Leopards provide public health benefits in Mumbai, India

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Populations of large carnivores are often suppressed in human-dominated landscapes because they can kill or injure people and domestic animals. However, carnivores can also provide beneficial services to human societies, even in urban environments. We examined the services provided by leopards (*Panthera pardus*) to the residents of Mumbai, India, one of the world's largest cities. We suggest that by preying on stray dogs, leopards reduce the number of people bitten by dogs, the risk of rabies transmission, and the costs associated with dog sterilization and management. Under one set of assumptions, the presence of leopards in this highly urbanized area could save up to 90 human lives per year. A further indirect benefit of leopard presence may be an increase in local abundance of other wildlife species that would otherwise be predated by dogs. The effective conservation of carnivores in human-dominated landscapes involves difficult trade-offs between human safety and conservation concerns. Quantitative assessments of how large carnivores negatively and positively affect urban ecosystems are critical, along with improved education of local communities about large carnivores and their impacts.

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Management of the world's large (>20 kg) carnivores is a polarizing issue (Ripple *et al*. 2014). In many areas, carnivores are vilified for attacks on livestock, charismatic wildlife species, and humans (Packer *et al*. 2005; Dickman 2015), which often leads to the retaliatory killing of carnivores (McManus *et al*. 2015). Yet large carnivores are often flagship species for many of the world's ecosystems (Ripple *et al*. 2014), and play essential roles in regulating numerous ecosystem processes, from controlling prey populations (Ripple *et al*. 2014) and suppressing smaller carnivores (Berger *et al*. 2008), to reducing parasite loads in humans (Harris and Dunn 2010) and promoting seed dispersal (Sarasola *et al*. 2016).

In a nutshell:

- Predation of stray dogs by leopards (*Panthera pardus*) in areas within Mumbai, India, likely benefits humans by reducing dog bite incidents, and thereby potentially preventing 90 people from dying of rabies
- The presence of leopards also saves US$18,000 per year in dog management costs
- The indirect beneficial impacts of large carnivores on human well-being may be substantial and are underestimated, especially in urban environments

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The contribution of large carnivores to human well-being in shared landscapes has received little attention. Along with the growth of human populations in many developing nations, there have been concomitant increases in the populations of "pests", such as stray dogs, in both urban and agricultural landscapes (Hughes and Macdonald 2013). We estimated the ecosystem service value of a small population of ~35 leopards (*Panthera pardus*; Surve *et al*. 2015) that feed on stray dogs. This population of leopards lives in and around the 104-km^2 Sanjay Gandhi National Park (SGNP), which borders the city of Mumbai, India, currently ranked as the sixth largest urban agglomeration in the world (UN 2015). Mumbai is home to an estimated 96,000 stray dogs (Hiby 2014), which regularly attack people (Harris 2012) and whose primary predator is the leopard (Hayward *et al*. 2006). The leopards of Mumbai are a striking example of humans and large carnivores living in close proximity, and of how a large carnivore may benefit humans through their regulation of stray dog populations.

Leopards living on an urban edge

Approximately 35 mature leopards live in SGNP and the adjoining Aarey Milk Colony, a suburb of Mumbai (Figure 1; Surve *et al*. 2015). Sanjay Gandhi National Park is a nationally designated protected area characterized by moist deciduous forest, whereas Aarey, a former dairy colony connected to the southwest corner of SGNP, consists of a 16-km^2 matrix of pastures, forest patches, and human settlements (Figure 2). The park

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Figure 1. *Leopards in Mumbai's Sanjay Gandhi National Park (SGNP) regularly leave the confines of the park to hunt stray dogs. (a) An adult female near an apartment block bordering the park's eastern edge; (b) a female at a Muslim sacred site overlooking the city of Mumbai; (c) a young leopard walking through a village in the Aarey Milk Colony; and (d) a young leopard at a construction site in an informal settlement.*

is slowly being encroached upon by some of the largest slums in Mumbai, and at present approximately 250,000 people are estimated to live within just 500 m of the park's borders (K Tiwari pers comm; Prasad and Tiwari 2009), with an additional 100,000 people living in and around Aarey (P Variyar pers comm; WebPanel 1).

Mumbai is home to one of the largest populations of stray dogs in the world (an estimated 96,000 animals), which roam freely throughout both urban and rural slums (Hiby 2014). This abundance of stray dogs arises as a result of human tolerance and the hundreds of tons of uncollected refuse and carrion that accumulate within slums (Prasad and Tiwari 2009), exacerbated by the catastrophic decline in carrion-eating vulture populations over the past 20 years due to the widespread use of diclofenac, an anti-inflammatory drug, to treat cattle (Markandya *et al.* 2008).

Leopard impacts on stray dog populations

Dogs have been the primary prey source for leopards in SGNP over the past 15 years (Edgaonkar and Chellam 2002; Prasad and Tiwari 2009; Surve *et al.* 2015). Dog biomass represents approximately 42% (range 25–58%; Edgaonkar and Chellam 2002; Surve *et al.* 2015) of the diet of leopards inhabiting this area. Assuming a leopard daily food intake of 4.7 kg (Odden and Wegge 2009), and given that 17.1 kg of an average dog can be consumed (assuming 95% of the carcass is eaten; Stander *et al.* 1997; Athreya *et al.* 2016), a population of 35 leopards will kill about 1500 dogs per year (range 878–2036, depending on diet range) in and around SGNP (see WebPanel 1 for a detailed explanation).

Few dogs, if any, live within the interior of SGNP itself (Surve *et al.* 2015), which may suggest behaviorally mediated distribution effects by leopards or a paucity of resources for the dogs (Butler *et al.* 2004). We assumed that leopard activity in urban areas is concentrated within 500 m of the forest edge, based on expert opinion and 10 sightings of leopards outside the park (see WebPanel 1). This 500-m strip around the park covers an area of 43 km^2 and, given a mean dog population density of 17.3 ± 0.3 dogs km^{-2} (Surve *et al.* 2015), we infer that this region could contain 730–760 dogs, or about half the number of dogs the leopards consume. This difference between the number of dogs on the periphery of the park and the number of dogs consumed by leopards in the same area suggests that dogs disperse into this low-density area from surrounding neighborhoods and are subsequently preyed upon.

The value of leopard predation in combating the stray dog problem can be assessed in comparison with the local government's ongoing dog sterilization program, which is conducted at a cost of US$11.90 per dog (www.wsdindia.org). If the total number of dogs that leopards consume in this system (ie ~1500 individuals) is multiplied by the cost of sterilizing each dog (US$11.90), then predation by leopards is arguably worth about US$18,000 in saved sterilization costs, equivalent to ~8% of Mumbai's existing annual sterilization budget (US$208,000; HT Correspondent 2015).

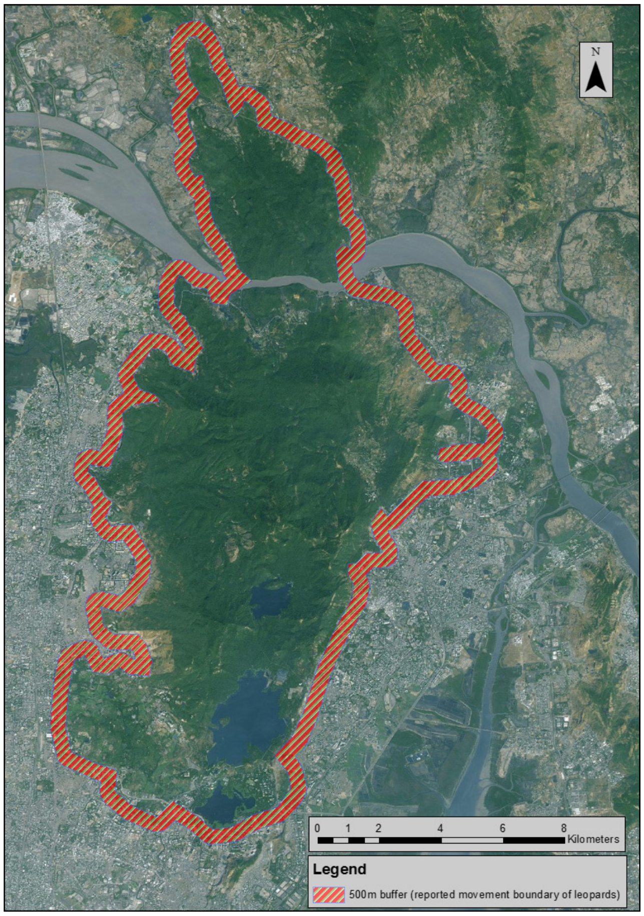

Figure 2. *Map of the 104-km² SGNP and 16-km² Aarey Milk Colony on the southwest side of the park. The hatched area represents a 500-m buffer zone from the forest edge (buffer area = 43 km²) where leopards predate on stray dogs and where an estimated 350,000 people live, mostly in informal settlements.*

Dog impacts on human populations

Although rabies – transmitted by stray dogs – is responsible for the deaths of over 20,000 people in India per year (Biswas 2016), it is illegal to kill stray dogs (Section 428 of the Indian Penal Code, 1860, and The Prevention of the Cruelty of Animals Act, 1960), so Mumbai citizens often carry rocks and bamboo rods to fend them off (Harris 2012). Stray dogs are the primary source of rabies transmission to humans (Knobel *et al.* 2005), and an average of 74,603 bite cases have been reported per year among a human population of 21 million people in Mumbai (2011–2015 5-year mean; WebTable 1). For Mumbai's 96,000 stray dogs, this corresponds to 0.78 bites per dog per year, or 3.6 bites per 1000 people per year. This is likely a conservative estimate, however, as disease incidents are greatly underreported in developing areas; for example, Singh *et al.* (2006) estimated that leishmaniasis was underreported by a factor of 8.13 in Bihar, India, and even in the US state of Pennsylvania, dog bites were greatly underreported in 1980 (Beck *et al.* 1985).

As stray dogs gravitate toward the resources available in and around slums, their populations often overlap with those of humans, and thus dog bites and rabies transmission disproportionately affect the poorest members of society (Acosta-Jamett *et al.* 2010; Gogtay *et al.* 2014). Although rabies vaccinations and post-exposure treatments are subsidized by some hospitals (Gogtay *et al.* 2014), they cost on average US$33.75 (range US$26–42; WebTable 2), which represents a substantial expenditure for the majority of bite victims, who typically live below the poverty line. On average, people living on the periphery of SGNP earn just US$0.75–1.50 per day (CPDR 2000).

Leopards may benefit human health and dog management

The statistics noted above can be used to estimate the reduction in exposure to dog bites for the 350,000 people living within the leopards' range (ie the 500-m buffer), as compared to typical exposure for those living elsewhere in the city. The estimated dog density in the park periphery (17.3 km^{-2}) is 40 times lower than densities in four urban slums located deeper within the city (a dog density of 688 dogs km^{-2} is found 2.5–13.6 km [mean = 7.4 km] from the park boundary; Hiby 2014) and nearly 10 times lower than the citywide average (96,000 dogs in 603 km^2 = ~160 dogs km^{-2}). Assuming that bite rates will be roughly proportional to both dog density and human population, we estimated that people living immediately adjacent to the park experience about 10 times fewer dog-bite incidents than is typical for the city. At an average bite rate of about 3.6 bites per 1000 citizens for the city as a whole (approximately 74,603 bitten out of a total population of 21 million), a region of 350,000 people would expect to see around 1200 bite incidents per year. However, because the dog density near the park is just 11% of the average density for the city, people living immediately alongside SGNP may experience just 11% of the number of bites, or perhaps fewer than 140 bites in total annually. In other words, leopard predation may prevent over 1000 bites per year in this region.

If leopards were absent from the park, then the surrounding dog population would increase not merely to the average value but to match the many hundreds of dogs per square kilometer that are found in other slums, suggesting that the benefit derived from the presence of these large carnivores is even greater than it would initially appear. We used a simple Lotka-Volterra predator–prey model to explore the potential increase in stray dog numbers and subsequent attacks on humans per year around the park in the absence of leopards (Figure 3). We assumed that the stray dog carrying capacity is equivalent to the highest documented dog density in the region (688 dogs km^{-2}), and that if leopards were removed from the system, then dog densities would increase to carrying capacity. We estimated the dog population growth rate (r) – based on

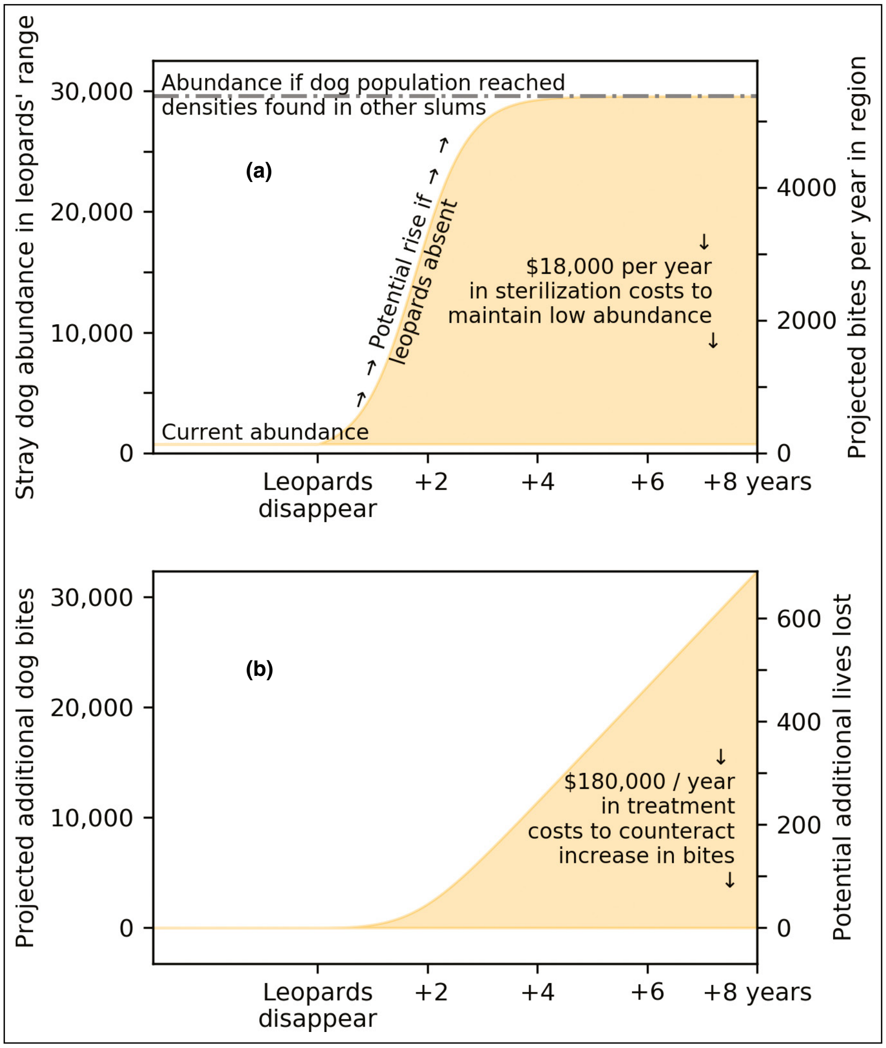

Figure 3. *(a) Projected dog bites per year and dog sterilization costs, along with (b) bite treatment costs and potential additional human lives lost if leopards were removed from SGNP.*

the assumption that leopards are holding the dog population around the park at its current density – using the equation $r = (p/N_0)/(1 - N_0/K)$, where p is the number of dogs predated by leopards per year, N_0 is the current number of dogs within the leopards' range, and K is the carrying capacity.

Under this scenario, the increase in dog numbers resulting from the absence of leopards could lead to increases in dog bites of humans from under 140 to over 5000 per year (Figure 3a). Given that >78% of dog bites in Mumbai require medical treatment and 2.14% require treatment with immunoglobulin (ie bites that pose a risk of rabies exposure; Gogtay *et al.* 2014), it follows that nearly 4000 medical treatments and 90 lives may be saved each year by leopards limiting the expansion of the dog population in this region. Under the worst-case scenario, medical treatment costs in this area could reach as high as ~US$200,000 per year (Figure 3b). This estimate is based on an average treatment cost of US$33.75 per person, 350,000 people, and a bite rate of 3.6 bites per 1000 people that increases to 15.5 bites per 1000 people as a result of the dog density rising from 160 to 688 dogs km^{-2}, and assuming that every bite victim requires post-exposure treatment.

With both human and dog populations likely to increase over the coming decades, the value of retaining the leopards in SGNP may become even greater than these estimates indicate. Mumbai's human population is projected to double by 2050 (to 42.4 million people; Hoornweg and Pope 2014), and if accompanied by a doubling of the dog population, epidemiological theory would predict that dog bite incidents, along with the associated costs to human health and livelihoods, would increase a further fourfold (Figure 3b).

Although our estimates are based on known leopard diet and dog densities within and around SGNP, there remains substantial uncertainty about the valuation of this ecosystem service. For example, we assumed that dogs continue to predominate in the leopards' diet; however, large carnivore diets are variable across space and time (Johnson *et al.* 1993). Moreover, only approximate estimates of dog bite rates on humans (Sharma *et al.* 2016) and the human population size for the area around the park are available. Recent research on bite rates from stray dogs in Delhi, India, revealed an annual per capita bite rate of 0.025, which is considerably higher than our estimate of 0.0034 bites $person^{-1}$ $year^{-1}$ (Sharma *et al.* 2016). We also assumed that dog bite rates were consistent across the region, reflecting the findings of Sharma *et al.* (2016), who determined that bite rates were similar across urban areas.

Regarding leopard spatial dynamics, local knowledge and newspaper reports led us to conclude that leopards frequently roam in and around a 500-m buffer zone bordering SGNP, but there are no published data detailing leopard movements in this area. Overall, it is unclear whether our work over- or underestimates the value of services provided by leopards in this system. Further research on the interactions among leopards, dogs, and people will improve the accuracy of these estimates and the areal extent over which they occur, but our analysis indicates the value of these services to be substantial. However, linking leopard predation of dogs to human well-being also requires careful assessment of the costs of leopards as well, including mental health effects (such as the stress and fear associated with living in such close proximity to an apex predator) that could offset any indirect benefits of leopard presence.

Human–wildlife conflict and the future of leopards in Mumbai

The negative impacts of leopards on humans around SGNP have been managed and largely mitigated, with leopard attacks in Mumbai dropping substantially (to one or two cases per year) following the abandonment of leopard translocation programs in 2003, and the development and implementation of dedicated environmental awareness and "best practice" campaigns directed toward people entering the forest. As of 2015, there had not been a single human death from leopards in Mumbai since October 2013 (Surve *et al*. 2015). By comparison, attacks on humans by leopards peaked at 25 incidents in 2002 (Athreya *et al*. 2011). Previous attacks were largely attributed to intraspecific conflict caused by translocations of foreign "problem leopards" to the park by local Forest Department personnel (Athreya *et al*. 2011; Bhatia *et al*. 2013). In March 2017, however, a leopard attacked a child in the Aarey Milk Colony near SGNP (Alok 2017). This attack, in combination with other reports of attacks on humans by neighboring leopard populations, will likely increase fear and stress levels among the local residents. The negative impacts of leopards also reach far beyond direct human injury and death, and include depredating both livestock and domestic pets in areas around the park, and reducing the abundance of bushmeat species that are valued by local people (Inskip and Zimmermann 2009).

Conservation of leopards in Mumbai will therefore be a challenge in the future. With urban Mumbai expected to grow 26% by 2020 (Moghadam and Helbich 2013), the slums will likely further encroach upon forested areas and the leopard habitat they provide (WebFigure 1). Furthermore, SGNP and the adjoining Aarey Milk Colony are under constant threat from development, and the recent approval of the Metro III train car shed project in the Aarey colony is likely to lead to the clearing of large swaths of leopard habitat.

Global impacts of large carnivores in urban environments

Nineteen other studies in Africa and Asia have shown that leopards prey on stray dogs (Butler *et al*. 2013), suggesting that our results are not isolated and that leopards – across their distribution – may benefit humans more broadly. More generally, these benefits may be realized in shared landscapes where wildlife frequently prey on stray dogs. This may be limited to areas where stray dogs and felids (eg jaguars *Panthera onca*) still occur. Dog attacks on humans have a wide range of consequences above and beyond direct injury, including time off work or even job loss, lost wages, medical expenses, and reduced ability to care for dependents (Knobel *et al*. 2005; Gogtay *et al*. 2014). In many countries, dogs are infected with rabies, which can be fatal to humans and livestock if post-exposure treatment is not administered quickly (Gogtay *et al*. 2014). Unfortunately, high densities of people and stray dogs often occur in the poorest communities, such as slums, where dog attacks can have the most severe impacts (Gogtay *et al*. 2014). As populations of large felids are threatened and declining in many areas (Ripple *et al*. 2014, 2017; Jacobson *et al*. 2016), there is a risk that the benefits of their regulatory effects on dog populations will be reduced or lost, further exacerbating the impacts of stray dogs on local human populations (Treves and Bonacic 2016).

Large carnivores are valued for their ecological roles in regulating trophic levels and habitat structure in protected areas (Fortin *et al*. 2005; Ripple and Beschta 2012). However, less is understood about the role of carnivores as ecosystem service providers in shared landscapes. Previous research has established that European jackals (*Canis aureus moreoticus*), a subspecies of the golden jackal (*Canis aureus*), and spotted hyenas (*Crocuta crocuta*) reduce organic waste by scavenging in urban areas of Serbia and Ethiopia, respectively (Yirga *et al*. 2015; Ćirović *et al*. 2016). In addition, Gilbert *et al*. (2016) postulated that indirect benefits to humans (eg reduced loss of life and injury, lower rates of property damage) would result from the re-colonization of North America by cougars (*Puma concolor*) via reductions in vehicle collisions with prey species as a result of lower prey densities. Further research is needed to better quantify the full range of social, economic, and ecological impacts of carnivores in shared landscapes (O'Bryan *et al*. 2018).

Wildlife attacks on humans, which are often featured in and sensationalized by the media (Bhatia *et al*. 2013), may result in risk-averse management strategies at local scales; for example, the Government of Western Australia initiated a shark-culling program as a direct result of media coverage of shark attacks (McCagh *et al*. 2015). It is critical that such attacks from carnivores, though tragic, do not prompt ill-considered and reactionary management responses, such as local eradication programs, because there is little or no evidence that such programs are effective and in fact they may even be counterproductive (McCagh *et al*. 2015). It is essential that the reduction in attacks on humans achieved through carnivore eradication be weighed against the potentially much greater number of lives saved, among other benefits, by the presence of these carnivores.

The long-term survival of carnivores in shared landscapes requires the effective management of human–carnivore conflict. Whereas the negative effects of carnivores have been well documented in the scientific literature (Inskip and Zimmerman 2009) and in the popular media (Bhatia *et al.* 2013; McCagh *et al.* 2015), the benefits provided by carnivores to human well-being and ecosystem services have not (eg Jacobson *et al.* 2012). Tolerance of large carnivores and their acceptance by humans (Bruskotter and Fulton 2012) are more likely to occur if the benefits of the species are understood (Bruskotter and Wilson 2014). Experimental studies have shown that the perceived benefit of the presence of large predators and scavengers by local societies is a predictor of tolerance levels (Bruskotter and Fulton 2012; Bruskotter and Wilson 2014). For example, Egyptian vultures (*Neophron percnopterus*), populations of which are declining globally, thrive in the towns and villages of Socotra, Yemen, an archipelago of four islands, because of local recognition of the valuable livestock and human waste processing services they provide. These services are otherwise lacking in this area (Gangoso *et al.* 2013). Tolerance of large carnivores is also highly dependent on social factors, such as whether or not a neighbor tolerates the species (Treves and Bruskotter 2014).

Education and communication initiatives are important components of programs geared toward improving tolerance. For example, Slagle *et al.* (2013) found that people were more tolerant of black bears (*Ursus americanus*) when given information describing the benefits of the presence of bears. In this regard, the popular media may be an important avenue for communicating carnivore benefits. For instance, Bhatia *et al.* (2013) found that mass media focused on human–carnivore conflicts in India, were willing to correct erroneous perceptions, and in some areas even helped to facilitate proper management and mitigation. Research into the ecosystem services associated with wildlife must be actively communicated in order to establish a more balanced perspective on the value of wildlife to the general public. The continued persistence of carnivores in shared landscapes is contingent upon identifying ways to mitigate detrimental impacts while simultaneously recognizing and facilitating the benefits provided by these species.

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Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.1776/suppinfo

