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Latin American Protected Areas: Protected from Chemical Pollution?

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ABSTRACT

Protected areas (PAs) are critically important means to preserve species and maintain natural ecosystems. However, the potential impacts of chemical pollution on PAs are seldom mentioned in the scientific literature. Research on the extent of the occurrence of chemical pollution inside PAs and in-depth assessments of how chemical contaminants may adversely affect the maintenance of species abundance, species survival, and ecosystem functions are scarce to nonexistent. We investigated 1) the occurrence of chemical contaminants inside 119 PAs in Latin America from publically available databases, and 2) reviewed case studies of chemical contaminants and pollution in 4 Latin American PAs. Cases of chemical pollution and contamination inside Latin American PAs mostly originated from sources such as mining, oil, and gas extraction. To date, the focus of the research on chemical pollution research inside Latin American PAs has been primarily on the detection of contamination, typically limited to trace metals. Where management actions have occurred, they have been reactive rather than proactive. Protected areas established in wetlands are the most affected by chemical pollution. Based on the information from the pollution and/or contamination occurrence and the case studies analyzed, Latin American PAs are not well safeguarded from chemical pollution, resulting in both challenges and opportunities to conserve biodiversity and ecosystems. *Integr Environ Assess Manag* 2016;00:000–000. © 2016 SETAC

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INTRODUCTION

The historic notion that the goal of protected areas (PAs) was to protect remote, iconic landscapes, and wildlife has shifted to a more complex set of conservation, social, and economic objectives (Watson et al. 2014). The International Union for the Conservation of Nature (IUCN) defined the term protected area as "a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (Dudley 2008). Currently, PAs are used worldwide to conserve biodiversity and ecosystems as the essential building blocks for nature conservation (Dudley 2008). Several types of PAs have been proposed with one central idea: the protection of wild biodiversity (Locke and Dearden 2005; Dudley 2008). Hence, PAs are critically important given the current biodiversity crisis (Vörösmarty et al. 2010; Loehle and Eschenbach 2012), where rates of extinction are approximately equal to 1000 times higher than background levels (Pimm et al. 1995). Globally, factors contributing to loss of biodiversity such as habitat loss (Naughton-Treves et al. 2005), illegal trading of species (Hilborn et al. 2006), and invasion and expansion of nonnative species (Simberloff et al. 2013) are in comparison, well covered in the scientific literature, and hence considered in the management plans of well-designed PAs to protect biodiversity (Chape et al. 2005). In contrast, discussion regarding the impacts of chemical pollution on PAs biodiversity has been virtually absent from the scientific literature (but see Rodriguez-Jorquera et al. 2015, 2016).

Protected areas have grown exponentially, particularly in developing economies such as Latin American countries (Naughton-Treves et al. 2005). Currently, there are approximately 6309 PAs in Latin America covering 12% of the region

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(Table 1). The human population in Latin America is projected to increase from 606 million to 780 million by 2050 (Haub 2013), and the average income is expected to rise; both relevant factors impacting natural areas in terms of biodiversity loss (Sanderson et al. 2002), water pollution (Jackson et al. 2001), and land modification (Machovina et al. 2015). For example, livestock production—the greatest habitat loss driver (Green et al. 2005)—is anticipated to increase in Latin America along with energy demand (Heres del Valle 2015). Furthermore, in Latin America, limited funding to maintain PAs has been identified as a driver of biodiversity loss (Leisher et al. 2013). All of these factors are expected to intensify impacts on PAs challenging their current status and management goals.

Chemical pollution is well-known to cause adverse effects on biota such as reproductive impairments (Burgess and Meyer 2008; Crump and Trudeau 2009; Frederick and Jayasena 2011), immune incompetence (Yang et al. 2002; Kenow et al.

Table 1. Protected areas and related human population metrics across Latin American countries

Country	Area (km^2)	Nr protected areas	Country coverage (%)	Biodiversity loss (%)	Population	Population density (per km^2)
Argentina	2 780 400	345	5	15	41 660 417	14.4
Bolivia	1 098 581	72	19	13	10 461 053	9
Brazil	8 515 767	1864	26	11	201 032 714	23.6
Chile	756 096	250	19	7	17 556 815	23
Colombia	1 141 748	639	21	14	47 387 109	41.5
Costa Rica	51 100	186	21	18	4 667 096	91.3
Cuba	109 884	274	6	21	11 061 886	100.6
Dominican Republic	48 442	87	22	25	10 219 630	210.9
Ecuador	283 560	126	25	13	15 439 429	54.4
El Salvador	21 040	176	0.83	29	6 108 590	290.3
French Guiana	83 534	58	48	29	250 109	3
Guadeloupe	1628	76	19	29	405 739	250
Guatemala	108 889	259	31	17	15 438 384	129
Haiti	27 750	8	0.27	25	9 996 731	350
Honduras	112 492	111	18	10	8 555 072	76
Martinique	1128	ND	ND	ND	386 486	340
Mexico	1 972 550	1004	11	17	118 395 054	57
Nicaragua	130 375	95	37	14	5 788 531	44.3
Panama	75 517	96	19	11	3 661 868	54.2
Paraguay	406 752	44	5	18	6 800 284	14.2
Peru	1 285 216	200	14	5	30 475 144	23
Puerto Rico	9104	59	10	17	3 615 086	397
Saint-Barthelme	53	4	ND	ND	36 286	682
Saint-Martin	25	ND	ND	ND	9,035	361
Uruguay	176 215	25	0.26	31	3 324 460	18.87
Venezuela	916 445	251	54	7	31 648 930	31.59
Total	20 114 291	6309	19[a]	17[a]	604 381 938	3690

ND = no data.
Protected areas and biodiversity loss data were obtained from World Conservation Monitoring Centre database (UNEP-WCMC 2014).
[a]Average value.

2007; Hawley et al. 2009), oxidative stress (Livingstone 2001), and endocrine disruption (Hotchkiss et al. 2008; Jayasena et al. 2011) potentially leading to species population reductions. Despite the difficulty in proving pollution effects on free-range species populations, there are numerous illustrious examples in the scientific literature. For example, antifouling chemicals have induced population declines in gastropods due to sterilization and sex change (Oehlmann et al. 1996). Kidd et al. (2007) demonstrated the collapse of an entire fish population exposed to a synthetic estrogen used in a contraceptive pill. Egg shell thinning effects caused by DDT have been known for decades (Porter and Wiemeyer 1969), and later research demonstrated the effects of DDT on raptor reproduction with population declines observed across Europe and North America (Vos et al. 2000). Population effects caused by pollutants on reptiles have also been reported (Guillette et al. 1999; Willemsen and Hailey 2001; van de Merwe et al. 2010), as well as reductions on the apparently more sensitive amphibians (Blaustein and Kiesecker 2002). Broadly, the decrease in egg hatchability of oviparous species exposed to pollution has been largely documented (Wolfe et al. 1998; Henny et al. 2002; Karasov et al. 2005; Tyor et al. 2012), with regional reduction in populations (Vasseur and Cossu-Leguille 2006). Recently, the effects of pollution on other biodiversity components such as primary producers (Lepp 1983; Clark et al. 2013) and bacteria have been reported more frequently (Imfeld and Vuilleumier 2012; Chakraborty and Bhadury 2015). Furthermore, ecosystem goods and services may have also been directly hampered by pollution (i.e., water quality) or indirectly as consequence of biodiversity loss because the latter is considered to be one of the major drivers of ecosystem change (Hooper et al. 2012). In this context, the issue of pollution inside PAs has a particular place in the fundamentals of conserving biodiversity.

Our central goal in this review was to answer the question: How well are Latin American PAs protected from chemical pollution? The challenges and opportunities to answer this question were discussed during the symposium "*Pollution in Latin American Protected Areas: Challenges and Opportunities in Protecting Biodiversity and Ecosystems*" (Society of Environmental Toxicology and Chemistry [SETAC] Latin America, Buenos Aires, Argentina, September 2015) organized by Ignacio A Rodríguez-Jorquera and Gurpal S Toor. Herein, we investigate the extent to which Latin American PAs may be affected by chemical pollution.

METHODOLOGY

To answer our question, we reviewed 2 databases, and we present 4 case studies as representative examples. The 2 reviewed databases were: 1) the World Conservation Monitoring Centre database (UNEP-WCMC 2014) to obtain PAs data in Latin America (Table 1), and 2) the Environmental Justice Organisations, Liabilities and Trade (EJOLT) database (Temper et al. 2015) to analyze the occurrence of contamination inside PAs (Supplemental Data Table S2). From Temper et al. (2015), we selected all cases categorized either under the category of "Establishment of reserves/national parks" or manually selecting cases when the words "Park/Parque," "Area," and "Reserve" were explicitly related to chemical contamination/pollution. The EJOLT database methodology gather cases that include at least 3 criteria: 1) economic activity or legislation that has negative environmental and social outcomes, 2) claims by environmental justice organizations and, 3) reporting of that particular conflict in 1 or more media stories. For more details on the methodology, refer to Temper et al. (2015). Finally, to exemplify how Latin American countries deal with chemical pollution issues inside PAs, we described 4 prominent cases from 4 countries (case studies) to provide a more detailed description. Prominent case studies from Mexico, Brazil, Argentina, and Chile (Figure 1) were selected as they are home to more than half of the people in Latin America (≈380 million, Table 1) and represent 4 of the most important economies in the region.

RESULTS AND DISCUSSION

Of the 520 cases reported in EJOLT for Latin America, 119 cases occurred inside or directly affect PAs (Table S2). These cases included the occurrence of chemical pollution and/or contamination from 16 Latin American countries PAs (Figure 2). Colombia has the most cases of chemical pollution and contamination inside PAs, followed by Ecuador (Figure 2). We divided the sources of chemical pollution into 8 categories (Figure 3). The main sources of chemical pollution in Latin American PAs were mining, oil, and gas extraction projects (Figure 3). There were cases that included several PAs in a region and transboundary impacts were common in extraction projects located in marine environments. For instance, an oil extraction project proposed within the Mesoamerican Reef System (Sistema Arrecifal Mesoamericano) may affect 14 PAs in Mexico, Belize, Guatemala, and Honduras, which reinforces the importance of including transboundary monitoring efforts. Our results included several cases where the pollution source was either "stopped" or is a "proposed" project. The rationale behind this was the fact that for most of the sources of chemical contaminants observed (i.e., mining), legacy contamination is very likely to occur even after the source had been stopped. For the cases that are "proposed," we assumed that a considerable portion of those cases would become an "ongoing" project in the short term because they are within the evaluation phase of the environmental impact.

The potential impacts related to nontraditional extraction projects such as Li mining (batteries) and Coltan (electronic devices) extraction are interesting cases, because these sources of pollution are new types in Latin America with stringent environmental regulation and new challenges in terms of chemical pollution types. Puerto Rico was a rare case because it had just one reported case of chemical pollution in PAs, which was related to military activities. The impact of tourism and aquaculture were reported in several countries inside PAs (Figure 2).

Here, we review 4 prominent case studies across Latin America PAs.

CASE STUDY 1

Mexico: Contaminant impacts in Lake Chapala

The Lerma-Chapala watershed has over 10% of Mexico's human population and is located within one of the most chemically contaminated regions in Mexico. Wastewater from industrial, agricultural, urban, and animal farm sources is discharged into the Lerma River without treatment (Toledo et al. 2009). The Lerma River delivers the wastewater directly into Lake Chapala, which is a major fishery for local communities and a recreation resource for national tourists. Lake Chapala was declared a RAMSAR site in 2011, when it was recognized as one of the most important wetlands in

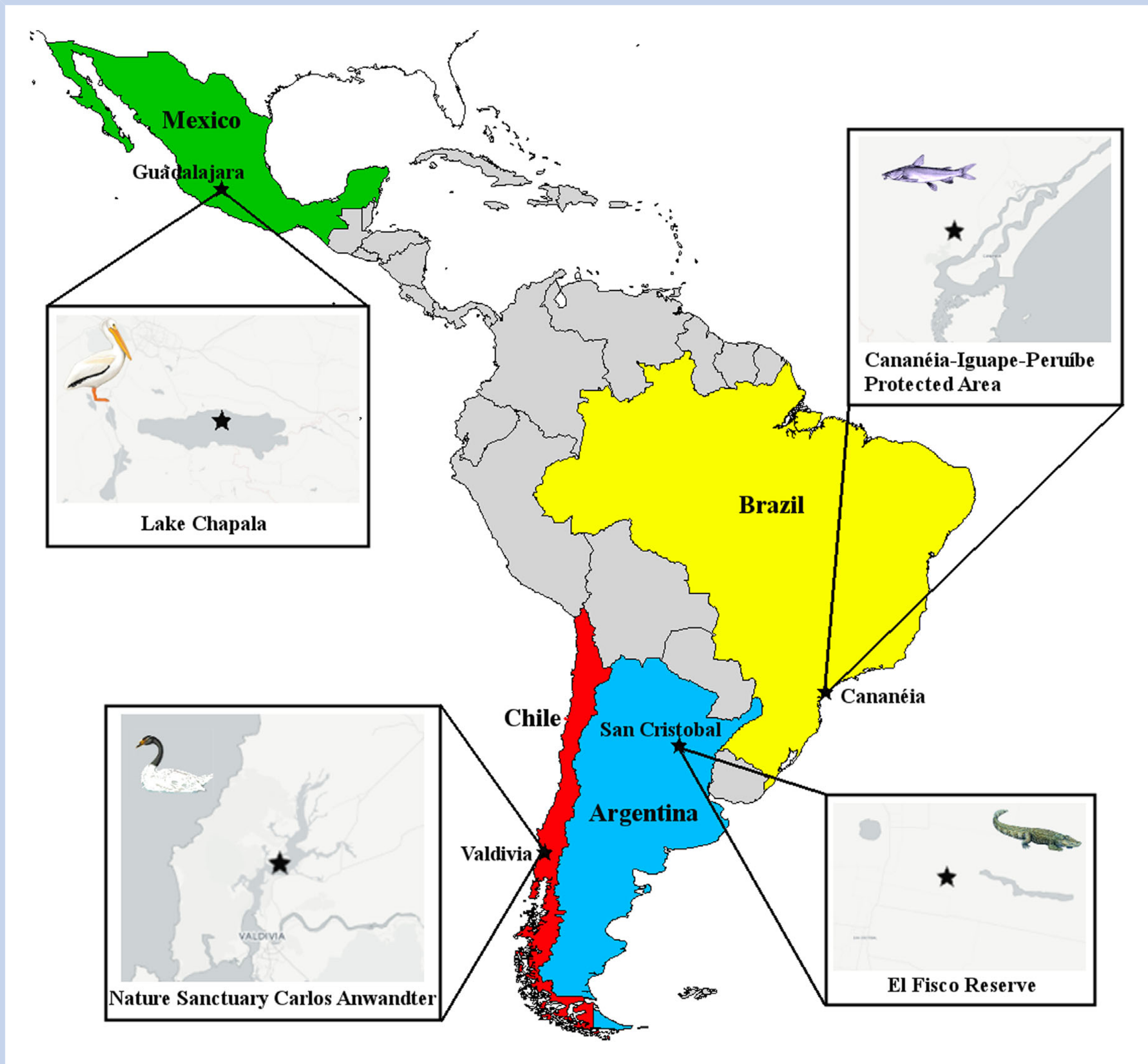

Figure 1. The 4 case study sites and main affected species in Latin America.

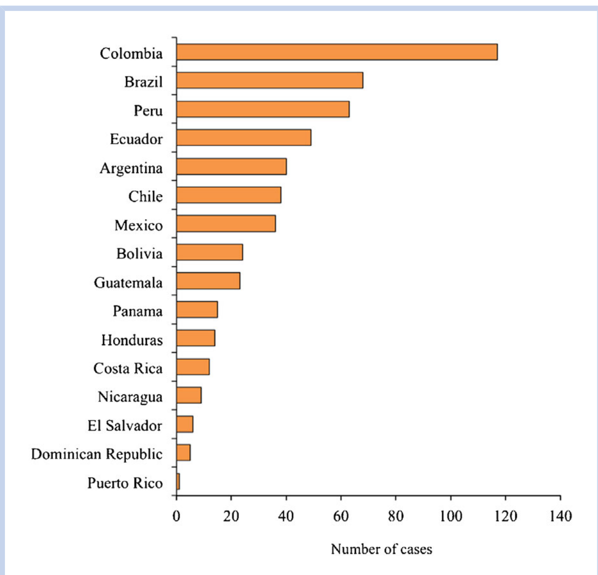

Figure 2. Number of cases of chemical pollution and contamination by country in Latin American protected areas.

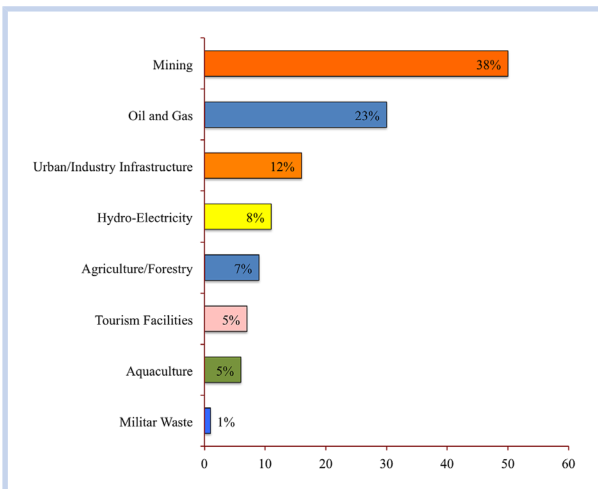

Figure 3. Number of cases by sources of chemical pollution and contamination in Latin America. Percentage from the total of reported cases are depicted inside the bars.

Mexico (http://www.cemda.org.mx/artman2/publish/biodiversidad_64/). More than 80 species of aquatic birds have been reported in Lake Chapala, which is one of the largest wintering areas for American white pelicans (*Pelecanus erythrorhynchos*).

For several decades, it has been a common belief that Lake Chapala is highly polluted as consequence of contamination emanating from the Lerma River, municipal discharges around the lake, and aerial deposition of contaminants generated by the city of Guadalajara. Contaminant studies in the lake have primarily included the occurrence of metals in water, sediments, and fish; however, there are limited studies of contaminants in wildlife. Studies conducted in the 1990s reported elevated concentrations of trace metals (Cr, Ni, and Cu) in sediments (Hansen and van Afferden 2004, 2012). Ford et al. (2000) observed seasonal variability in the concentrations of metals in the water, with increases during the dry season (likely due to evaporation) and decreases during the rainy season (likely due to dilution). During the rainy season, there is also an influx of contaminants from the Lerma River. Elevated concentrations of Hg in charal fish (*Chirostoma* sp.) from Lake Chapala (Ford et al. 2000) pose potential risks to human health through dietary intake (Jay and Ford 2001). Thus, the focus of research has generally been on Hg contamination in fish (Trasande et al. 2010; Stong et al. 2013; Torres et al. 2014), but the potential impact of Hg contamination in Lake Chapala on American white pelicans and other aquatic birds has not been well assessed (Torres et al. 2014).

Deposition of airborne contaminants (including transboundary contamination) has been suspected to occur in Lake Chapala. The North American Agreement on Environmental Cooperation was established in 1994 with the purpose of promoting environmental cooperation among Canada, the United States, and Mexico (CEC 1997). An Expert Advisory Panel emphasized the need for collaboration in ecological research and monitoring of terrestrial and aquatic ecosystems in the 3 countries. The Panel emphasized that understanding the problem of transboundary pollution is essential and should be supported, and the presence of flame retardants in industrial and commercial products could have a "significant and adverse effect on the environment and human health" (CEC 2015). Evidently, research on the potential effects of known contaminants and the determination of the occurrence of emerging pollutants is needed in Lake Chapala.

CASE STUDY 2

Brazil: A biosphere reserve threatened by former mining activities and urban settlements

Cananéia-Iguape-Peruíbe Environmental Protected Area (APA-CIP), located in the Southeastern Brazil (Figure 1), is an estuarine lagoon ecosystem recognized by UNESCO as part of the Biosphere Reserve of the Atlantic Rainforest due to its international relevance to environmental conservation. Since 2000, the region has been part of the global list of UNESCO World Heritage Sites, in addition to being a priority area for a RAMSAR site (Brazil 2012).

The APA-CIP is a sensitive region exposed to contamination mainly from the Ribeira de Iguape River (Abessa et al. 2014; Gusso-Choueri et al. 2015, 2016), which flows into the estuarine lagoon within the PA. The Ribeira de Iguape river basin was, in the recent past, an important region of mining activities in Brazil. For decades, until the 1990s, tailings and metallurgical slags were directly dumped into the river, where they remain subject to leaching and weathering (Guimarães and Sígolo 2008; Abessa et al. 2014). Before mining activities ceased in 1995, approximately 89 000 m^3 of residues were deposited on the riverbanks, posing environmental risks to the river and the estuarine-lagoon environment (Abessa et al. 2014; Gusso-Choueri et al. 2015, 2016). Other sources of contaminants in the APA-CIP include wastewater disposal from 3 cities with inadequate sanitation infrastructure (Iguape, Ilha Comprida, and Cananéia), with a total estimated population of 51 900 inhabitants (IBGE 2014).

Elevated concentrations of metals (Pb, Zn, Cu, Cr) and metalloid (As) in the waters, bottom, and suspended sediments of the Ribeira de Iguape River have been related to mining activities at the river headwaters (Guimarães and Sígolo 2008; Abessa et al. 2014). In the estuarine lagoon of the APA-CIP, de Mahiques et al. (2013) assessed the historical record of 150 years of metals input and found that the concentrations of metals (especially Pb) in sediments increased after the construction of an artificial navigational channel (the "Valo Grande" Channel) connecting the Ribeira de Iguape river to the estuarine lagoon. This study also reported that the most critical period of metal input occurred between the 1940s and the 1990s, the period of most intensive mining operations, with consequent contamination of the estuarine lagoon sediments (de Mahiques et al. 2013; Cruz et al. 2014; Tramonte et al. 2015).

The lack of a sanitary infrastructure for the city of Cananéia has also contributed to the input of contaminants to APA-CIP (Cruz et al. 2014; Gusso-Choueri et al. 2015, 2016). The Metals (Cd, Cu, Fe) and total recoverable oils and greases have been associated with chronic toxicity to marine copepods (*Nitokra* sp.), and Zn has been associated with acute toxicity to the burrowing amphipod *Tiburonella viscana* (Cruz et al. 2014). Recent studies focused on the biota have shown toxicological effects (oxidative stress, neurotoxicity, and genotoxicity) associated with bioaccumulated metals in resident catfish (*Cathorops spixii*) along the APA-CIP. In some instances, metal and As loads in catfish muscle tissue exceeded levels safe for human consumption (Gusso-Choueri et al. 2015, 2016).

The APA-CIP was established as a PA of Sustainable Use, and the subcategory of "Environmental Protected Area" (in Portuguese, Área de Proteção Ambiental, or, as it is better known in Brazil, "APA"). APA is the less restrictive category among all categories in the Brazil National System of Protected Areas. This subcategory of PA is in general, an extensive area with some degree of human occupation, which may encompass other PAs, urban ecosystems, agricultural land, and zones for wildlife protection, with the aim of conciliation of land use with the maintenance of essential ecological processes. The APA-CIP is inserted into the extensive network of PAs of the coastal zone of the State of São Paulo, which together makes a large ecological corridor, encompassing terrestrial, marine, and estuarine areas.

Despite the substantial differences in ecosystems processes, historical perceptions, and regulatory frameworks between marine and terrestrial environments, marine PAs (including estuarine PAs) are usually planned, created, and managed following the same concepts and theories of terrestrial PAs (Houde 1982). Marine ecosystems are highly dependent on or influenced by a broader landscape and seascape, not only because marine organisms can travel long distances to settle, spawn, feed, or nurse (Lee 1983), but also because coastal waters receive inputs from rivers that, in some instances, flow across large drainage basins, and therefore transport nutrients and contaminants to coastal ecosystems. Consequently, contaminants may be introduced into marine PAs from adjacent areas (Perra et al. 2011), which is an important issue in the APA-CIP.

The other issue concerning pollution in the APA-CIP involves the establishment of CIP into the category of APA. Because this is the least restrictive category, poor public policies usually aim to stimulate economic development in these areas through the use of natural resources to the detriment of environmental conservation (Padua 2001).

Community engagement associated with environmental enforcement and environmental monitoring are key factors for a successful management regime in marine PAs (Pomeroy and Douvere 2008). Unfortunately, conflicts involving local communities that are unsatisfied with the management plan of the APA-CIP have long been reported (Diegues 1986) and effective enforcement is poor due to the few economic resources destined to PAs. Environmental monitoring in marine PAs (including the APA-CIP) usually ignores the issue of chemical pollution, especially effects on the biota. Most biological assessments carried out in marine PAs only consider direct or indirect effects of fishing on the biota (Fraschetti et al. 2002). Studies in marine PAs regarding contamination usually focus on measuring contaminant concentrations in environmental matrices such as water, sediments, and organisms (Perra et al. 2011), rather than the effects of contaminants on the biota to be protected (Cruz et al. 2014). In PAs like the APA-CIP, where contamination is acknowledged as an important issue for environmental management, monitoring effects on the biota, in addition to measuring chemical contaminants, would provide important information on the environmental risks and the effectiveness of environmental protection.

CASE STUDY 3

Argentina: The soybean rush and its potential impact on reptiles

Argentina's soybean sector emerged in the early 1970s due to a strong natural comparative advantage over other cereals production. A significant portion of the pesticides applied to these crops, mainly from November to March, dissipates into the environment by drift, runoff, and leaching, and thus affects wild flora and fauna populations in the surrounding PAs (Peruzzo et al. 2008).

As a result of the expansion of the agricultural frontier, many areas where caimans and lizards inhabit, particularly broad snouted caiman (*Caiman latirostris*) and tegu lizards (*Salvator merianae*), are being exposed to contaminants such as pesticides. Female caiman build nests near water bodies and female tegu lizards dig holes under roots adjacent to crops. PAs located near and/or downstream of agricultural activities indirectly receive pesticides. Meanwhile, the soybean rush continues its expansion toward other natural ecosystems including PAs.

The natural reserve "El Fisco" (Figure 1), located in Santa Fe Province, Argentina, is a PA free of farming and urban activity where C. *latirostris* and S. *merianae* eggs were collected as part of management and research programs performed by the Yacaré Project and Iguana Project (ICiVet-UNL-CONICET). They assessed the effects of pesticides released into the environment (Siroski et al. 2016) as the period of maximum pesticide application coincides with the breeding season (November–March) of these species, which poses a serious contamination risk for developing embryos and neonates (Poletta et al. 2011). For example, in ovo and in vivo exposures of C. *latirostris* and S. *merianae* to pesticide mixtures at environmentally relevant concentrations induced detrimental effects such as genotoxicity, immunological, enzymatic, developmental, and metabolic alterations (Poletta et al. 2011; Schaumburg et al. 2012; Siroski et al. 2016). They also showed detrimental effects on postnatal caiman growth and lower relative weight (Beldomenico et al. 2007; Poletta et al. 2011). The alterations found in enzymatic and metabolic systems mainly at birth and 3 months after hatching were no longer observed at 12 months old (Poletta et al. 2011), revealing the relevance of the timing of exposure to pesticides to these species.

Constant exposure of wild species to low concentrations of pesticides may not cause acute detectable effects in organisms but may induce genetic disorders and physiological alterations and, in the long term, reduce their fitness. Even when direct pesticide spray over caiman nests is not a common situation, neighboring cropland habitats receive continuous exposure to low concentration of pesticides that could have cumulative deleterious effects on animals. The moment of maximal pesticide application (November–March) coincides with the incubation period and hatching of caimans and lizards; thus, these species suffer repeated pesticide exposures as embryos and neonates. These reptiles can receive new successive exposures at 8 to 12 months of age, which coincides with the extensive fumigations due to the second soybean harvesting (Paruelo et al. 2006).

The reptiles are opportunistic carnivores (caimans) and omnivores (lizards); the local inhabitants consider them charismatic species, and they have a strong presence in the regional economy and culture. Thus, these species could play the role of flagship species in local ecosystems, whose viability guarantees the whole system's conservation. Consequently, conducting studies on the effects of pesticide exposure in caimans and lizards is of particular interest, particularly because these and other reptiles face a multitude of challenges when exposed to chemicals in the environment and have been poorly studied in ecotoxicology (Hopkins 2000).

CASE STUDY 4

Chile: Black-necked swans and a pulp mill

In 2004, a significant decline in the abundance of the black-necked swan, *Cygnus melancoryphus*, occurred in the Cruces River-Carlos Anwandter Nature Sanctuary located in Valdivia, Chile (Figure 1). This sanctuary is a wetland designated in 1981 as a RAMSAR site and considered the main reproductive site for black-necked swans globally (Schlatter et al. 2002). A pulp mill was built 15 km upstream of this PA and began operations 4 months before the decline of the swans (Muñoz-Pedreros 2005). The mortality (and emigration) of the swans concurrently with pulp mill operations rapidly became a nationally prominent environmental conflict in Chile.

The population of black-necked swans decreased from 8000 individuals in April 2004 to approximately 400 individuals in June 2006. Some 50 swans were found dead during 2004 for unknown causes (collisions and shot birds were not considered in this count); they were emaciated, with a low content of plant material in their stomachs and with Fe-specific stained spots in their liver cells (Jaramillo et al. 2007). The surviving swans inhabiting the wetland had a body mass reduction of 30% ($n = 122$), with blood chemistry parameters indicating malnutrition (Artacho et al. 2007a). These effects were correlated with the disappearance of the swans' primary food source, the Brazilian seaweed *Egeria densa* (Jaramillo et al. 2007). The cause of the seaweed die-off was determined to be Fe contamination (Pinochet et al. 2004), resulting in emigration and death of the swans due to malnutrition (Artacho et al. 2007a, 2007b).

The above events challenged the system of environmental impact assessment in Chile. Leading experts from academia, government, nongovernment organizations (NGOs), and the pulp mill industry were actively involved in resolving this issue, which clearly affected the environment, economy, and welfare of the region. In Chile, the denomination of Natural Sanctuary is among the types of official PAs in the national systems of PAs. Notably, this sanctuary was the first Chilean RAMSAR site designated because it was a high abundance-nesting site for black-necked swans. In 2013, the Chilean National Council sued the pulp mill and mandated to mitigate the damage (evoking Environment Law No. 19.300) by creating 5 alleviation steps: assessing the current state of the wetland, creating an artificial sentinel wetland, constant wetland monitoring, creation of a wetland research center, and creation of a community development program (http://www.humedalriocruces.cl/).

Chilean PAs coverage is nearly 22% of the nation yet the system is still underrepresented in the most heavily used zone (Central Chile) and in land-marine transition environments (Squeo et al. 2012). The land–marine transition environment is anticipated to have one of the greatest loads of chemical contamination due to the transport of contaminants in water from upstream sites and the direct contamination load from marine activities near the coast. This enhances the need for improved assessments of chemical contaminant effects on biodiversity especially regarding PAs attributes.

The swans and pulp mill issue promoted a relevant discussion about the role of Chilean environmental policies and regulations (Jaramillo et al. 2007). It also caused an examination of the performance of institutions in charge of environmental protection in Chile (Sepúlveda and Villarroel 2012), which authorized the pulp mill to discharge its effluent despite uncertainties regarding the potential impacts.

OPPORTUNITIES AND CHALLENGES

Our database review and case studies showed that Latin American PAs are not protected from either the occurrence or the deleterious effects of chemical pollution. These effects have the potential to affect individuals and populations initially regarded as protected. The bulk of chemical pollution and contamination cases inside PAs came from mining and hydrocarbon extraction but not from food production projects (agriculture or aquaculture). Most of the recent debate about the effectiveness of conservation strategies is based on agricultural production. For example, substantial arguments have been stated about the opposing biodiversity conservation strategies such as land sharing (integration of conservation and production) or land sparing (separation of conservation and production) (Green et al. 2005; Fischer et al. 2014). Unfortunately, the mobilization of significant levels of contaminants through the air or carried by water make the debate about land sharing and land sparing artificial, because apparently PAs located near the major commodities production projects, cities, or intense agricultural areas are not going to be free of pollution effects. Thus, diminution of pollution and contamination at the source appear to be the most logical step to deal with pollution inside PAs.

Despite that this analysis may represent the largest data set of chemical pollution and contamination cases inside PAs, it is not comprehensive. It is clear that not all cases of chemical pollution inside PAs are reported. For example, one of our case studies (Brazil) was not reported in EJLOT. We expect that in the near future this database will expand so we can better assess this issue. In terms of types of ecosystems affected, at least 42 of the cases of chemical pollution or contamination occurred in PAs where wetlands were the main protection subject. Others cases of reported pollution or contamination occurred on wetlands but were located in PAs where wetlands were not the main conservation subject.

Our selected case studies, represented sources of contaminants categories such as urban or industry infrastructure, mineral mining, and agriculture or forestry. A common factor among 3 of the 4 case studies (except for Argentina) is the fact that chemical contamination issues in the PAs were focused on metals. Other compounds, such as emerging contaminants (i.e., perfluoroalkyl substances, pharmaceuticals, and personal care products) were not measured. Moreover, half of the case studies showed an absence of pollution effects assessment. In the Chile case study, mitigation activities have been developed. Nevertheless, this is an exceptional case due to the high public visibility given a reduction of approximately equal to 95% of the charismatic swan population in the PA. Previously, pollution has been considered in recommendations for mitigation of acid rain effects in PAs in Europe (Phillips 1994), and work has been conducted to assess light pollution effects on PAs (Aubrecht et al. 2010). Pollution is mentioned in reports and scientific articles related to biodiversity conservation inside PAs, however, in-depth assessments to understand impacts on biodiversity were not a major focus of these documents in Latin America or globally.

Assessment of the relative impact of chemical pollution on biodiversity is a requisite to better assess the impact of this issue. For instance, Burkhead (2012) estimated that chemical pollution accounted for 17% of the fish extinctions in North America. Nonetheless, there is no estimation of the relative impact of chemical pollution on biodiversity in Latin American PAs. Latin American countries with less land area have fewer PAs, highest human density, and the highest impact on biodiversity loss (Table 1). These factors increase pressure on biodiversity and ecosystems and therefore challenge the PAs idea in protecting natural resources such as freshwater wetlands, land–marine transitional environments (estuaries and coastal wetlands), and marine environments. Generally, chemical pollution is only mentioned and implicitly recognized in PAs when the impact on biodiversity (including population declines) is clearly evident, as was the case with the black-necked swans. This reactive approach needs to be changed to a monitoring approach where fate, transport, and toxicity of chemical contaminants are considered. Clearly, there is a pressing need to develop explicit programs to assess the current extent of chemical pollution in PAs neighboring large urban areas or areas with agricultural, industrial, and aquaculture production.

Aquatic environments might be the most threatened habitats within PAs in Latin America as shown in these case studies. Because wetlands sustain biodiversity and provide essential ecosystem services (Zedler and Kercher 2005), they have become PAs. However, if wetland PAs do not address explicitly water pollution as a concern by monitoring chemical contaminant concentrations and effects in the aquatic environment, one of the most basic ecosystem services (the provision of clean water) will be lost. Research and monitoring must go beyond the mere identification of contaminants. They must predict the impact of chemical pollution at population and/or ecosystem levels of biological organization for informed management of PAs.

Chemical contaminants reach PAs from multiple direct and indirect sources, including water and air. Assessment and, where necessary, mitigation, will not be easy and will require much larger efforts than have been undertaken to date. For example, in the case study from Lake Chapala (Mexico), an international agreement pursuing environmental cooperation among Canada, the United States, and Mexico highlighted the necessity to assess transboundary pollution. This may be generally necessary for all PAs. Nevertheless, the situation of the RAMSAR sites reviewed here indicated that international agreements do not necessarily improve the PAs outcomes with regard to pollution. Two of the 4 case studies examined here are RAMSAR sites, a PA denomination based on an international agreement between contracting parties to protect wetlands of global importance. Frazier (1999) determined early on that for RAMSAR sites in the Neotropical ecozone (a region that essentially included all Latin American countries), pollution was the most commonly reported factor of change affecting the ecological character of these wetlands. This emphasized the vulnerability of aquatic environments due to chemical pollution and demonstrates that this is a widespread issue in the region.

The effects of chemical pollution in Latin American PAs challenge their effectiveness to protect biodiversity and ecosystems functionality. Public calls for action (e.g., the black-necked swans in the Chilean case study) resulted in a reactive management of the problem. However, reactive management is inadequate and inefficient; by contrast there is a clear and pressing need for more proactive approaches. Collaboration among ecotoxicologists and protected area managers is crucial for understanding contaminants effects on PAs performance. Specifically, we recommend that for all PAs that there is an initial assessment of potential sources of specific chemical contaminants that are not restricted to metals. This should be followed by site-specific assessment and monitoring of chemical contaminants of potential concern in appropriate environmental matrices (water, sediment, tissue) along with biological effects assessments. Only by collecting appropriate and necessary information can informed management decisions be made to proactively protect the biodiversity and function of Latin American (and other) PAs.

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SUPPLEMENTAL DATA

Table S1. Review of the status of the main sources of chemical pollution in protected areas in Latin America

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