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SYNOPSIS

DDT Strikes Back: Galapagos Sea Lions Face Increasing Health Risks

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INTRODUCTION

Dichlorodiphenyltrichloroethane (DDT) is an effective and relatively cheap anti-malaria pesticide which has saved human lives, but also brought Northern wildlife species to the brink of extinction due to its persistence, bioaccumulation in the food-web, and hormone-mimicking characteristics (Carson 1962; Vallack et al. 1998; UNEP 2001; ATSDR 2002; Blus 2003; WHO 2006; Colborn and Carroll 2007; Van den Berg 2008). Thirty-two years after its ban in the US and its inclusion on Schedule 2 of the UN Stockholm Convention on Persistent Organic Pollutants (POPs) because of its damaging health effects in human and wildlife populations (UNEP 2001; ATSDR 2002; WHO 2006; Vallack et al. 1998; Colborn and Carroll 2007; Blus 2003), the WHO has recommitted to the use of the malaria-fighting pesticide DDT in tropical countries because of an increase in malaria cases in tropical countries (e. g., Peru, Bolivia, Paraguay, Brazil, and African nations), where DDT use was halted or low application rates were used (Van den Berg 2008; WHO 2006; Roberts et al. 1997, 2000).

Although evolutionary adaptation of the malaria vector has triggered insecticide resistance to DDT (Denholm et al. 2002), the return to an increased reliance on DDT use is testament to DDT's effectiveness in combating malaria at a low cost. Large volumes of DDT (i.e., 4,000–5,000 tonnes of active ingredient per year) were used in India and Africa countries to overcome the malaria crisis (Van den Berg 2008). However, 50 years of research on DDT in the temperate and arctic regions of the Northern hemisphere have documented that human health benefits go hand in hand with detrimental effects on wildlife populations (Carson 1962; De Guise et al. 1998; Lahvis et al. 1995; Guillette et al. 1994; Blus 2003;). Since wildlife provides life support, sustenance, and economic opportunities through harvesting and ecotourism in many developing tropical countries, the health of wildlife cannot be viewed in isolation of human health. A balance needs to be struck between health benefits and health risks of DDT use. This requires an understanding of the fate, trends, and dose–response relationship for DDT in tropical wildlife. Such information does currently not exist and monitoring and source control programs that can help to document this relationship are as absent in tropical countries to date as they were in the Western world when DDT was first used in the 1940s and 1960s (Roberts et al. 2000; ATSDR 2002; Blus 2003; Colborn and Carroll 2007; Van den Berg 2008).

From a global perspective, the protection of coastal food webs from contamination by chemical pollutants is critical to the long term conservation of the biodiversity and native inhabitants residing in unique places of the Earth, including UNESCO Global Heritage sites such as the Galapagos Islands. Coastal waters that are contaminated with persistent chemicals and pathogens can lead to human illness and adverse health, reduced fisheries quality and quantity, and impacts of the health of marine wildlife. This had obvious social and economic consequences. Conversely, coastal waters that are protected from chemical pollutants provide for an abundance of clean fisheries products and wildlife, and essential foundation for the well-being of the local biodiversity, human residents and the ecotourism sector.

At the top of the marine-coastal food chain, marine mammals can provide an "integrated" overview of ecosystem health. As aquatic animals, they are also vulnerable to infection by pathogens of terrestrial origin. By documenting the presence of chemical pollutants in this species, we are able to deliver science-based advice to conservationists, managers, regulators, and stakeholders, on the implementation of best management practices. Equivalent to the role of killer whales as global sentinels of pollution in the Northeastern Pacific, the Galapagos sea lion has recently been used as a sentinel of marine pollution and a key indicator of the ecosystem functioning and oceanic-coastal environmental health in Galapagos Islands. Therefore, this synopsis aims to synthesize our recent findings on DDT contamination in Galapagos sea lions and its use as a sentinel-model species of environmental pollution by POPs.

DDT IN GALAPAGOS SEA LIONS

As most marine mammals, Galapagos sea lions do not escape from the global contamination by POPs and other chemical assaults, including oil spills (Fig. 1). Persistent organic pollutants have the capacity to bioaccumulate in marine food webs, resulting in the biomagnification of these contaminants in high trophic level predators such as marine mammals, as shown in Fig. 1. To start documenting the response of tropical wildlife to an increased use in DDT, we measured DDT concentrations in blubber biopsy samples collected from endemic and endangered Galapagos sea lion pups (*Zalophus wolleabeki*; Fig. 2) of the Galapagos Islands, located at 1,000 km offshore from continental Ecuador, in 2005 ($n = 21$ pups) before the 2006 WHO recommendation and in 2008 ($n = 20$ pups) after the WHO recommendation (Alava et al. 2011); we also conducted a risk assessment of the health impacts of DDT concentrations and its main metabolite p,p'-DDE by comparing the detected concentrations in pups against toxic effect reference values documented in the literature as documented elsewhere (Alava 2011; Alava et al. 2011).

DDT mean ± (SE) concentrations in samples collected in 2008 (530 ± 110 μg kg^{-1} lipid) were significantly greater than concentrations (280 ± 150 μg kg^{-1} lipid), measured in 2005 (t test $= 3.465$, $P = 0.0013$), indicating a plausible increase of 86% in DDT levels (Alava et al. 2011). Based on the 2008 data (Alava et al. 2011), we found evidence that 1% of the p,p'-DDE concentrations exceeded the p,p'-DDE anti-androgenic effect reference values causing endocrine disruption in mammalian cell cultures (Kelce et al. 1995), 12% of the p,p'-DDE concentrations were above the minimum p,p'-DDE immunotoxic effect concentration reported for bottlenose dolphins (Lahvis et al. 1995). This indicates that DDT concentrations in Galapagos sea lion pups are near levels expected to be associated with impacts on the immune system. Synergetic and/or additive toxic effects due to mixtures with other pollutants with similar mode of toxicity can contribute to impacts on the immune and endocrine systems as concentrations of polychlorinated biphenyls (PCBs) and polybrominated diphenyl ether (PBDEs) flame retardants were also recently detected in these animals (Alava et al. 2009). POPs can bioaccumulate in oceanic and coastal–marine food chains of the Galapagos sea lion, compromising its heath and reproductive status (Alava et al. 2010; Alava 2011; Alava et al. 2011). A compromised immune and endocrine system affects the ability of animals to combat disease and to successfully reproduce, which is especially relevant during periods of nutritional and other types of stress in stochastic environments (e.g. El Niño events) when mass mortality occurs and populations often approach the critical point of extinction (Alava and Salazar 2006; Vargas et al. 2007).

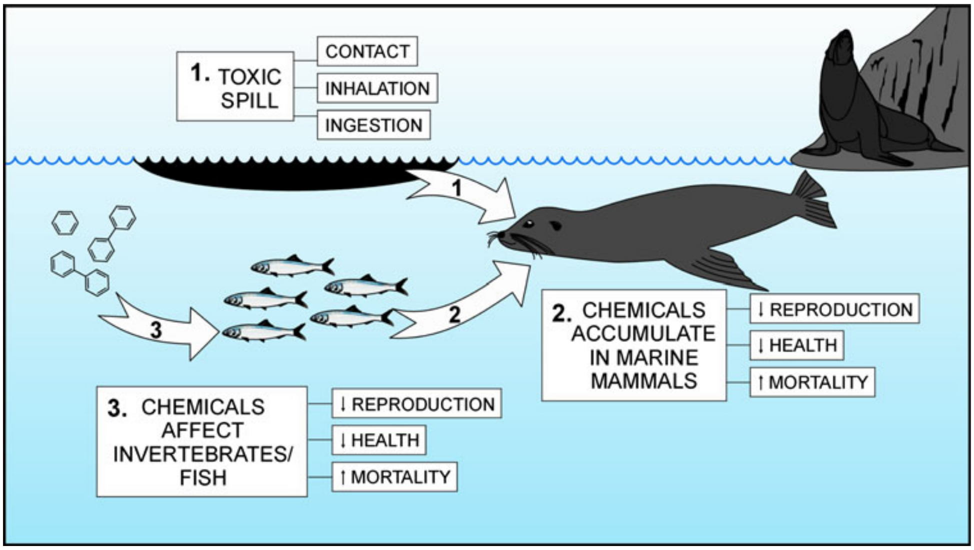

Fig. 1 Galapagos sea lion can be exposed to oil spills, which can possess acute and chronic toxic effects, and Persistent Organic Pollutants (*1*), which can be accumulated mainly through dietary ingestion and by inhalation, causing potential health effects, including impairments to reproduction (*2*), due to contamination of diet items (fish preys) in the food chain (3). The prey can be also affected by contaminants (*3*). Adapted from Alava (2011)

Fig. 2 The Galapagos sea lion is an endemic marine mammal to the Galapagos Islands and an endangered pinniped species, which have declined from 40,000 to 16,000 animals since the late 1970s (Picture: J.J. Alava)

THE DDT LEGACY CONTINUES

The apparent increase of DDT levels in remote Galapagos sea lions is not an isolated event since concentrations of DDT in Adélie penguins (*Pygoscelis adeliae*) from remote areas of the western Antarctic Peninsula have not decreased between 2004 and 2006 (Geisz et al. 2008). Likewise, concentrations of DDT in human breast milk from Japan have not decreased since 1998 (Kunisue et al. 2006). DDT concentrations in Galapagos sea lion pups are lower than those detected in pinnipeds from the Northern Hemisphere (Kajiwara et al. 2001; Kannan et al. 2004; Debier et al. 2005; Del Toro et al. 2006; Blasius and Goodmanlowe 2008; Mos et al. 2010), but greater than those detected recently in adult subdominant males, adult females, juveniles and pups of southern elephant seals (*Mirounga leonina*) from Elephant Island, Antarctica (Miranda-Filho et al. 2007). Interestingly, Galapagos sea lion pups exhibited DDT concentrations similar to those detected in juveniles of Hawaiian monk seals (*Monachus schauinslandi*) from several subpopulations in the Northwestern Hawaiian Islands (Ylitalo et al. 2008). The maximum levels of DDT concentration (1,200–3,100 $\mu g\ kg^{-1}$ lipid) detected in six Galapagos sea lion pups are comparable to or higher than the concentrations recently found in Amazon River dolphins (*Inia geoffrensis*; 1,624 $\mu g\ kg^{-1}$ lipid) (Torres et al. 2009) and higher than concentrations measured in human milk (370 $\mu g\ kg^{-1}$ lipid) samples from the Brazilian Amazon (Azeredo et al. 2008), where DDT has been widely sprayed.

Although it is uncertain what the sources are from which DDT is delivered to the Galapagos, the long-range global atmospheric-oceanic transport (i.e. "multi-hopping effect") and DDT revolatilization to the atmosphere (Iwata et al. 1994; Wilkening et al. 2000; Guglielmo et al. 2009) are likely the major mechanisms responsible for the incidence of DDT in the Galapagos. Recent modeling work reports that residence times and proportions of the total global masses of DDT are 10–15 days and 2% in the atmosphere, and 1.2 years and 26% in the global ocean with 30% of the DDT mass bounded to the organic matter phase in the equatorial Pacific Ocean, where high primary productivity exists due to nutrient-enriched waters (i.e., wind driven upwelling) (Guglielmo et al. 2009), as those found in Galapagos waters (Alava 2009). These observations portray that the physical–chemical properties of DDT, oceanographic conditions, and chronic atmospheric inputs are the driving forces explaining the presence of DDT in wild life of the islands.

CONSERVATION AND MANAGEMENT IMPLICATIONS

The Galapagos is one of the last living natural labs to study evolution and was already a UNESCO-Heritage site at risk due to invasive species, escalating human population growth and burgeoning tourism (Watkins and Cruz 2007), but the impact by persistent organic pollutants, including DDT, has been scarcely studied (Alava and Salazar 2006;

Alava et al. 2009). While additional temporal monitoring of DDT levels in Galapagos sea lions will provide greater insight into environmental responses to recent DDT use, our study provides a timely warning signal of the dangers of an increased reliance of DDT for malaria control in tropical countries. DDT is not presently used in the Galapagos Islands, underscoring the ready transport away from applications zones, and emphasizing the vulnerability of remote tropical regions. The rise of DDT concentrations in tropical wild life species is of great concern because of the well known toxicity of DDT and the demonstrated effects of DDT on bird (Hickey and Anderson 1968; Blus 2003) and other wildlife species in the Northern hemisphere (Guillette et al. 1994; De Guise et al. 1998; Vallack et al. 1998; Ylitalo et al. 2005). To ensure that tropical wildlife species will not meet a similar fate in the future, it is important that the DDT issue is brought to global attention immediately as well as the urgent need of environmental monitoring programs.

Here, we show that DDT concentrations in endangered Galapagos sea lion pups increased significantly between 2005 and 2008 and have attained levels that can affect the immune system and population dynamics during periods of nutritional stress (El Niño events). Concentrations of DDT and associated health risks in wildlife are generally believed to be declining but this may no longer be the case in tropical countries where DDT is increasingly used. The toxicological principle "*the dose makes the poison*" provides the scientific rationale for benefiting from the anti-malaria properties of DDT while minimizing or avoiding damage to local and global wildlife and advocates the implementation of source control. However, its precautionary application requires a commitment to monitoring remote environments, including the much-valued Galapagos Island Archipelago, and impact assessment and source control programs that have received scant attention in developing nations to date.

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