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Urban health and ecology: the promise of an avian biomonitoring tool

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Abstract

Urban-dwelling birds have the potential to serve as powerful biomonitors that reveal the impact of environmental change due to urbanization. Specifically, urban bird populations can be used to survey cities for factors that may pose both public and wildlife health concerns. Here, we review evidence supporting the use of avian biomonitors to identify threats associated with urbanization, including bioaccumulation of toxicants and the dysregulation of behavior and physiology by related stressors. In addition, we consider the use of birds to examine how factors in the urban environment can impact immunity against communicable pathogens. By studying the behavior, physiology, and ecology of urban bird populations, we can elucidate not only how avian populations are responding to environmental change, but also how unintended consequences of urbanization affect the well-being of human and non-human inhabitants.

Key words: avian biomonitor, pollutant bioaccumulation, urban ecology, zoonotic disease.

Introduction

Urbanization is expanding worldwide, with over 50% of humans now inhabiting urban areas (United Nations 2014). Pressing environmental concerns with significant health implications for both human and non-human species include overpopulation, disease transmission, and exposure to pollutants in air, water, and soil. One major challenge for urban ecologists is to determine how specific features of the urban environment influence the well-being of city-dwelling organisms, including humans (Pataki 2015). Because of their distribution, behavioral traits, and demonstrated responsiveness to factors associated with urbanization, bird species that commonly inhabit cities can help address this challenge by serving as biomonitors.

In general, biomonitors and bioindicators are species or ecological communities that respond in observable ways to anthropogenic disturbances (Gerhardt 2001), making them useful for either qualitative or quantitative assessments of environmental quality and threats. While "biomonitor" typically refers to the former function and "bioindicator" refers to the latter, we will use "biomonitor" to reference species used for both qualitative and quantitative measures for the sake of simplicity. In part, the use of biomonitors to assess ecosystem condition developed as a response to criticisms that laboratory toxicology studies poorly recapitulate the "real world" effects of pollution on free-living organisms, since individual toxicants in the environment act within a complex array of other chemicals, physical conditions (e.g., climate and food availability), and social conditions (Siddig et al. 2016). The potential for interaction among factors—which may manifest either as synergism or antagonism—raises the possibility that toxicants impact free-living organisms in ways that would be difficult to predict or interpret based solely on laboratory studies (e.g., Rohr and Crumrine 2005).

As a complement to laboratory investigations, studies involving free-living biomonitors can provide a more complete view of how anthropogenic disturbances threaten the health of species and their biological communities. For example, seabirds are commonly used to study the effects of environmental change on the structure and function of marine ecosystems (Piatt and Sydeman 2007). Amphibian population sizes, diversity, and health are sensitive to environmental change and used as benchmarks for evaluating the impacts of landscape restoration projects (Welsh and Ollivier 1998;

Hayes et al. 2002; Rosenblum et al. 2010). In addition, birds inhabiting urban environments (e.g., song sparrows, house sparrows, and rock pigeons) are used to gauge the prevalence of issues associated with urbanization and industrialization, such as widespread exposure to heavy metals (Roux and Marra 2007; Hoff Brait and Antoniosi Filho 2010; Albayrak and Mor 2011). Such studies support the use of biomonitors to reveal how factors associated with urbanization influence the health of ecosystems and individual species.

Urban species, which have adapted to using urban resources either as a complement or alternative to natural resources (Shochat et al. 2006), provide especially fruitful opportunities for uncovering widespread urbanization consequences that transcend species boundaries. In particular, urban birds are uniquely suited as biomonitors because they are ubiquitous and relatively easy to catch, sample, and observe. In addition, because urban species engage in a full assortment of behaviors in the presence of humans, including nesting on buildings and consuming human subsidies and waste, they can act as reasonable correlates of human exposure to urban pollutants (Chace and Walsh 2006; Kark et al. 2007). Widely distributed species may be used for inter-population comparisons that could reveal how habitat differences across an urbanization gradient influence behavioral and physiological traits (e.g., Fokidis and Deviche 2012; Foltz et al. 2015; Bailly et al. 2016). If these widely distributed species also have small home ranges, they can serve as representatives of micro-urban environments across multiple cities (allowing for replicates), which is an important consideration given that urban areas are a heterogeneous mixture of habitats (e.g., commercial vs. residential districts, green space vs. asphalt or concrete, etc.). For example, rock pigeons *Columbia livia* exhibit strong site fidelity to their birth sites, generally remaining in a small area (<2 km) for their entire lives (Sol and Senar 1995; Rose et al. 2006; Przybylska et al. 2012). This trait makes them useful for investigating the geographic spread of bioavailable toxicants with a high level of locational specificity (Frantz et al. 2012; Cai and Calisi 2016).

Because avian species richness decreases with increasing urbanization (Blair 1999; Melles et al. 2003; Sandström et al. 2006), entire avian communities can also serve as composite biomonitors that reveal the ecosystem-wide effects of urbanization. Specifically, undisturbed areas often have the greatest abundance and biomass of native bird species, while urban areas typically contain the greatest abundance of exotic and invasive bird species (Blair 1999). Monitoring bird species diversity and demographics could help assess the contribution of urban populations to conservation efforts and forecast avian diversity in an increasingly urbanized world (Chamberlain et al. 2009).

In the sections that follow, we review a selection of studies that demonstrate specific applications of avian biomonitors for understanding urbanization-associated threats to the health of humans and other wildlife. Furthermore, we present a framework to help guide the design of research that uses avian biomonitors to assess public health concerns in urban areas (Figure 1). Because urban-dwelling birds and humans are subjected to many of the same urban factors—including noise, light, and chemical pollution—birds can serve not only as proxies for human exposure, but as models for investigating the mechanisms underlying the effects of urbanization on health and behavioral changes. In addition, birds constitute important monitoring tools for zoonotic diseases, which are of particular concern in densely populated cities. Lastly, the use of avian biomonitors can provide insight into the influence of urbanization on animal behavior and physiology, as well as provide initiative and direction for parallel investigations in humans.

Using Avian Biomonitors to Detect and Monitor Pollutants

Assessing urban birds' exposure to pollutants, like heavy metals, can help predict relative levels of exposure of other animals to these compounds. Such a tool would be particularly useful for monitoring sublethal exposures, which may be too low to cause readily identifiable symptoms in humans and wildlife. For instance, heavy metal pollution has adverse effects on human health, even at low levels of bioaccumulation, and may linger in the environment long after original deposition (Järup 2003; Roux and Marra 2007; Tchounwou et al. 2012). Lead from gasoline can persist in soils near roads, long after bans are instituted, creating a legacy of contamination that is detectable decades later (Roux and Marra 2007). In addition to serving as an informant of contamination legacies, urban birds could be used to assess regional differences in levels of heavy metal pollution within developing cities and neighborhoods, where bans may not be in place or well-enforced. These assessments could reveal health risks present within particular areas and inform public health approaches to controlling exposure for humans and urban wildlife.

Urban bird species have been used to monitor heavy metal pollution—including levels and effects of lead, cadmium, chromium, selenium, zinc, and mercury. In general, heavy metal concentrations observed in wild avian populations increase with urbanization or pollution gradients (Schilderman et al. 1997; Hoff Brait and Antoniosi Filho 2010; Albayrak and Mor 2011; Bichet et al. 2013; Meillère et al. 2016; but see Burger et al. 2004). Blood lead levels in feral pigeons are positively correlated with traffic gradients in Amsterdam, suggesting that urban birds could be used to monitor the relationship between leaded gas in car exhaust and toxicity levels in urban neighborhoods (Schilderman et al. 1997). Similarly, feral pigeons sampled in a developed area of Brazil have significantly greater levels of cadmium, lead, and chromium compared with a population from rural regions (Hoff Brait and Antoniosi Filho 2010). The relevance of these findings for human health is underscored by a recent report that, in New York City, changes in the blood lead levels of rock pigeons track changes in the blood lead levels of children across neighborhoods (Cai and Calisi 2016). These examples demonstrate how urban-dwelling birds can be used to link urban areas with environmental contamination, particularly at a local or neighborhood scale.

Heavy metals may have differential patterns of bioaccumulation across tissue types, which may cause greater damage to certain physiological systems (Doumouchtsis et al. 2009; Salamat et al. 2014). Thus, validation of a wide variety of sampling techniques—many of them minimally invasive—to measure trace metals across avian tissues and developmental stages highlights the utility of birds as biomonitors. Methods include measuring heavy metal concentrations in tissue samples, feathers, small amounts of blood, and eggs (Hutton and Goodman 1980; Dauwe et al. 2005; Hoff Brait and Antoniosi Filho 2010; Coeurdassier et al. 2012). Blood can provide reliable information about trace metal exposure occurring within a few weeks of sampling, thereby reflecting transient or seasonal exposure, while bones and feathers can be used to show the accumulation of trace metals over a greater period of time (e.g., Hutton and Goodman 1980; Bianchi et al. 2008; Kerr et al. 2010). In addition, external contamination has been measured by comparing lead concentrations in washed versus unwashed outermost tail feathers (Scheifler et al. 2006). Furthermore, both cadmium and lead concentrations measured in the erythrocytes of Eurasian blackbirds *Turdus merula* can accurately estimate circulating levels, demonstrating that

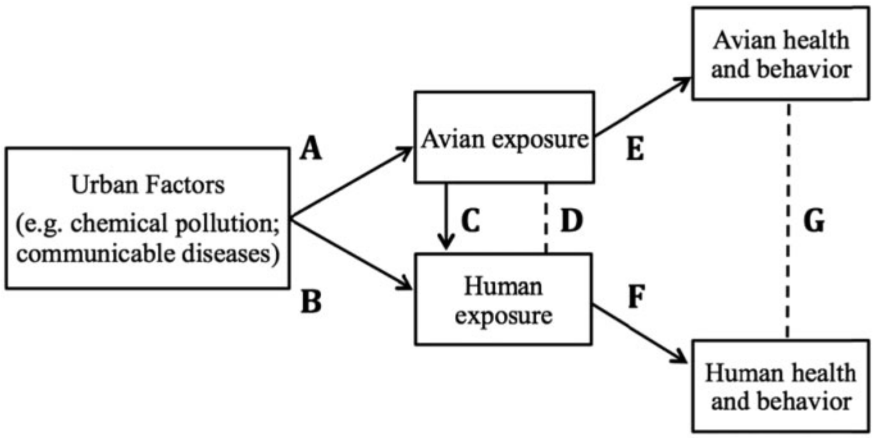

Figure 1. Flowchart representing the use of avian biomonitors to examine the effects of urban factors on health and behavior in humans.
Humans and birds in urban habitats are exposed to many of the same potential threats, such as chemical pollution and disease-causing pathogens (arrows A and B), which in turn can have effects on health and behavior (arrows E and F). By measuring toxicant bioaccumulation in urban birds, researchers can use these species as biomonitors for toxicant exposure risk in human populations (dashed line D). Because of their potential status as reservoirs and vectors for zoonotic diseases, monitoring pathogen loads and disease incidence in urban birds can inform our understanding of human disease risk (arrow C). Finally, the use of avian biomonitors may provide insight into the influence of urbanization on wildlife behavior and physiology, as well as provide initiative and direction for parallel investigations in humans (dashed line G).

very small blood samples are sufficient to measure these metals (Coeurdassier et al. 2012). Portable blood analyzers have also been used to measure lead concentrations in blood within natural populations, which allows for immediate in-field assessment (Brown et al. 2006).

Like heavy metals, many flame retardants present significant health risks to both wildlife and humans, and growing concerns about their biological activity have prompted investigations of how these chemicals bioaccumulate in wild bird populations (Birnbaum and Staskal 2004; Covaci et al. 2006; Chen and Hale 2010; Dodson et al. 2012). Flame retardants of particular concern include polybrominated diphenyl ethers (PBDEs), hexabromocyclododecanes (HBCDs), and organophosphate flame retardants (PFRs). These compounds are associated with toxicity and deleterious health effects in humans and non-human species, and have been measured in a variety of bird tissues, as well as feathers and eggs (Marteinson et al. 2011, 2012; Baron et al. 2014; Eulaers et al. 2014a, 2014b; Sun et al. 2014). Body feather concentrations constitute a reliable predictor of both internal PBDE and HBCD burden in barn owls *Tyto alba* (Eulaers et al. 2014b). In white-tailed eagles *Haliaeetus albicilla*, feather concentrations of PFR are similar to atmospheric concentrations, indicating that PFR deposition on feathers could be a useful way to monitor relative atmospheric levels of flame retardants (Eulaers et al. 2014a). Researchers have also used concentrations of flame retardants in both feathers and eggs to document the consequences of a recent government-mandated decrease in PBDE use and the subsequent increase in HBCD use, an effort that has demonstrated the long-term persistence of both chemical types in the biome (Baron et al. 2014; Eulaers et al. 2014b). By measuring the bioaccumulation of these chemicals, researchers reveal not only the toxic burden within individual birds, but also the patterns of accumulation and persistence in the local environment as a whole (Covaci et al. 2006; Chen and Hale 2010).

Because of their sensitivity to both heavy metals and flame retardants, birds are useful for examining mechanisms underlying the physiological and behavioral consequences of real-world toxicant exposure. For instance, sublethal lead exposure in wild white storks *Ciconia ciconia* alters their adrenocortical stress response, suggesting that heavy metal toxicity could have far-reaching consequences on behavior and metabolic processes regulated by the hypothalamic–pituitary–adrenal axis (Baos et al. 2006). A study of urbanization and lead in South Korea revealed that young rock pigeons living in more polluted regions display lower growth rates and lower fledging success, suggesting that lead bioaccumulation has a negative effect on breeding success in this urban species (Nam and Lee 2006). Similarly, sublethal exposure to flame retardants affects avian health and behavior. For example, exposure to HBCDs alters mating behavior in both male and female captive American kestrels *Falco sparverius*; furthermore, females show a reduction in egg size, while males display smaller testes and lower circulating testosterone levels (Marteinson et al. 2011, 2012). In addition, kestrels exposed to environmentally relevant levels of PBDEs display altered thyroid and retinol concentrations, hepatic oxidative stress, and marginal lipid peroxidation, indicating that the accumulation of these toxicants in wild birds has the potential to disrupt normal physiological processes (Fernie et al. 2005). Such findings demonstrate the damaging effects of flame retardants on avian physiology, as well as provide general insights into how these toxicants may influence the health of species living in the same environment.

Using Avian Biomonitors to Detect and Track Disease-Causing Pathogens

Transmission of disease-causing pathogens can, in some cases, increase in urban adapted wildlife (Becker et al. 2015; Bradley and Altizer 2007), a trend that may contribute to higher incidences of inter- and intraspecies transmission of pathogens in urban areas compared with undeveloped regions. For example, the prevalence and severity of poxvirus and coccidian infections in house finches *Haemorhous mexicanus* is associated with the degree of urbanization, such that infection rates are higher in urbanized areas (Giraudeau et al. 2014). Increased population density in urban habitats may drive these elevated infection rates, though other urban-related variables may also negatively influence immunity. Because wild birds are capable of transmitting pathogens to humans, monitoring avian populations is of critical importance for evaluating their role as vectors for zoonotic diseases (Halliday et al. 2012).

Urbanization has been linked to outbreaks of several different zoonotic viruses, including West Nile Virus (WNV) and avian influenza (H5N1; Olsen et al. 2006). For instance, in the northeastern United States the incidence of human infection with WNV, transmitted between its avian hosts and humans via a mosquito vector, correlates with urban land use. This finding persists even after controlling for human population density, indicating that factors in the urban landscape enhance zoonotic transmission at a regional scale (Andreadis et al. 2001; Petersen and Roehrig 2001; Brown et al. 2008; Neiderud 2015). Similarly, in the American northeast, WNV-positive crow carcasses are more prevalent in highly developed regions when compared with less developed areas (DeCarlo et al. 2011). These studies suggest a potential association between WNV disease prevalence and factors associated with urban environments. Wild birds may also act as reservoirs for viruses, such as H5N1, thereby extending the time that these pathogens persist in the environment and increasing the possibility of transmission to other birds that humans commonly encounter (e.g., via domesticated poultry; Olsen et al. 2006).

Reports such as those previously mentioned underscore the importance of identifying urban-specific factors that impact disease-causing pathogen prevalence. The immunocompromising effects of chemical pollutants, which may make urban birds more susceptible to pathogen infections, constitute one such factor. For instance, trace metal concentrations are positively correlated with oxidative stress in rock pigeons (Gasparini et al. 2014), and lead concentrations are associated with higher plasmodium prevalence in house sparrows *Passer domesticus* (Bichet et al. 2013). Furthermore, a correlation between high levels of lead and *Chlamydophila psittaci* infection in feral pigeons collected in Paris, France suggests that trace metal pollution in urban areas may modify host–parasite interactions by impairing some facet of the immune response (Gasparini et al. 2014).

Like environmental toxicants, inadequate nutrition could increase the susceptibility of urban birds to disease-causing pathogens by limiting metabolic investment in immune responses to infections. The widespread availability of calorically rich, but nutrient-poor food sources in cities may in part underlie reports that urban birds, despite their abundance, often display poorer body condition relative to their rural conspecifics (Shochat 2004; Liker et al. 2008; Heiss et al. 2009; Meillère et al. 2015). For example, nutritionally poor food may restrict fat deposition and overall growth in juvenile house sparrows, resulting in smaller adult body size in urban versus rural birds and potentially long-term life-history consequences for urban-reared sparrows (Meillère et al. 2015).

Although low food quality may prime individuals for infection, high population densities may set the stage for inter- and intra-species transmission of disease-causing pathogens and establish avian reservoirs for zoonotic pathogens (Becker et al. 2015). The presence of reservoirs could increase the time that microorganisms persist in urban environments, allowing for the evolution of enhanced pathogenicity (Morse et al. 2012). In addition, seasonal migrations with stopover points in or near cities create opportunities for the introduction of pathogens into densely populated urban areas. For example, the presence of disease-carrying neotropical ticks on migratory and residential birds in urban areas indicates that avian movement may contribute to the introduction and transmission of high-risk pathogens (Hamer et al. 2012). Furthermore, in growing urban areas, where the built environment pushes into previously untouched habitat, city inhabitants may have more frequent encounters with wildlife and their pathogens, some of which may cause novel zoonoses (Neiderud 2015). Since pandemic zoonoses are one of the most significant growing threats to global public health, understanding the ecological systems surrounding their emergence is of great consequence (Jones et al. 2008; Morse et al. 2012).

Several approaches may prove useful for combatting the spread of pathogens in densely populated areas. For example, human infection rates may be correlated with the proximity between human establishments and clusters of dead birds (Johnson et al. 2006). Thus, simple surveys of inter-individual proximity, both among birds and between humans and birds, could be employed for predicting the incidence of infection and potential micro-urban sites of pathogen transfer. In addition to assessing inter-individual proximity, regular monitoring of the microorganisms that urban birds carry can help survey disease prevalence and aid predictions of infection risk for other species (Halliday et al. 2012; Phan et al. 2013). Pathogen monitoring is particularly important in cities, as high population densities of urban wildlife may enhance conditions for inter- and intraspecies pathogen transfer (Plowright et al. 2011; Morse et al. 2012; Becker et al. 2015; Neiderud 2015). This concern is especially salient for growing cities in developing nations, where human overcrowding, insufficient sanitation, and overburdened infrastructure can contribute to the proliferation of disease vectors (Macpherson 2005; Neiderud 2015).

Using Avian Biomonitors to Understand the Behavioral and Physiological Implications of Urbanization

Inter-population comparisons have revealed striking differences in the behavior and physiology of birds living in rural versus urban environments (Partecke et al. 2004; Atwell et al. 2012; Costantini et al. 2014; Foltz et al. 2015; Isaksson 2015). For example, in male song sparrows *Melospiza melodia*, territorial aggression is greater in urban areas and increased by food supplementation, suggesting that higher resource availability in urban environments may promote aggressive behavior in this species (Foltz et al. 2015). The potential for urbanization to yield heritable differences in behavior is underscored by common garden experiments, which demonstrate that birds collected from urban and rural sites display dissimilar behavioral phenotypes despite rearing in identical conditions. Specifically, urban dark-eyed juncos *Junco hyemalis thurberi* raised in captivity are more exploratory compared with rural birds, presumably because urban environments, where novel resources and anthropogenic stimuli are abundant, select for boldness (Atwell et al. 2012). Interestingly, another common garden study revealed that urban Eurasian blackbirds are more neophobic than individuals collected from forests; the authors posit that a heightened probability for dangerous interactions in novel urban areas may favor more cautious individuals (Miranda et al. 2013). Such studies suggest that urbanization creates selective pressures that influence microevolutionary patterns in the behavior of urban birds. This prediction is supported by a report that urban Eurasian blackbirds display greater variation in their SERT alleles, which are candidate genes associated with harm avoidance behavior and anxiety (Mueller et al. 2013). Further clarification of urbanization-induced evolutionary trends will aid in predicting how rapid development will influence urban biota in the future.

The physiological mechanisms underlying links between urbanization and behavioral variation are largely unknown, although at least some behavioral changes are likely caused by the effects of urbanization on the hypothalamic–pituitary–adrenal axis, an evolutionarily conserved neuroendocrine system that mediates the stress response (Bonier 2012; Uchoa et al. 2014). A reasonable hypothesis is that a suppressed stress response to novelty helps urban birds successfully colonize cities; however, several reports suggest that this is not always the case. For example, both urban Eurasian blackbirds and dark-eyed juncos display a suppressed stress response to capture relative to their rural conspecifics (Partecke et al. 2006; Atwell et al. 2012). In contrast, Fokidis et al. (2009) found in an investigation of five species—house sparrows, northern mockingbirds *Mimus polyglottos*, curve-billed thrashers *Toxostoma curvirostre*, Abert's towhee *Pipilo aberti*, and the canyon towhee *Pipilo fuscus*—that capture and handling stress tends to induce higher blood glucocorticoid levels in urban birds, although this effect varies by life-history stage. These reports emphasize the value of employing multiple avian species as biomonitors, since urban factors could alter stress physiology differently across species, as well as developmental and life-history stages (Partecke et al. 2006; Atwell et al. 2012).

The integrated effects of specific facets of the urban environment, particularly pollution and disease, on behavior and physiology are largely unknown and require attention if we are to move beyond a generalized understanding of how individuals respond to urbanization. Also worth considering is the probability that variations in behavioral phenotype impact individual differences in survival and reproductive success within urban environments (Sih et al. 2012). For instance, birds with greater exploratory tendencies may spend more time interacting with other individuals, increasing the probability that they will acquire new infections (Sih et al. 2012). Connecting individual responses to toxicant and pathogen loads in urban environments is an essential next step to better understanding the influence of urban environments on city dwellers.

Finally, further clarification of the impacts of urbanization on avian behavior and physiology stands to inform our understanding of how living in urban environments impacts human and wildlife health. Noise and light pollution, exposure to chemical contaminants, overpopulation, and the associated spread of diseases—all of these urban-associated factors may have potentially negative consequences on physiological processes, particularly during the sensitive developmental periods of early life and puberty (e.g., noise pollution for humans, Stansfeld and Matheson 2003; Goines and Hagler 2007). Such concerns are applicable not only to humans and birds, but also to a wide range of taxa inhabiting urban areas.

The Upside to Urban Habitats

Although this review focuses primarily on the utility of urban birds as biomonitors for urbanization-associated health threats, it is worth noting that, for at least some species, urban habitats also present important benefits. For those species that are able to exploit resources in cities, urban areas may increase their fecundity or support their conservation by providing access to habitats with greater availability of food and nesting sites, and/or fewer predators (Faeth et al. 2005; Anderies et al. 2007; Goddard et al. 2010). For instance, a population of black-crowned night-herons *Nycticorax nycticorax* in the United States was able to maintain an urban colony within a city park, despite their endangered status in surrounding regions (Hunt 2016). In addition, cities can offer increased habitat for some species, since urban adapted birds are often rock nesters that take advantage of tall buildings for nesting habitat (Kark et al. 2007). Furthermore, higher levels of water and food availability, combined with the heat island effect of cities, can turn urban areas into "pseudo-tropical bubbles," characterized by lower temporal variability in climate and access to resources (Shochat et al. 2006). These conditions may allow some species, including invasive birds, to undergo significant population growth (Shochat et al. 2006).

Finally, in some cases urban environments have been associated with declines in disease prevalence. Pathogen type, as well as the nature of urban resource provisioning, might explain the variation in infection rates found across urban populations (Becker et al. 2015). Although provisioning by humans can lead to an increase in disease transmission due to increased host aggregation, it also has the potential to reduce transmission if provisioned food decreases dietary exposure to parasites, either by improving physical condition or decreasing consumption of intermediate hosts (Becker et al. 2015).

Conversely, urban birds may benefit urban ecosystems by playing essential roles within emerging communities; for instance, as a key predator of invertebrates, birds are critical for the regulation of urban insect populations (Faeth et al. 2005). How factors in the urban environment influence the ability of birds to perform this task, which has important implications for the trophic dynamics of urban ecosystems, remains poorly understood. Comparisons among multiple cities and their adjacent wildlands could reveal general principles underlying the effects of urbanization on ecosystems (e.g., Aronson et al. 2014), as well as how specific environmental factors, such as pollution and disease, contribute to differences among urban communities. Although we tend to think of urban ecosystems as inherently fragmented and in flux, monitoring the health of urban birds can inform our understanding of population dynamics, and thus ecosystem stability, in an increasingly urban world.

Conclusion

The expansion of urban areas is unlikely to slow down in the foreseeable future; particularly since continuing human population growth is projected to add 2.5 billion people to urban areas over the next 35 years (United Nations 2014). The United Nations predicts that in less than 15 years, at least 41 urban areas will qualify as "mega-cities" that contain more than 10 million people (United Nations 2014). The majority of this growth will occur in developing nations, where inadequate city planning, poor sanitation, degrading infrastructure, and pollution already present significant challenges for human and non-human inhabitants. Thus, it is imperative that we develop an understanding of how factors associated with urbanization mediate changes in biological systems, as well as devise ways to monitor these effects in urban environments across the globe. Avian biomonitors constitute powerful tools for accomplishing these goals because they allow us to investigate a number of facets of urbanization that threaten both humans and urban wildlife, such as bioaccumulation of toxicants and the spread of disease. Finally, by providing insights into the general principles underlying the behavioral and physiological consequences of urbanization, studies using bird biomonitors could initiate new lines of inquiry in other species.

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