environmental processes. The models can be set up for different spatial and temporal scales and for a wide range of chemicals; recently, models that take into account the specific properties of engineered nanoparticles have also been presented (Praetorius et al. 2012).

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