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The ecology and biodiversity of urban ponds[1]

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Abstract
Recent research has demonstrated that ponds contribute a great deal to biodiversity at a regional level as networks of habitat patches that also act as "stepping stones" to facilitate the movement of species through the landscape. Similarly, a great deal of biodiversity persists in urban environments where synanthropic communities are supplemented by species that thrive in disturbed environments. Aquatic urban biodiversity appears to persist despite anthropogenic stressors: an array of anthropogenic pollutants (road salt, heavy metals), invasive species, and active mismanagement – particularly the removal of riparian vegetation. Optimising urban ponds for different ecosystem services results in conflicting priorities over hydrological, geochemical, ecological, aesthetic and cultural functions. The socio-ecosystem approach to environmental management opens a path to greater incorporation of biodiversity into town planning and sustainability, while acco cultural attitudes to urban ecosystems. I identify a range of research needs: (i) the roles of design and location of urban ponds in influencing biodiversity, (ii) the function of urban wetlands for stormwater and pollution management, and (iii) public perceptions of urban ecosystems and how those perceptions are influenced by interactions with natural systems. Urban wetlands offer an important opportunity to educate the general public on natural systems and science in general using a resource that is located on their doorstep. In the face of increasing pressures on natural systems and increasing extent and intensity of urbanisation, a more comprehensive appreciation of the challenges and opportunities provided by urban ponds could play a substantial role in driving sustainable urban development.

Introduction
Land use change, whether a conversion from natural habitat to agricultural or urban land, is likely to be the principle driver of biodiversity declines over the next century in all biomes [1]. Current projections of urban land use suggest that between 2000 and 2030 there will be at least a 185% increase in the extent of urban areas [2] (Figure 1), posing a serious threat to biodiversity around the world, and much of this threat is concentrated in high biodiversity areas in developing countries [3]. However, concomitant plans for urban intensification in developed countries bring a parallel set of problems through a reduction in remaining habitat patches through processes such as infill housing [4, 5]. When attempting to mitigate the environmental consequences of this rapid expansion of towns and cities, it is important that the creation of these urban areas not be thought of simply as the removal of natural habitat. The processes that drive urbanisation involve complex, interacting sets of physical, social, economic, and governmental institutions with complex sets of interacting stakeholders [6]. With increasing demands being placed upon the natural world, it is important to consider this range of institutions when attempting to safeguard biodiversity in the long-term. Furthermore, regional variations in socio-political priorities necessitate local approaches to the management of this problem. Approaches to the protection of biodiversity in the face of urbanisation require interdisciplinary collaboration with researchers and practitioners in a range of other fields, including urban planners, economists, and sociologists, to provide a broader perspective on the "socio-ecosystem" [7, 8]. Indeed, successful interdisciplinary approaches to the protection and enhancement of biodiversity under urbanisation could not only offset the negative impacts on biodiversity but facilitate a more rapid transition to sustainability [6].
Freshwaters represent a set of habitats that suffer greater biodiversity declines than terrestrial habitats [1], perhaps due to the disproportionate biodiversity that is found in inland waters [9]. Threats to these habitats tend to result from five key factors: species invasion, habitat degradation, water pollution, over-exploitation, and flow modification [9]. The remainder of this paper will consider the topic

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of urban pond ecology from two opposite angles: after providing an overview of the ecology of ponds and the nature of urbanisation, I shall first discuss the positive and negative impacts that urbanisation has on pond ecosystems. This will cover topics such as pollution, habitat connectivity, and neglect, but also pond creation for amenity. Second, I shall provide an overview of the contributions made by ponds to ecosystem services within urban areas. In particular, I will emphasise the conflict between competing interests in limited urban spaces, but in closing I will summarise some of the many promising avenues for the protection, use and development of this habitat. The review will focus predominantly on the literature from northwest Europe, where the majority of work has been carried out, with notes about future directions in other regions.

THE VALUE OF URBAN PONDS

Biodiversity

Pond ecosystems

Before giving closer consideration to ponds in urban areas, it is useful to understand the nature of small, lentic water bodies in general. The definition of a "pond" is an artificial one which varies between researchers. While a wide range of potential definitions exist, ponds are generally defined in terms of their area: being either <2ha [10] or <5ha [11]. Small landscape elements such as ponds have traditionally be considered as providing insignificant biodiversity to the regional species pool compared to larger habitats such as lakes and rivers [12]. However, while many individual ponds may contain relatively few species (α-diversity), these habitats constitute an enormous diversity of abiotic and biotic conditions. This diversity of environments creates a concomitant diversity in ecological communities (β-diversity) which, in turn, results in a greater contribution to landscape-level biodiversity (γ-diversity) than those of larger wetlands that are more homogeneous [13-15]. In addition to this complexity, the small size of ponds is thought to break down standard species-area relationship due to the small island effect [16, 17]. This stochasticity means that a pond that holds a high biodiversity at one time point may not remain of high ecological value at another [18], rendering site-specific conservation measures ineffective and instead necessitating the conservation of pond clusters or networks [19].

Ponds have also been overlooked from a legislative standpoint, being omitted from the EU Water Framework Directive (2000/60/EC) which dictates standards for water quality [12]. While monitoring of lakes and rivers occurs in the EU and worldwide to ensure compliance with environmental legislation such as the WFD, ponds are not monitored. Certain standing waters are protected under EU legislation such as the EU Habitats Directive (92/43/EEC) Annex I, including dystrophic lakes/ponds and Mediterranean temporary ponds, and others can be protected based on floral or faunal communities. In some countries, such as the UK, high quality ponds have been recognised as priority habitats, and therefore receive some statutory protection. However, an absence of monitoring of sites may lead to conservationists failing to recognise such sites.

Urban ecosystems

Since the urban environment is tailored to human needs, urban areas share many features in common irrespective of geographical proximity [20] and are influenced by the same network of processes [21]. This fact, combined with the unique socio-economic and cultural interactions between urban habitats and human populations has led to a call for a discrete field of "urban ecology" to be founded [22]. It is often considered that by creating such uniform environmental conditions, urbanisation homogenises biological communities [23]. This "biotic homogenisation" [24] occurs through three complementary processes of (i) exclusion of native species through habitat modification, (ii) the introduction of exotic species through human processes (explored in more detailed below), and (iii) the establishment of exotic species through habitat disturbance. However, the details of these processes remain unclear [25]. Based on published floral inventories for 54 Central European cities, Pyšek [26] found that an average of 40% of urban floral communities comprised alien species (range: 20-60%). It has been argued that this modification of floral communities is the only direct biological modification made by humans, and that faunal responses are determined by this plant "template" [27]. Similar ratios occur in introduced vs. native bird communities [28]. The net result of urbanisation is not always a decline in species richness: studies comparing varying levels of urbanisation show that while invertebrates and birds exhibit considerable monotonic declines (though cf [29] with respect to birds) with increasing urbanisation, plant species richness peaks at intermediate levels [30]. Furthermore, trends seems to vary markedly between studies [30] and even between rural-urban transects in the same region [31].

Urban ponds

In a review of anthropogenic refuges for freshwater biodiversity, Chester and Robson describe 16 types of man-made freshwaters of which "urban pond" is a single category [32]. However, urban ponds are a diverse group of habitats that vary in their characteristics, and in Table 1 I have proposed a typology of these urban ponds in terms of their primary function: garden pond, industrial ponds, ornamental lakes, drainage systems, and nature reserves. Note that this table is by no means comprehensive. I have omitted unusual (though fascinating) systems such as bomb crater ponds e.g. [33, 34], swimming pools e.g. [35], and monumental fountains e.g. [36], in favour of those habitats that are more common and better-studied. Note that while some other "unusual" habitats (such as stormwater management facilities) are very well-studied, ponds dedicated to the preservation of nature in urban areas are less well-known. This leaves open the question of whether urban nature reserves either contain a large number of urban species, or represent a non-urban, "natural" community within an urban matrix. Further, it is important to note that the typology is not static: it is not uncommon for water bodies to change functions, such as the adoption of industrial ponds by angling clubs [37]. While this management can reduce diversity, it also reduces the likelihood of the water body being lost due to development or drainage [37, 38]. Such studies of the fate of urban wetlands under demographic and economic transitions are rare, but will become important as developing countries move away from industrial and manufacturing economies towards the service industry.

The extent of biodiversity contained within urban ponds varies markedly in terms of extent and composition. While a range of studies have reported (with some surprise) that urban wetlands can support substantial biodiversity despite being in close proximity to human habitats [39-42], it is unclear as to whether this is due to the lack of reporting of poor-quality urban wetlands that are considered uninteresting. Table 2 gives a summary of studies that have been conducted involving the measurement of biodiversity in urban ponds. Biodiversity of certain groups has received more attention than that of others, and amphibians have been particularly well-studied. Amphibians appear to follow the general trend of a decline in diversity and abundance towards the centre of built-up areas [43], which is likely due to a combination of low habitat quality (in particular, ornamental edging made from stone or wood reduces amphibian diversity due to amphibians not being able to climb the vertical surface) and poor connectivity between habitat patches [44]. However, it is important to consider species-specific sensitivity, as some species appear to be quite resilient to the effects of urbanisation [45], and so declines in diversity may represent the loss of particular, disproportionately-affected species rather than a uniform effect on the entire species pool.

Fish diversity is rarely considered within urban ponds, apart from in the contexts of (i) introductions of alien species by residents [46], or (ii) as a presence/absence variable influencing the composition of macroinvertebrate communities [47]. While the low dispersal ability of fish species through terrestrial matrices, particularly in urban areas, likely reduces the incidence of natural ecological processes of colonisation, extinction, and community assembly, urban fish populations require greater study as they are key drivers of ecosystem functioning. Similarly, urban aquatic plant communities tend to be viewed as anthropogenic imports rather than embattled native communities (more on invasive plants below). One exception is planktonic communities, which have received particular attention because of the potential for nuisance species to become established periodically in disturbed and temporary wetlands [48, 49].

Insect biodiversity has also been measured, although to a lesser extent. Urban ponds in Germany have been shown to have the potential to contain a large number of dragonfly and damselfly (Odonata) species, although diversity is strongly related to the presence of vegetation [50]. Urban water bodies can house a considerable portion of the national species pool for some invertebrate taxa (e.g. Hirudinea, Gastropoda, Tricladida), but more sensitive taxa (e.g. Plecoptera, Ephemeroptera) tend to be excluded [39]. However, the converse can also be true: in natural areas that are influenced by human activity, certain artificial water bodies such as reservoirs can act as refugia for species [40, 51, 52]. A brief consideration of the range of biodiversity studies reveals two significant patterns. The first is that there have been no comprehensive food web studies looking at urban environments. This step will be important because of the unique combinations of anthropogenic factors that are influencing these habitats and the health consequences for humans living in the surrounding terrestrial matrix in terms of pathogens, disease vectors and pollutants. Indeed, there is a general lack of comparable studies which might enable us to test for the homogenisation of urban freshwater ecosystems [53]. While we generally consider urban ponds to be “ponds in urban environments”, it could be that we need to consider these habitats as no-analog, qualitatively different ecosystems from those ponds that exist in other landscape contexts. Also, different anthropogenic pressures act on different components of the ecosystem: invasive fish act as top predators, eutrophication influences primary production, and habitat isolation acts on macroinvertebrates and amphibians. Second, there are a number of species that persist despite intensive human activity. Examples include the damselfly *Ischnura elegans* which tolerates and thrives in urban areas even when other Odonata are highly sensitive to pollution and pond morphology [50], the goldfish *Carassius auratus* which is also tolerant of degraded water bodies [53], and the mallard (*Anas platyrhynchos*), urban populations of which show genetic differentiation from nearby rural populations [54]. In the past these eurytopic species have been considered as generalists that can survive a range of conditions, and attention has been focused on why excluded species are unable to persist in urban environments. However, a greater consideration of the drivers of “commonness” is called-for. In particular, where biodiversity is reduced through the exclusion of a portion of the species pool, this magnifies the ecological role of those common species that remain [55]. What are the traits that enable species to occur in a wide range of environments and what are the consequences of declines in the abundance of these common species for biodiversity and ecosystem function?

Function

Ecological function

Ponds act as more than just containers of biodiversity, providing a range of ecosystem services [56]. Ponds constitute a network of distributed, discrete habitat patches sometimes referred to as the “pondscape”, [57]. This network can function in two ways depending on the focal species. For amphibians, for example, ponds can function as “stepping stones” across a matrix of inhospitable terrain [58] where individual ponds might be unsuitable for breeding but are vital temporary habitats during onward dispersal across the terrestrial matrix [59-61]. This function in particular was highlighted by the European Habitats Directive (98/83/EC), which points out that “…stepping stones (such as ponds or small woods), are essential for the migration, dispersal and genetic exchange of wild species”. For other species, the discrete nature of the aquatic environment within a terrestrial matrix creates a classical metapopulation situation [62], where most or all ponds are suitable habitat and dispersal occurs between generations. The introduction of the Natura2000 network across EU member states has further emphasised the need to consider ecological coherence in conservation planning, providing a strong motivation for the creation and protection of habitats such as ponds. Complementing existing network corridors by reducing the barrier effects of urban areas can be accomplished by enhancing habitat connectivity within those areas, for example through the creation and maintenance of a high quality urban pondscape.

Water management and treatment

Within an urban context, ponds are frequently used to control stormwater flow [63]. This practice (called "sustainable urban drainage") is mandatory under building regulations in a number of countries and results in heavily managed wetlands [64]. Studies of these wetlands have shown that while there is considerable variation in community structure, these water bodies can provide a surprising amount of diversity to a regional species pool [39], particularly when other habitats are rare [65, 66]. This run-off from human-modified land brings with it heavy metals and nutrients that can be retained by ponds [67, 68] The retention of nutrients within agricultural landscapes leads to extremely high productivity and associated levels of carbon sequestration that exceed those in any other habitat on the planet [69].
Social function

A further set of functions that differ from the direct and indirect uses described above relate to less tangible processes. Ponds certainly contain a greater proportion of the landscape-level biodiversity than other comparable habitats, as discussed above, and therefore allow humans to contribute to the conservation of endangered species that have specific habitat requirements [14]. Urban ponds also contribute to green space in cities which may play a role in improving individual and community health and well-being [70]. Furthermore, there is a traditional and cultural link with wetlands that has been lost in many areas of the developed world but that is being increasingly encouraged as a focus in the conservation of wetlands [71]. This area in particular drives a need for interdisciplinary research incorporating both the physical/chemical/biological sciences and the social sciences in order to ensure that information about, and conservation of, wetlands is presented in such a way as to appeal to past or present cultural associations with those habitats [71]. Through a deeper understanding of the social function and value of wetlands and other ecosystems we can not only tailor our message to particular communities but also gain an insight into whether or how those cultural associations need to be shifted in order to ensure community buy-in to sustainable development [72].

Sidebar title: Bioremediation using wetland biota
Among the many ecosystem services provided by urban water bodies, bioremediation has been identified as a plausible alternative to chemical filtering to remove heavy metals [73]. Wetlands can remove heavy metals and nutrients from run-off either through binding in sediments [74] or accumulation in plant tissues [73]. Certain applications (such as heavy metal removal) require harvesting of plants in which metals are accumulated, providing a potential source of biomass for use as fuel [75]. However, there is evidence that pre-existing microbial communities may have the ability to cleanse contaminated sites without interference in cases such as petroleum spills [76]. Recent advances in genetic engineering could lead to the application of such microorganisms in other situations [77]. A more complex issue within urban environments is the use of benthic sampling to monitor water or sediment quality, in which many systems of habitat monitoring make use of "reference sites". The difficulty in urban environments is that a wide range of aspects of biological functioning can be influenced by urban processes, making it difficult to tell whether, for example, water quality is driving the variation in biological communities. A solution to this problem would require either (i) the identification of new reference sites that are indicative of the types of water bodies found in urban environments but which are minimally impaired relative to other urban wetlands, or (ii) the quantification of impact within a region such that comparisons are made internally and reflect *relative* quality rather than reference to an absolute standard [78].

THE CHALLENGES OF URBAN BIODIVERSITY
Pollution
Partly as a result of their proximity to human activity and partly as a result of their deliberate use as filters of the waste from that activity, urban wetlands tend to accumulate pollutants. Heavy metals also enter freshwaters through their association with deicing treatments. The application of road salt (predominantly NaCl, $CaCl_2$, and $MgCl_2$) as a treatment against ice is a common practice in many temperate, developed nations for a review, see [79]. The salt itself causes problems for amphibian osmoregulation [80, 81] but also carries with it heavy metals which accumulate in the tissues of plants

and animals (see [82] for a review). While we understand the direct effects that salinisation of urban wetlands can have on the constituent biota through the use of ecotoxicological assays and *in situ* biomonitoring, what is less clear are the indirect effects. For example, in an insightful mesocosm experiment, Meter et al. [83] demonstrated that salt has an adverse direct effect on zooplankton, reducing competition for algae, which then increases the size and developmental rates of amphibians. Once more, this highlights the need to consider the ecosystem in its entirety, rather than focusing on a small number of species or components.

Invasive species

Out of 891 species listed in the Global Invasive Species Database (http://www.issg.org/database), 277 (31%) are associated with urban areas, 395 (44%) are associated with water (wetlands, lakes or water courses), and 147 are associated with both urban areas and water (16%, Figure 2). Urban wetlands provide two means for enhanced invasions. First, large numbers of species are imported into urban areas (either on purpose or by accident) creating a high propagule pressure that facilitates successful invasion [84]. Urban centres are nodes in trade and transport networks, which act as conduits and end-points for invasive species [85] and provide opportunities for a range of different introduction pathways [86].

Primary taxa that are imported deliberately into urban areas include ornamental species such as goldfish and aquatic plants, and pets such as terrapins and snakes. Particular issues arise when commercial suppliers of freshwater species misidentify what is being sold or fail to ensure adequate biocontrol measures are in place to prevent contamination with unordered organisms (such as molluscs and crustaceans) [87]. The frequency of occurrence of aquarium species in shops [88] and the degree of importation of non-native species [89] have been shown to correlate with the likelihood of a species establishing in the wild for freshwater and marine fish, respectively. Garden plant communities can be extremely diverse [90] but these diverse communities often comprise many ornamental, alien species (see above) and so act as a source for invasives to enter the surrounding natural or semi-natural areas [91, 92]. Similarly, the occurrence of non-native fish in natural wetlands around urban centres increase with higher importation rates [93]. Deliberate human introductions of fish are also strongly implicated through the release of ornamental fish or sports fishing [93] and the increased chances of finding non-native species closer to human access points [46].

However, a second mode by which urbanisation can facilitate invasive species is through the disturbance of existing ecosystems. Ehrenfeld [94] gives a list of direct impacts from the presence of humans in or around aquatic environments which can be summarised as follows: (i) modification of channels and banks; (ii) disturbance from traffic; (iii) presence of pet animals; (iv) dumping of rubbish, and (v) reductions in permeability of surrounding land. However, as this list suggests, the impacts of urbanisation are a heterogeneous in and of themselves. Rather than producing a single, invadable habitat type, human-wetland interactions in urban areas create a diversity of habitat types that sometimes favour invasive species [94].

Pond loss

Ponds have been lost across the developed world at a high rate as their function in agricultural and industrial settings declined and land was needed for urbanisation or the intensification of agriculture. Much of this loss (50-70%) occurred during the late 19th and early 20th centuries, and what we witness now is a much-reduced rate of loss [95]. Table 3 gives an international comparison of rates of pond loss, showing that such rates are similar across different countries and regions. Pond density is a key predictor of biodiversity [96], which is unsurprising given the substantial barrier posed by the urban terrestrial matrix [97]. Pond loss, therefore, poses a far greater risk to the coherence of pond networks within urban environments than it does within other land use contexts, and must be central to plans for the conservation of species in urban environments [43]. In some regions, such as the UK, new initiatives are seeking to create new ponds to replace those that are lost and those that are damaged, under the assumption that the restoration of degraded ponds is expensive and that those sites will never reach their former quality [98]. However, this hypothesis has received little empirical attention. In urban environments, where space is limited, the restoration of existing ponds may be the only option. The key factor that will determine whether these pond creation initiatives can succeed is engagement with stakeholders such as the mineral extraction industry, developers, and the general public.

What is interesting is that the only study to have investigated changes in pond numbers in the last decade has shown a substantial increase in pond numbers from 1998-2007, mostly as part of the concerted effort to reverse the declines experienced in the UK over the past century mentioned above [99]. This pattern of change highlights the dynamic aspect of the pondscape, where ponds are created and lost at a much higher rate than is the case for other habitat types, needs to be taken into account when designing conservation measures. Conventional conservation practices tend to focus on particular sites, but a "high quality pond" at one time may not remain high quality (or even continue to exist) in the long-term [19]. There is also a lack of understanding about *how* to create a new pond. Observational studies based on pre-existing sites suggest that the key requirements are as follows (summarised from the findings in Table 2):

- Avoid vertical walls which prevent amphibians from exiting the water [44],
- Maintain submerged and emergent plant communities [50] with light management [100],
- Situate to maximise connectivity with existing ponds [44, 96, 101],
- Be aware of human access which may influence species introductions [93],
- Use for functions other than biodiversity, such as stormwater management, may not reduce diversity but may influence the composition of communities that occur [66],
- Plan a variety of pond types, as different conditions (e.g. fish/fishless, water chemistry, morphology) support different communities in a wide range of taxa [42, 50, 65, 102, 103].

The field of freshwater conservation would benefit a great deal from experimental studies that investigate the accumulation and extent of biodiversity in networks of newly-created ponds of varying kinds and configurations to establish best practice. Such studies should follow the example of Williams et al. [104] in planning, monitoring, and critically evaluating the success of pond network creation schemes, although methods would have to be adapted for urban environments.

ECOSYSTEM SERVICES AND CONFLICTING PRIORITIES

Biodiversity: the good, the bad and the ugly

In attempting to encourage aquatic biodiversity in urban areas, there is a need to consider the potential impacts of increasing nuisance species. Mosquitoes are a particular problem, and modifications of wetland design to reduce mosquito abundance (e.g. steepening of banks, removal of vegetation, increased water depth [105]) tend to remove those aspects of the habitat that promote other elements of biodiversity [17]. Mosquitoes bring with them potentially-fatal diseases such as West Nile Virus (transmitted primarily by the *Culex pipiens-restuans* complex) [106] in North America and Dengue fever (transmitted by *Aedes aegypti*, a species adapted to urban environments, and *A. albopictus*) in southern Europe [107]. *A. albopictus* in particular is spreading through Europe [108], and climate change may increase the latitude at which Dengue fever can be transmitted to produce seasonal waves of transmission in southern Europe [109]. However, mosquito production tends to be limited to a small number of sites, and so monitoring and management there can reduce the need to homogenise all urban wetlands [110]. Mosquitoes are also fewer in number when insect predators are present, providing an additional motivation for enhancing biodiversity in a broader sense [106]. Other nuisance species may be more innocuous, such as the loud calling of the striped marsh frog *Rana ridibunda*. Even for harmless animals, the general public holds deep-seated negative views (and even fear) of biodiversity [111] and these views influence their preference for highly-managed urban green space vs. semi-natural areas [112]. However, such distaste can be overcome by gradual introduction of successively "more-natural" sites coupled with outreach and education [113].

Aesthetics vs. ecology

Many surveys of residents show that there are generally positive views of urban wetlands [114-116]. However, those wetlands are perceived as more attractive if they have highly-visible mown areas and a clear view of the water without dense macrophyte beds [117], suggesting that cultural sustainability needs to be considered alongside ecological integrity. The kind of management that seems to appeal most to residents also reduces biodiversity, for example the removal of vegetation from city park ponds vastly reduces dragonfly richness [50]. The challenge, then, is to appeal to cultural sensitivities which may require ecological innovation [118], or the provision of both "natural" and "formal" green spaces from which the public extract different benefits [119].

Sidebar title: Educational value of urban ponds

It has been proposed that the key to future conservation of wildlife is through increasing the exposure of the general public (whose tax money will fund much of the conservation work) to nature in urban areas [120]. Aside from the substantial value of urban biodiversity to the functioning of urban ecological systems, there is great benefit to be obtained from the provision and use of urban wetlands in public education. These applications are straightforward in subjects such as the sciences [121], but are easily adapted to other parts of the curriculum, and health and safety considerations are laid out elsewhere [122]. Some have suggested that negative perceptions of wetlands are not innate but learnt through childhood, and so exposure to ponds in a positive light may enhance the next generation's perceptions of water [123]. This may be appropriate not only in schools, where small wetlands can be used as teaching resources, but also around community centres and nature reserves with access to the general public. Indeed, any time that a wetland is created or retrofitted there exist opportunities to promote recreation and education through the integration of interpretative signage and public access [124].

OPPORTUNITIES FOR THE FUTURE

Green space

Increasing urbanisation involves not only the sprawl of urban margins but also the intensification of land use within already built-up areas and this reduction in land per unit population leads to a concomitant reduction in available green space. It is generally accepted that green space has a positive effect on a range of health outcomes [70]. In particular, biodiversity seems to be strongly associated with psychological benefits [125]. However, the construction of new developments necessitates the construction of drainage which can provide wetland habitats [126], and these wetlands can contain considerable biodiversity [39, 127, 128]. The creation of wetlands within such developments can be guided by ecological theory, but this will require ecologists to turn our observations of variation in biodiversity in artificial, urban wetlands e.g. [39, 128, 129, 130] into guidance for developers. Further opportunities may lie in the green buildings themselves, into the walls and roofs of which water features can be integrated

Garden ponds

Based on an analysis of multiple estimates of pond prevalence in UK gardens, Davies et al [131] suggest that around 16% (95% CI: 0.11 - 0.20) of gardens contain ponds. The authors extrapolate from these surveys to give a predicted garden pond resource of 2.5-4.5 million ponds across the country, with an estimated surface area of 3.5km^2. The difficulty with monitoring this resource is the size and the lack of detailed mapping data: estimates of mean garden pond size vary from 1m^2 [131] to 2.5m^2 [132], and these are not shown on maps. Furthermore, difficulty with access for researchers to garden ponds may have deterred earlier work [95]. However, garden ponds are well-used by amphibians, which show little habitat preference but may be influenced by the presence of fish [133]. Attempts at experimental supplementation of garden ponds using small mesocosms (0.21m^2) suggest that a range of animals may readily and rapidly colonise even these small wetlands, and that there could be an additional value as supplementary habitat for amphibians [132]. This resource must be incorporated into urban ecology in a more comprehensive way in order to adequately evaluate aquatic ecological processes.

Research

Urban wetlands provide a replicated set of habitats that are close to centres of research as well as large numbers of lay people. This opens the way for citizen science, a growing area with many innovative and extensive research projects [134]. Particular ecological questions that can be asked include investigations of metapopulation [135] and metacommunity [136] ecology, within the context of network theory [58]. The harsh environmental pressures exerted on urban ecosystems also provide opportunities to study evolutionary processes [137]. What effect does acute and chronic exposure to road salt pollution have on invertebrates and amphibians? Can low matrix permeability facilitate speciation in urban vs. rural populations? How do mutualists adapt when urbanisation removes one component of the interaction? The developing world, where systems are far closer to natural prior to urbanisation, would give a clearer picture of the impacts of urbanisation than the space-for-time urban-rural gradient studies that are conducted in Europe and North America e.g. [138].

In parallel to the opportunities presented for fundamental research, applied research must also be directed towards the needs of end-users. These include hydrologists who use stormwater facilities to manage surface flow – while some studies show evidence of successful use of wetlands to reduce flooding [139], smaller-scale interventions have been little-studied. As discussed above, conservation agencies require evidence for the efficacy of particular designs and configurations of ponds in order to maximise benefits from limited resources. Interest in nutrient and pollutant retention has also tended to rest on observational studies, while studies of the efficacy of different methods of pollutant retention and of the impacts of urban pollutants are required [140].

Conclusion

The biodiversity resource represented by urban ponds is currently poorly quantified and described. The majority of urban ponds are likely to be located in residents' gardens and represent a habitat that is almost completely unknown, although the high quality urban ponds are likely to be larger, more diverse habitats managed as nature reserves or stormwater management facilities. A biotic homogenisation of biological communities seems to be a useful concept within which to consider deliberate modifications of the environment, although it seems that there is a great deal of variation in the extent to which homogenisation occurs. The few studies of habitats such as stormwater ponds and industrial ponds highlight the diversity of factors affecting biodiversity and the impact of a wetland's past use on its future management. Given the increasing rate of urbanisation, particularly in the developing world, a better understanding of urban ecosystems is essential to the protection of biodiversity in general.

The interaction between humans and urban freshwater ecosystems stands as a representative case study for the interplay between natural and anthropological processes. I have tried to illustrate some of these in Figure 3. First, it is becoming increasingly clear that the desire for ecosystem services and development can both increase and decrease freshwater resources, along with their constituent biodiversity. This phenomenon serves to emphasise the opportunity for sustainable urbanisation and incorporation of diverse wetlands but this kind of complementary consideration of biodiversity and other ecosystem services requires effective, interdisciplinary, socio-ecosystem approaches. The mismanagement of the existing freshwater resource can cause or exacerbate a range of problems, often due to limited evidence base for the management of urban wetlands. There is a great need to study further the interactions between natural and artificial water bodies within urban contexts to be able to advise land managers and the general public about best practice for urban freshwater management. In addition, better communication of the damage done by, for example, invasive species would not only benefit native biodiversity but also reduce the costs of dealing with nuisance invasive species once they are established. Finally, on the ecological interactions between ponds, it is clear that simple gain and loss of particular habitats will be amplified through the effects on isolation (or, conversely, connectivity).

Particularly exciting are the opportunities to engage the general public (particularly school children) in biodiversity conservation efforts in an attempt to bring about broader support for environmental protection through increased familiarity with nature. Evidence-based engagement, designed to bring the public into contact with nature without evoking negative reactions, will be necessary. More broadly, urban wetlands bring a range of scientific phenomena to the taxpayer's doorstep, including bioremediation, ecology, conservation, chemistry, hydrology, and climate change research. Indeed, for each opportunity that wetlands present for researchers, there is an accompanying opportunity for public engagement in the process and outcome of that scientific research. Taking advantage of these opportunities, pro-active engagement with the public, and innovation to accommodate competing ecosystem services will pay dividends in terms of accelerated progress towards sustainability.

References

1. Sala OE, Chapin FS, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke LF, Jackson RB, Kinzig A, et al. Global Biodiversity Scenarios for the Year 2100. *Science* 2000, 287:1770-1774.
2. Seto KC, Güneralp B, Hutyra LR. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences* 2012, 109:16083-16088.
3. McDonald RI, Kareiva P, Forman RTT. The implications of current and future urbanization for global protected areas and biodiversity conservation. *Biological Conservation* 2008, 141:1695-1703.
4. Doody B, Sullivan J, Meurk C, Stewart G, Perkins H. Urban realities: the contribution of residential gardens to the conservation of urban forest remnants. *Biodiversity and Conservation* 2010, 19:1385-1400.
5. Communities and Local Government. *Policy Planning Statement 3: Housing*. London: Communities and Local Government; 2006.
6. Seto KC, Sánchez-Rodríguez R, Fragkias M. The new geography of contemporary urbanization and the environment. *Annual Review of Environment and Resources* 2010, 35:167-194.
7. Alberti M, Marzluff JM, Shulenberger E, Bradley G, Ryan C, Zumbrunnen C. Integrating humans into ecology: opportunities and challenges for studying urban ecosystems. *BioScience* 2003, 53:1169-1179.
8. Berkes F, Colding J, Folke C. *Navigating social–ecological systems: building resilience for complexity and change*. Cambridge, UK: Cambridge University Press; 2003.
9. Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard AH, Soto D, Stiassny MLJ, et al. Freshwater biodiversity: Importance, threats, status and conservation challenges. *Biological Reviews* 2006, 81:163-182.
10. Biggs J, Williams P, Whitfield M, Nicolet P, Weatherby A. 15 years of pond assessment in Britain: results and lessons learned from the work of Pond Conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems* 2005, 15:693-714.
11. De Meester L, Declerck S, Stoks R, Louette G, Van De Meutter F, De Bie T, Michels E, Brendonck L. Ponds and pools as model systems in conservation biology, ecology and evolutionary biology. *Aquatic Conservation: Marine and Freshwater Ecosystems* 2005, 15:715-725.
12. Céréghino R, Biggs J, Oertli B, Declerck S. The ecology of European ponds: defining the characteristics of a neglected freshwater habitat. *Hydrobiologia* 2008, 597:1-6.
13. Oertli B, Joye DA, Castella E, Juge R, Cambin D, Lachavanne J-B. Does size matter? The relationship between pond area and biodiversity. *Biological Conservation* 2002, 104:59-70.

14. Williams P, Whitfield M, Biggs J, Bray S, Fox G, Nicolet P, Sear DA. Comparative biodiversity of rivers, streams, ditches and ponds in an agricultural landscape in Southern England. *Biological Conservation* 2004, 115:329-341.
15. Davies B, Biggs J, Williams P, Whitfield M, Nicolet P, Sear D, Bray S, Maund S. Comparative biodiversity of aquatic habitats in the European agricultural landscape. *Agriculture, Ecosystems & Environment* 2008, 125:1-8.
16. Lomolino MV. Ecology's most general, yet protean pattern: the species-area relationship. *Journal of Biogeography* 2000, 27:17-26.
17. Hassall C, Hollinshead J, Hull A. Environmental correlates of plant and invertebrate species richness in ponds. *Biodiversity and Conservation* 2011, 20:3189-3222.
18. Jeffries MJ. The temporal dynamics of temporary pond macroinvertebrate communities over a 10-year period. *Hydrobiologia* 2011, 661:391-405.
19. Hassall C, Hollinshead J, Hull A. Temporal dynamics of aquatic communities and implications for pond conservation. *Biodiversity and Conservation* 2012, 21:829-852.
20. Werner P. The ecology of urban areas and their functions for species diversity. *Landscape and Ecological Engineering* 2011, 7:231-240.
21. Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM. Global change and the ecology of cities. *Science* 2008, 319:756-760.
22. Niemelä J. Is there a need for a theory of urban ecology? *Urban Ecosyst* 1999, 3:57-65.
23. McKinney ML. Urbanization as a major cause of biotic homogenization. *Biological Conservation* 2006, 127:247-260.
24. Lockwood JL, McKinney ML, eds. *Biotic Homogenization*. New York: Kluwer; 2001.
25. Olden JD. Biotic homogenization: a new research agenda for conservation biogeography. *Journal of Biogeography* 2006, 33:2027-2039.
26. Pyšek P. Alien and native species in Central European urban floras: a quantitative comparison. *Journal of Biogeography* 1998, 25:155-163.
27. Faeth SH, Bang C, Saari S. Urban biodiversity: patterns and mechanisms. *Annals of the New York Academy of Sciences* 2011, 1223:69-81.
28. Savard J-PL, Clergeau P, Mennechez G. Biodiversity concepts and urban ecosystems. *Landsc Urban Plann* 2000, 48:131-142.
29. Marzluff JM. Island biogeography for an urbanizing world: how extinction and colonization may determine biological diversity in human-dominated landscapes. *Urban Ecosyst* 2005, 8:157-177.
30. McKinney ML. Effects of urbanization on species richness: a review of plants and animals. *Urban Ecosyst* 2008, 11:161-176.
31. Dallimer M, Rouquette JR, Skinner AMJ, Armsworth PR, Maltby LM, Warren PH, Gaston KJ. Contrasting patterns in species richness of birds, butterflies and plants along riparian corridors in an urban landscape. *Diversity and Distributions* 2012, 18:742-753.
32. Chester ET, Robson BJ. Anthropogenic refuges for freshwater biodiversity: Their ecological characteristics and management. *Biological Conservation* 2013, 166:64-75.
33. Martens K, De Roeck E, Colson L, Goddeeris B, Ercken D, De Meester L, De Bie T, Declerck S, Vyverman W, Van Der Gucht K, et al. *Towards a sustainable management of pond diversity at the landscape level (PONDSCAPE) - Final Report Phase 1*. Brussels Belgian Science Policy (Research Programme Science for a Sustainable Development); 2009.
34. Warwick T. The colonization of bomb-crater ponds at Marlow, Buckinghamshire. *Journal of Animal Ecology* 1949, 18:137-141.
35. Carlson J, Keating J, Mbogo CM, Kahindi S, Beier JC. Ecological limitations on aquatic mosquito predator colonization in the urban environment. *J Vector Ecol* 2004, 29:331-339.
36. Cuzman OA, Ventura S, Sili C, Mascalchi C, Turchetti T, D'Acqui LP, Tiano P. Biodiversity of phototrophic biofilms dwelling on monumental fountains. *Microb Ecol* 2010, 60:81-95.

37. Wood PJ, Greenwood MT, Barker SA, Gunn J. The effects of amenity management for angling on the conservation value of aquatic invertebrate communities in old industrial ponds. *Biological Conservation* 2001, 102:17-29.
38. Wood PJ, Barker S. Old industrial mill ponds: a neglected ecological resource. *Applied Geography* 2000, 20:65-81.
39. Vermonden K, Leuven RSEW, van der Velde G, van Katwijk MM, Roelofs JGM, Jan Hendriks A. Urban drainage systems: An undervalued habitat for aquatic macroinvertebrates. *Biological Conservation* 2009, 142:1105-1115.
40. Brand AB, Snodgrass JW. Value of artificial habitats for amphibian reproduction in altered landscapes. *Conservation Biology* 2010, 24:295-301.
41. Santoul F, Gaujard A, Angélibert S, Mastrorillo S, Céréghino R. Gravel pits support waterbird diversity in an urban landscape. *Hydrobiologia* 2009, 634:107-114.
42. Ejsmont-Karabin J, Kuczyńska-Kippen N. Urban rotifers: structure and densities of rotifer communities in water bodies of the Poznań agglomeration area (western Poland). *Hydrobiologia* 2001, 446-447:165-171.
43. Hamer AJ, McDonnell MJ. Amphibian ecology and conservation in the urbanising world: A review. *Biological Conservation* 2008, 141:2432-2449.
44. Parris KM. Urban amphibian assemblages as metacommunities. *Journal of Animal Ecology* 2006, 75:757-764.
45. Rubbo MJ, Kiesecker JM. Amphibian breeding distribution in an urbanized landscape. *Conservation Biology* 2005, 19:504-511.
46. Copp GH, Wesley KJ, Vilizzi L. Pathways of ornamental and aquarium fish introductions into urban ponds of Epping Forest (London, England): the human vector. *J Appl Ichthyol* 2005, 21:263-274.
47. Hamer AJ, Parris KM. Predation modifies larval amphibian communities in urban wetlands. *Wetlands* 2013, 33:641-652.
48. Peretyatko A, Teissier S, Backer SD, Triest L. Assessment of the risk of cyanobacterial bloom occurrence in urban ponds: probabilistic approach. *Annales de Limnologie - International Journal of Limnology* 2010, 46:121-133.
49. Olding DD, Hellebust JA, Douglas MSV. Phytoplankton community composition in relation to water quality and water-body morphometry in urban lakes, reservoirs, and ponds. *Canadian Journal of Fisheries and Aquatic Sciences* 2000, 57:2163-2174.
50. Goertzen D, Suhling F. Promoting dragonfly diversity in cities: major determinants and implications for urban pond design. *Journal of Insect Conservation* 2013, 17:399-409.
51. Clements R, Koh LP, Lee TM, Meier R, Li D. Importance of reservoirs for the conservation of freshwater molluscs in a tropical urban landscape. *Biological Conservation* 2006, 128:136-146.
52. Schaeffer JS, Bland JK, Janssen J. Use of a storm water retention system for conservation of regionally endangered fishes. *Fisheries* 2012, 37:66-75.
53. Rahel FJ. Homogenization of freshwater faunas. *Annual Review of Ecology and Systematics* 2002, 33:291-315.
54. Baratti M, Cordaro M, Dessì Fulgheri F, Vannini M, Fratini S. Molecular and ecological characterization of urban populations of the mallard (*Anas platyrhynchos* L.) in Italy. *Italian Journal of Zoology* 2009, 76:330-339.
55. Gaston KJ, Fuller RA. Commonness, population depletion and conservation biology. *Trends in Ecology & Evolution* 2008, 23:14-19.
56. Zedler JB, Kercher S. Wetland resources: status, trends, ecosystems services, and restorability. *Annual Review of Environment and Resources* 2005, 30:39-74.
57. Boothby J. Pond conservation: towards a delineation of pondscape. *Aquatic Conservation: Marine and Freshwater Ecosystems* 1997, 7:127-132.

58. Fortuna MA, Gómez-Rodríguez C, Bascompte J. Spatial network structure and amphibian persistence in stochastic environments. *Proceedings of the Royal Society: Series B (Biological Sciences)* 2006, 273:1429-1434.
59. Denoël M, Ficetola GF. Conservation of newt guilds in an agricultural landscape of Belgium: the importance of aquatic and terrestrial habitats. *Aquatic Conservation: Marine and Freshwater Ecosystems* 2008, 18:714-728.
60. Semlitsch RD. Biological delineation of terrestrial buffer zones for pond-breeding salamanders. *Conservation Biology* 1998, 12:1113-1119.
61. Garden JG, McAlpine CA, Possingham HP. Multi-scaled habitat considerations for conserving urban biodiversity: native reptiles and small mammals in Brisbane, Australia. *Landscape Ecology* 2010, 25:1013-1028.
62. Hanski I. Metapopulation dynamics. *Nature* 1998, 396:41-49.
63. Mitsch WJ, Gosselink JG. The value of wetlands: importance of scale and landscape setting. *Ecological Economics* 2000, 35:25-33.
64. Werritty A. Sustainable flood management: oxymoron or new paradigm? *Area* 2006, 38:16-23.
65. Hamer A, Smith P, McDonnell M. The importance of habitat design and aquatic connectivity in amphibian use of urban stormwater retention ponds. *Urban Ecosyst* 2012, 15:451-471.
66. Moore TLC, Hunt WF. Ecosystem service provision by stormwater wetlands and ponds – A means for evaluation? *Water Research* 2012, 46:6811-6823.
67. Di Luca GA, Maine MA, Mufarrege MM, Hadad HR, Sánchez GC, Bonetto CA. Metal retention and distribution in the sediment of a constructed wetland for industrial wastewater treatment. *Ecological Engineering* 2011, 37:1267-1275.
68. Hefting MM, van den Heuvel RN, Verhoeven JTA. Wetlands in agricultural landscapes for nitrogen attenuation and biodiversity enhancement: Opportunities and limitations. *Ecological Engineering* 2013, 56:5-13.
69. Downing JA, Cole JJ, Middelburg JJ, Striegel RG, Duarte CM, Kortelainen P, Prairie YT, Laube KA. Sediment organic carbon burial in agriculturally eutrophic impoundments over the last century. *Global Biogeochemical Cycles* 2008, 22:GB1018.
70. Lee ACK, Maheswaran R. The health benefits of urban green spaces: a review of the evidence. *Journal of Public Health* 2011, 33:212-222.
71. Papayannis T. Integrating nature and culture in wetland management. In: Papayannis T, Pritchard D, eds. *Culture and Wetlands in the Mediterranean: An Evolving Story*. Athens: Mediterranean Institute for Nature and Anthropos (Med-INA); 2011.
72. Ehrlich PR. Human natures, nature conservation, and environmental ethics. *Bioscience* 2002, 52:31-43.
73. Rai PK. Heavy metal pollution in aquatic ecosystems and its phytoremediation using wetland plants: an ecosustainable approach. *Int J Phytoremediat* 2008, 10:133-160.
74. Faulkner S. Urbanization impacts on the structure and function of forested wetlands. *Urban Ecosyst* 2004, 7:89-106.
75. Van Ginneken L, Meers E, Guisson R, Ruttens A, Elst K, Tack FMG, Vangronsveld J, Diels L, Dejonghe W. Phytoremediation for heavy metal-contaminated soils combined with bioenergy production. *Journal of Environmental Engineering and Landscape Management* 2007, 15:227-236.
76. Mills MA, Bonner JS, McDonald TJ, Page CA, Autenrieth RL. Intrinsic bioremediation of a petroleum-impacted wetland. *Marine Pollution Bulletin* 2003, 46:887-899.
77. Singh JS, Abhilash PC, Singh HB, Singh RP, Singh DP. Genetically engineered bacteria: An emerging tool for environmental remediation and future research perspectives. *Gene* 2011, 480:1-9.
78. Tixier G, Lafont M, Grapentine L, Rochfort Q, Marsalek J. Ecological risk assessment of urban stormwater ponds: Literature review and proposal of a new conceptual approach

providing ecological quality goals and the associated bioassessment tools. *Ecological Indicators* 2011, 11:1497-1506.
79. Marsalek J. Road salts in urban stormwater: an emerging issue in stormwater management in cold climates. *Water Science and Technology* 2003, 48:61-70.
80. Karraker NE, Gibbs JP, Vonesh JR. Impacts of road deicing salt on the demography of vernal pool-breeding amphibians. *Ecological Applications* 2008, 18:724-734.
81. Sanzo D, Hecnar SJ. Effects of road de-icing salt (NaCl) on larval wood frogs (*Rana sylvatica*). *Environmental Pollution* 2006, 140:247-256.
82. Trombulak SC, Frissell CA. Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology* 2000, 14:18-30.
83. Meter RJ, Swan CM, Leips J, Snodgrass JW. Road salt stress induces novel food web structure and interactions. *Wetlands* 2011, 31:843-851.
84. Kolar CS, Lodge DM. Progress in invasion biology: predicting invaders. *Trends in Ecology & Evolution* 2001, 16:199-204.
85. Hulme PE. Trade, transport and trouble: managing invasive species pathways in an era of globalization. *Journal of Applied Ecology* 2009, 46:10-18.
86. Hulme PE, Bacher S, Kenis M, Klotz S, Kühn I, Minchin D, Nentwig W, Olenin S, Panov V, Pergl J, et al. Grasping at the routes of biological invasions: a framework for integrating pathways into policy. *Journal of Applied Ecology* 2008, 45:403-414.
87. Keller RP, Lodge DM. Species invasions from commerce in live aquatic organisms: Problems and possible solutions. *Bioscience* 2007, 57:428-436.
88. Duggan IC, Rixon CAM, MacIsaac HJ. Popularity and propagule pressure: Determinants of introduction and establishment of aquarium fish. *Biological Invasions* 2006, 8:377-382.
89. Semmens BX, Buhle ER, Salomon AK, Pattengill-Semmens CV. A hotspot of non-native marine fishes: evidence for the aquarium trade as an invasion pathway. *Mar Ecol Prog Ser* 2004, 266:239-244.
90. Thompson K, Austin KC, Smith RM, Warren PH, Angold PG, Gaston KJ. Urban domestic gardens (I): Putting small-scale plant diversity in context. *J Veg Sci* 2003, 14:71-78.
91. Weber E. *Invasive Plant Species of the World. A Reference Guide to Environmental Weeds*. Wallingford CABI Publishing; 2003.
92. Smith RM, Thompson K, Hodgson JG, Warren PH, Gaston KJ. Urban domestic gardens (IX): Composition and richness of the vascular plant flora, and implications for native biodiversity. *Biological Conservation* 2006, 129:312-322.
93. Copp GH, Templeton M, Gozlan RE. Propagule pressure and the invasion risks of non-native freshwater fishes: a case study in England. *Journal of Fish Biology* 2007, 71:148-159.
94. Ehrenfeld JG. Exotic invasive species in urban wetlands: environmental correlates and implications for wetland management. *Journal of Applied Ecology* 2008, 45:1160-1169.
95. Wood PJ, Greenwood MT, Agnew MD. Pond biodiversity and habitat loss in the UK. *Area* 2003, 35:206-216.
96. Gledhill DG, James P, Davies DH. Pond density as a determinant of aquatic species richness in an urban landscape. *Landscape Ecology* 2008, 23:1219-1230.
97. Hitchings SP, Beebee TJC. Genetic substructuring as a result of barriers to gene flow in urban *Rana temporaria* (common frog) populations: implications for biodiversity conservation. *Heredity* 1997, 79:117-127.
98. Oertli B, Céréghino R, Hull A, Miracle R. Pond conservation: from science to practice. *Hydrobiologia* 2009, 634:1-9.
99. Williams P, Biggs J, Crowe A, Murphy J, Nicolet P, Weatherby A, Dunbar M. *Countryside Survey: Ponds Report from 2007*. Pond Conservation and NERC Centre for Ecology & Hydrology: Technical Report No. 7/07; 2010.
100. Fontanarrosa MS, Collantes MB, Bachmann AO. Aquatic insect assemblages of man-made permanent ponds, Buenos Aires City, Argentina. *Neotrop Entomol* 2013, 42:22-31.

101. McCarthy K, Lathrop R. Stormwater basins of the New Jersey coastal plain: Subsidies or sinks for frogs and toads? *Urban Ecosyst* 2011, 14:395-413.
102. Dodson SI. Biodiversity in southern Wisconsin storm-water retention ponds: Correlations with watershed cover and productivity. *Lake Reservoir Manag* 2008, 24:370-380.
103. Pinel-Alloul B, Mimouni EA. Are cladoceran diversity and community structure linked to spatial heterogeneity in urban landscapes and pond environments? *Hydrobiologia* 2013:1-18.
104. Williams P, Whitfield M, Biggs J. How can we make new ponds biodiverse? A case study monitored over 7 years. *Hydrobiologia* 2008, 597:137-148.
105. Russell RC. Constructed wetlands and mosquitoes: Health hazards and management options—An Australian perspective. *Ecological Engineering* 1999, 12:107-124.
106. Gingrich JB, Anderson RD, Williams GM, O'Connor L, Harkins K. Stormwater ponds, constructed wetlands, and other best management practices as potential breeding sites for West Nile Virus vectors in Delaware during 2004. *J Am Mosq Control Assoc* 2006, 22:282-291.
107. Semenza JC, Menne B. Climate change and infectious diseases in Europe. *The Lancet Infectious Diseases* 2009, 9:365-375.
108. Scholte EJ, Schaffner F. Waiting for the tiger: establishment and spread of the *Aedes albopictus* mosquito in Europe. In: Takken W, Knols BGJ, eds. *Emerging pests and vector-borne disease in Europe*. Wageningen Wageningen Academic Publishers; 2007.
109. Hales S, de Wet N, Maindonald J, Woodward A. Potential effect of population and climate changes on global distribution of dengue fever: an empirical model. *Lancet* 2002, 360:830-834.
110. Irwin P, Arcari C, Hausbeck J, Paskewitz S. Urban wet environment as mosquito habitat in the Upper Midwest. *EcoHealth* 2008, 5:49-57.
111. Kellert SR. Values and perceptions of invertebrates. *Conservation Biology* 1993, 7:845-855.
112. Bixler RD, Floyd MF. Nature is scary, disgusting, and uncomfortable. *Environment and Behavior* 1997, 29:443-467.
113. Hunter MR, Hunter MD. Designing for conservation of insects in the built environment. *Insect Conservation and Diversity* 2008, 1:189-196.
114. Manuel PM. Cultural perceptions of small urban wetlands: Cases from the Halifax regional municipality, Nova Scotia, Canada. *Wetlands* 2003, 23:921-940.
115. Kaplowitz M, Kerr J. Michigan residents' perceptions of wetlands and mitigation. *Wetlands* 2003, 23:267-277.
116. Boyer T, Polasky S. Valuing urban wetlands: A review of non-market valuation studies. *Wetlands* 2004, 24:744-755.
117. Nassauer JI. Monitoring the success of metropolitan wetland restorations: Cultural sustainability and ecological function. *Wetlands* 2004, 24:756-765.
118. Nassauer JI, Kosek SE, Corry RC. Meeting public expectations with ecological innovation in riparian landscapes. *Journal of the American Water Resources Association* 2001, 37:1439-1443.
119. Özgüner H, Kendle AD. Public attitudes towards naturalistic versus designed landscapes in the city of Sheffield (UK). *Landsc Urban Plann* 2006, 74:139-157.
120. Dunn RR, Gavin MC, Sanchez MC, Solomon JN. The Pigeon Paradox: dependence of global conservation on urban nature. *Conservation Biology* 2006, 20:1814-1816.
121. Howarth S, Slingsby D. Biology fieldwork in school grounds: a model of good practice in teaching science. *School Science Review* 2006, 87:99-105.
122. Danks SG. Schoolyard ponds: safety and liability. *Green Teacher* 2001, 64:29-30.
123. Anderson S, Moss B. How wetland habitats are perceived by children: consequences for children's education and wetland conservation. *International Journal of Science Education* 1993, 15:473-485.
124. Zedler JB, Leach MK. Managing urban wetlands for multiple use: research, restoration, and recreation. *Urban Ecosyst* 1998, 2:189-204.

125. Fuller RA, Irvine KN, Devine-Wright P, Warren PH, Gaston KJ. Psychological benefits of greenspace increase with biodiversity. *Biology Letters* 2007, 3:390-394.
126. Syme GJ, Fenton DM, Coakes S. Lot size, garden satisfaction and local park and wetland visitation. *Landsc Urban Plann* 2001, 56:161-170.
127. Scher O, Chavaren P, Despreaux M, Thiéry A. Highway stormwater detention ponds as biodiversity islands? *Archives des Sciences* 2004, 57:121-130.
128. Scher O, Thiery A. Odonata, Amphibia and environmental characteristics in motorway stormwater retention ponds (Southern France). *Hydrobiologia* 2005, 551:237-251.
129. Hansson L-A, Brönmark C, Anders Nilsson P, Åbjörnsson K. Conflicting demands on wetland ecosystem services: nutrient retention, biodiversity or both? *Freshwater Biology* 2005, 50:705-714.
130. Hsu C-B, Hsieh H-L, Yang L, Wu S-H, Chang J-S, Hsiao S-C, Su H-C, Yeh C-H, Ho Y-S, Lin H-J. Biodiversity of constructed wetlands for wastewater treatment. *Ecological Engineering* 2011, 37:1533-1545.
131. Davies ZG, Fuller RA, Loram A, Irvine KN, Sims V, Gaston KJ. A national scale inventory of resource provision for biodiversity within domestic gardens. *Biological Conservation* 2009, 142:761-771.
132. Gaston K, Smith R, Thompson K, Warren P. Urban domestic gardens (II): experimental tests of methods for increasing biodiversity. *Biodiversity and Conservation* 2005, 14:395-413.
133. Beebee TJC. Habitats of the British amphibians (2): suburban parks and gardens. *Biological Conservation* 1979, 15:241-257.
134. Silvertown J. A new dawn for citizen science. *Trends in Ecology & Evolution* 2009, 24:467-471.
135. Briers RA, Warren PH. Population turnover and habitat dynamics in *Notonecta* (Hemiptera: Notonectidae) metapopulations. *Oecologia* 2000, 123:216-222.
136. Cottenie K, Michels E, Nuytten N, De Meester L. Zooplankton metacommunity structure: regional vs local processes in highly interconnected ponds. *Ecology* 2003, 84:991-1000.
137. Shochat E, Warren PS, Faeth SH, McIntyre NE, Hope D. From patterns to emerging processes in mechanistic urban ecology. *Trends in Ecology & Evolution* 2006, 21:186-191.
138. Diamond JM. Rapid evolution of urban birds. *Nature* 1986, 324:107-108.
139. Turner RK, van den Bergh JCJM, Söderqvist T, Barendregt A, van der Straaten J, Maltby E, van Ierland EC. Ecological-economic analysis of wetlands: scientific integration for management and policy. *Ecological Economics* 2000, 35:7-23.
140. Collins KA, Lawrence TJ, Stander EK, Jontos RJ, Kaushal SS, Newcomer TA, Grimm NB, Cole Ekberg ML. Opportunities and challenges for managing nitrogen in urban stormwater: A review and synthesis. *Ecological Engineering* 2010, 36:1507-1519.
141. Goddard MA, Dougill AJ, Benton TG. Scaling up from gardens: biodiversity conservation in urban environments. *Trends in Ecology & Evolution* 2010, 25:90-98.
142. Foltz S, Dodson S. Aquatic Hemiptera community structure in stormwater retention ponds: a watershed land cover approach. *Hydrobiologia* 2009, 621:49-62.
143. Hamer AJ, Parris KM. Local and landscape determinants of amphibian communities in urban ponds. *Ecological Applications* 2010, 21:378-390.
144. Ackley JW, Meylan PA. Watersnake Eden: Use of stormwater retention ponds by mangrove salt marsh snakes (*Nerodia clarkii compressicauda*) in urban Florida. *Herpetological Conservation and Biology* 2010, 5:17-22.
145. Gagné S, Fahrig L. Effect of landscape context on anuran communities in breeding ponds in the National Capital Region, Canada. *Landscape Ecology* 2007, 22:205-215.
146. Birx-Raybuck D, Price S, Dorcas M. Pond age and riparian zone proximity influence anuran occupancy of urban retention ponds. *Urban Ecosyst* 2010, 13:181-190.
147. Apinda Legnouo EA, Samways MJ, Simaika JP. Value of artificial ponds for aquatic beetle and bug conservation in the Cape Floristic Region biodiversity hotspot. *Aquatic Conservation: Marine and Freshwater Ecosystems* 2013.

148. Burdíková Z, Čapek M, Švindrych Z, Gryndler M, Kubínová L, Holcová K. Ecology of testate amoebae in the Komořany Ponds in the Vltava Basin. *Microb Ecol* 2012, 64:117-130.
149. Akasaka M, Takamura N, Mitsuhashi H, Kadono Y. Effects of land use on aquatic macrophyte diversity and water quality of ponds. *Freshwater Biology* 2010, 55:909-922.
150. Backer S, Onsem S, Triest L. Influence of submerged vegetation and fish abundance on water clarity in peri-urban eutrophic ponds. *Hydrobiologia* 2010, 656:255-267.
151. Backer S, Teissier S, Triest L. Stabilizing the clear-water state in eutrophic ponds after biomanipulation: submerged vegetation versus fish recolonization. *Hydrobiologia* 2012, 689:161-176.
152. Beresford JE, Wade PM. Field ponds in North Leicestershire: their characteristics, aquatic flora and decline. *Transactions of the Leicester Literary and Philosophical Society* 1982, 76:25-34.
153. Beebee TJC. Changes in dewpond numbers and amphibian diversity over 20 years on chalk downland in Sussex, England. *Biological Conservation* 1997, 81:215-219.
154. Langton T. The London pond survey *Oryx* 1985, 19:163-166.
155. Boothby J, Hull AP. A census of ponds in Cheshire, North West England. *Aquatic Conservation: Marine and Freshwater Ecosystems* 1997, 7:75-79.
156. Heath DJ, Whitehead A. A survey of pond loss in Essex, South east England. *Aquatic Conservation: Marine and Freshwater Ecosystems* 1992, 2:267-273.
157. Jeffries MJ, Mills D. *Freshwater Ecology: Principles and Applications*. Chester: Wiley; 1990.
158. Rackham O. *The history of the countryside: the classic history of Britain's landscape, flora and fauna*. London: Dent; 1986.
159. Williams PJ, Biggs J, Barr CJ, Cummins CP, Gillespie MK, Rich TCG, Baker A, Baker J, Beesley J, Corfield A, et al. *Lowland Pond Survey*. London: DETR; 1998.
160. Bailey-Watts T, Lyle A, Battarbee R, Harriman R, Biggs J. Lakes and ponds In: M A, ed. *The Hydrology of the UK: A Study of Change* London Routledge; 2000, 180-203.
161. Bjureke K, Dahlgren U, Fronaeus M, Hansen C, Heister V, Larssen A, Li H. *Margel I Lundabygden*. Lund, Sweden: Environmental Protection Programme; 1976.
162. Hull AP. The pond life project: a model for conservation and sustainability. In: Boothby J, ed. *British Pond Landscapes: Action for Protection and Enhancement*. Liverpool: Pond Life Project; 1997.
163. Weinreich JA, Musters CJM. *The Situation of Nature in the Netherlands*. Den Haag, Netherlands: SDU Publishers; 1994.
164. Glindt D. *Situation, plege unt Neuanlage kleiner Stillgewasser im Flachland Norwestdeutschlands*. Metelen, Germany; 1993.
165. Sukopp H. Grundwasserabsenkungen - Ursachen unt Auswirkungen auf Natur unt Landschaft Berlins. In: *Wasser - Berlin 1981: Vol. 1, Die technischwisenschaftlichen Vortrager auf dem Kongree Wasser*. Berlin; 1981.
166. Ryszkowshi L, Balazy S. *Agricultural Landscapes in Wielkopolska: Threats and Protection*. Poznan, Poland: Research Center for Agricultural and Forest Environment, Polish Academy of Science; 1995.
167. Guadagnin DL, Peter ÂS, Perello LFC, Maltchik L. Spatial and temporal patterns of waterbird assemblages in fragmented wetlands of southern Brazil. *Waterbirds* 2005, 28:261-272.
168. Jeffries MJ. Ponds and the importance of their history: an audit of pond numbers, turnover and the relationship between the origins of ponds and their contemporary plant communities in south-east Northumberland, UK. *Hydrobiologia* 2011, 689:11-21.

Figures

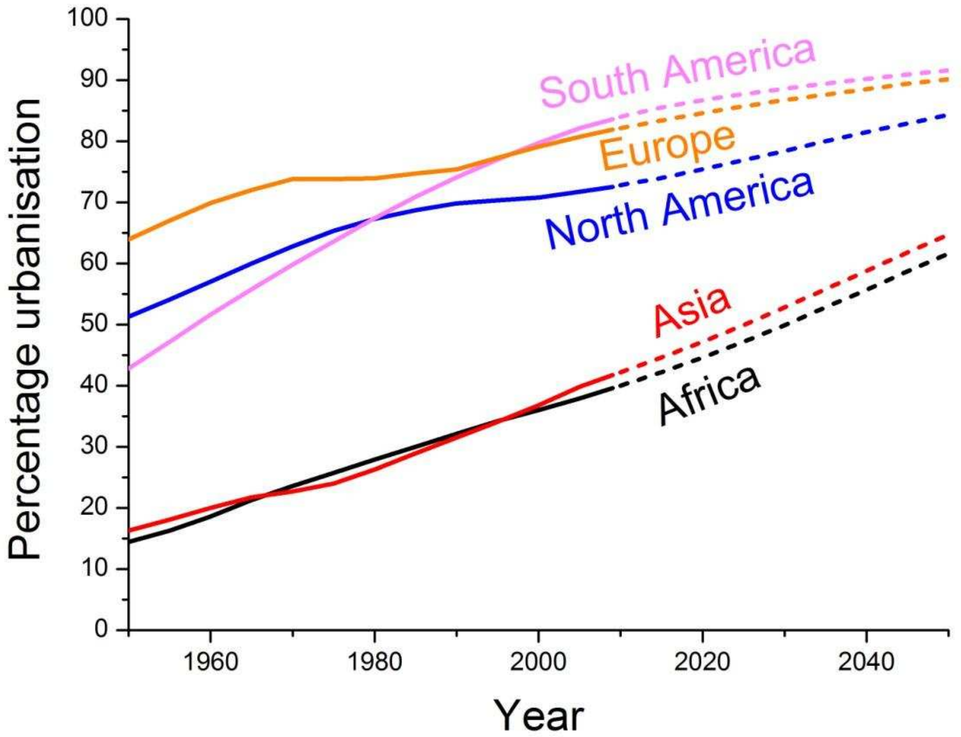

Figure 1 – Past trends and future projections of urbanisation (% population living in urban areas) by continent. Source: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat World Population Prospects: The 2008 Revision and World Urbanization Prospects: The 2009 Revision http://esa.un.org/wup2009/unup/.

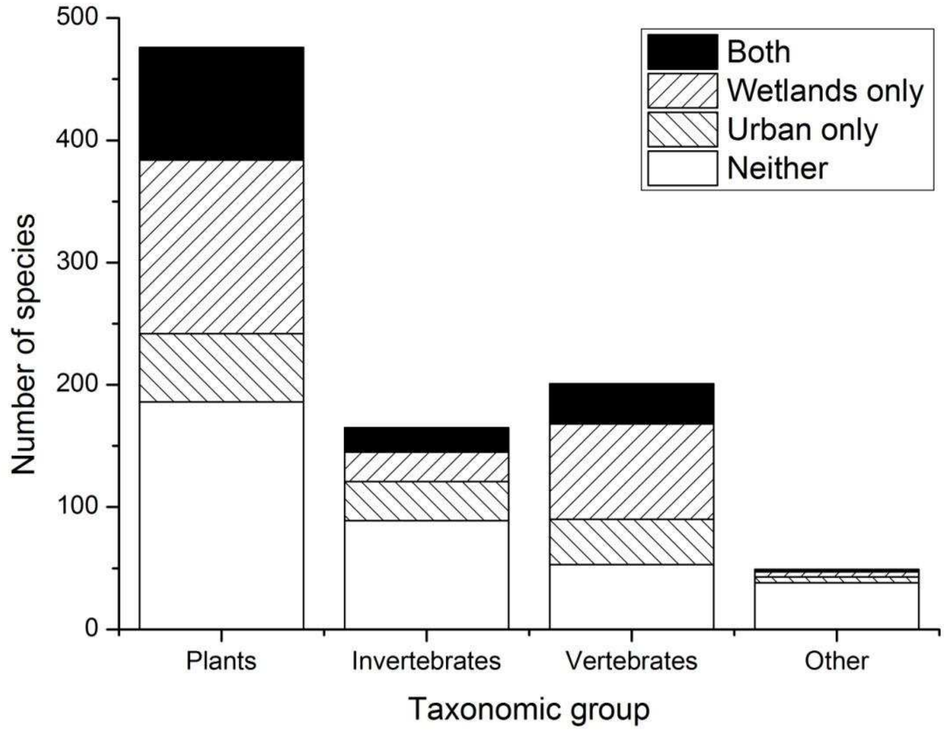

Figure 2 – Habitat use of 891 invasive species listed in the Global Invasive Species Database. "Other" (n=49) includes corals, fungi, micro-organisms, oomycetes, sponges, and tunicates.

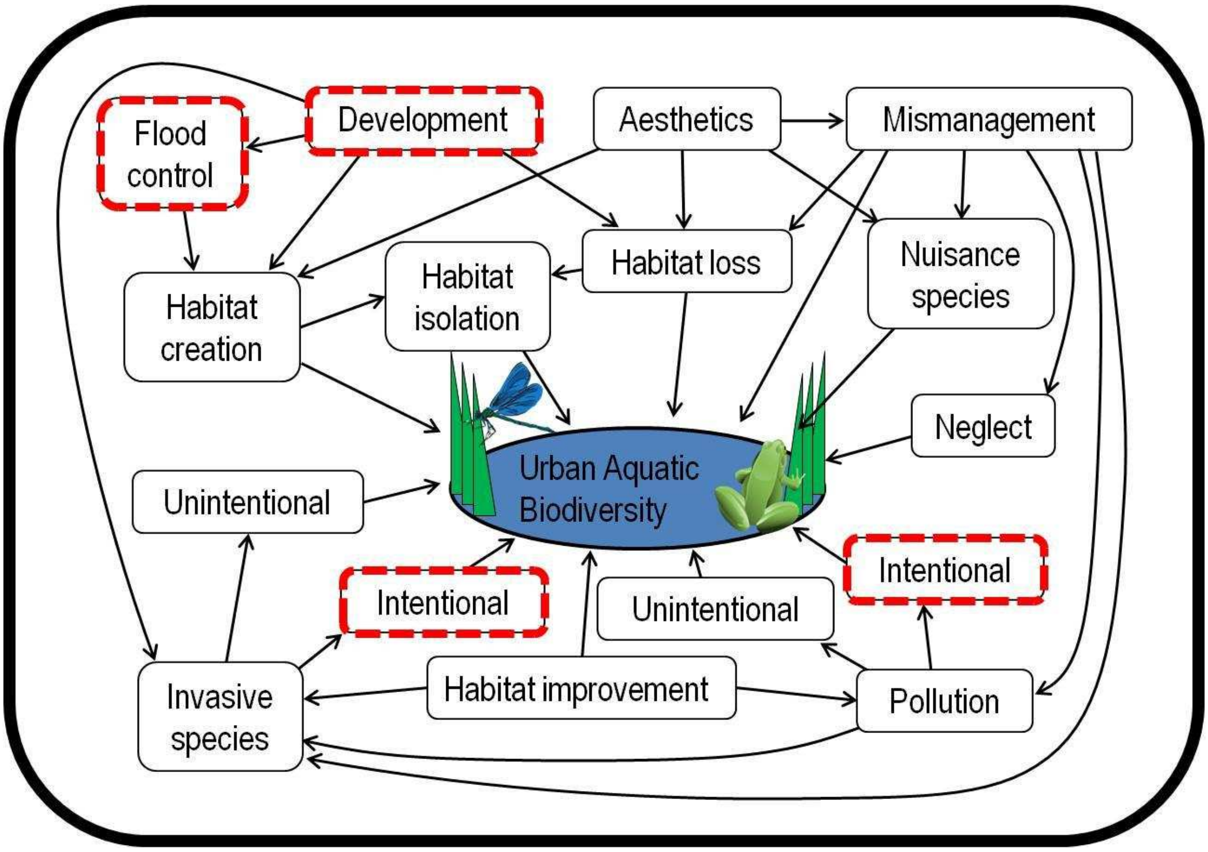

Figure 3 – Multiple interacting factors affecting urban aquatic biodiversity. Red, dotted boxes indicate areas of legal influence.

Tables

Table 1: A proposed typology of urban ponds based on primary function

Urban pond type	Characteristics	Refs
Garden pond	• Small size ($10^1 m^2$) • Set within an impervious matrix • Often stocked with fish • Very rarely dry out • Maintained to prevent succession	131, 132, 141
Industrial ponds	• Medium size (10^2-$10^4 m^2$) • Urban or peri-urban, often away from residential areas • Sometimes contaminated • Constructed to hold water for use, or left after mineral extraction • Rarely in use for original purpose	37, 38, 41
Ornamental lakes and ponds	• Medium-large size (10^2-$10^6 m^2$) • Heavily managed for aesthetics • Hypertrophic • Fish and ducks encouraged and fed • Access to public is encouraged and uncontrolled • Often with vertical sides that may pose problems for animals	44, 50
Drainage systems	• Highly variable in size (10^2-$10^6 m^2$) • Primary function is hydrological management • Diverse design • Wide variation in "naturalness" • Temporary ("detention basins") or permanent ("retention ponds")	40, 52, 65, 66, 101, 142-144
Nature reserves	• Medium-large size (10^2-$10^6 m^2$) • Managed primarily for biodiversity (often birds) • Either co-opted natural ponds or created to appear natural • Access to public is encouraged but controlled	

Table 2: Summary of a range of biodiversity studies conducted on urban ponds (sp=species, gen=genera, fam=families, ord=orders, *=diversity not stated)

Groups studied	Water chemistry	Location	N	Types of ponds	Finding	Ref
Amphibians (6 sp)	None	Maryland, USA	53	16 stormwater ponds, 16 artificial ponds, 21 natural ponds	Artificial ponds are valuable breeding habitat for amphibians, especially when natural wetlands are scarce	40
Amphibians (7 sp)	pH, conductivity	New Jersey, USA	39	Stormwater ponds	Connectivity and fish presence determine presence and composition of amphibian communities	101
Amphibians (9 sp)	Conductivity	Australia	30	Stormwater ponds	Nine frog species were found, which responded differently to disturbance, vegetation and connectivity	65
Amphibians (6 sp)	Conductivity	Australia	65	Stormwater, ornamental, other constructed	Amphibian diversity was higher with greater surrounding green space, and lower with high human population density and water conductivity	143
Amphibians (9 sp)	None	Australia	104	Park and garden ponds in urban and rural areas	Urban amphibians exist in metacommunities, with diversity related to isolation and size of ponds and the presence of vertical walls	44
Amphibians (6 sp)	pH	Canada	29	Urban, agricultural and forested ponds	Amphibian diversity and abundance was lower in urban areas	145
Amphibians (12 sp)	None	North Carolina, USA	25	Stormwater ponds	Anuran presence decreased with increasing distance to the riparian zone, and pond age had a range of effects on different species	146
Autecological study of *Rana temporaria*	None	UK	13	Garden, park and rural comparison	Urban areas constitute barriers to gene-flow in amphibians	97
Autecological study of *Nerodia clarkii compressicauda*	None	Florida, USA	2	Stormwater retention ponds	SWPs harboured exceptionally high biomass of snakes until treatment with glyphosate	144
Fish (11 sp, several varieties)	None	UK	18	Urban park ponds (range of origins)	Introductions of non-native fish increase with public access to a pond	46
Fish (4 sp)	Dissolved oxygen, pH, alkalinity, turbidity, conductivity, chlorides, nitrogen, total dissolved solids, volatile solids, chlorophyll *a*, iron, sulphates	Illinois, USA	1	Stormwater ponds	Stormwater retention ponds can provide a habitat for native, endangered fish	52
Water birds (39 sp)	None	France	11	Gravel pits	Eleven urban gravel pits contain more than	41

					half the regional species pool of water birds.	
Invertebrates (56 fam)	pH, conductivity, dissolved oxygen, nitrate, phosphate	UK	36	Industrial	Former industrial ponds provide refuge for invertebrates in urban areas. Conversion to angling ponds reduces diversity but decreases the probability of pond loss through drainage.	37, 38
Aquatic Hemiptera (26 sp)	Specific conductance, total dissolved solids, salinity, dissolved oxygen	Wisconsin, USA	28	Stormwater ponds	Pond shape, land cover and fish abundance impact Hemiptera communities.	142
Odonata (30 sp)	None	Germany	33	Range from forest/bushland, agricultural land, residential/commercial areas and city parks	Different odonate assemblages are associated with different pond types, and at least one species thrives in urban areas.	50
Coleoptera (40 sp), Hemiptera (17 sp)	Conductivity, dissolved oxygen, pH	South Africa	18	Urban and peri-urban irrigation reservoirs and attenuation ponds	Artificial ponds provide valuable habitat for insects in a biodiversity hotspot	147
Insects (32 sp)	pH, hardness, conductivity, chloride, total phosphorus, ammonium, dissolved oxygen	Argentina	4	Natural and artificial ponds in city parks	Removal of aquatic vegetation during management influences aquatic insect communities	100
Molluscs (21 sp)	pH, calcium	Singapore	24	Reservoirs, park ponds, canals, streams	Reservoirs are an important refuge for molluscs in tropical urban areas, but also harbour invasive species.	51
Cladocera (26 sp)	Total phosphorus	Canada	18	Temporary ponds, permanent lakes, and wetlands	Cladoceran communities varied between temporary ponds, permanent lakes, and wetlands, but all contributed to gamma diversity	103
Testate amoebae (49 sp)	pH, electrolytic conductivity, As, Pb, Cd, Mn, total organic carbon, total nitrogen, inorganic nitrogen, phosphorus, dissolved oxygen, oxygen saturation, polyaromatic hydrocarbons	Poland	4	Stormwater ponds	Negative effect of mineral ions and variable effects of nutrients and temperature on testate amoebae., strong seasonal variations	148
Rotifers (114 sp)	Total phosphorus, total nitrogen	Poland	19	Natural and artificial ponds, clay-pits and pools	Urban ponds contained 25% of total Polish rotifer species pool, with strong variation in assemblages between the diverse array of sites.	42

Macrophytes (49 sp)	pH, dissolved oxygen, total nitrogen, total phosphorus, DOC, suspended solids, chlorophyll *a*	Japan	55	Range of ponds selected on basis of land cover, including urban	Urban land cover and pond enlargement reduced macrophyte diversity	[149]
Macrophytes (57 sp), invertebrates (119 sp), amphibians (4 sp)	pH, conductivity, dissolved oxygen, hardness	UK	37	Not stated, range of successional states and ages	Connectivity is the primary driver of urban pond biodiversity	[96]
Macrophytes (>50 sp), invertebrates (31 fam)	None	North Carolina, USA	20	10 constructed stormwater wetlands (CSWs) and 10 artificial urban ponds	Ponds and CSW have similar invertebrate diversity but different community structure	[66]
Macrophytes (3 sp), zooplankton (19 sp), molluscs (3 sp), amphibians (8 sp), fish (6 sp)	Chlorophyll *a,* total nitrogen, total phosphorus, total dissolved nitrogen, total dissolved phosphorus, dissolved nitrate, specific conductance, % oxygen saturation, chloride, sulphate, total dissolved solids	Wisconsin, USA	23	Artificial ponds	Water chemistry, pond morphology and land cover (particularly % cover of lawns and meadows) correlated with diversity of different components of the biota.	[102]
Invertebrates (7 ord), amphibians (1 sp)	None	UK	19	Experimental garden ponds	Colonisation of small garden ponds over 23 months mostly by Diptera, with other invertebrates infrequent. Ponds were used by amphibians, although no breeding was recorded.	[132]
Cladocera (16 gen), fish (16 sp), rotifers*, copepods*, phytoplankton*	Chlorophyll a, total phosphorus, soluble reactive phosphorus, dissolved inorganic nitrogen	Belgium	13	Overflow and flow-through ponds in Forest and park artificial ponds	Fish recolonisation after biomanipulation to restore clear-water states in ponds affects zooplankton communities, and this is mediated by submerged macrophyte cover	[150, 151]

Table 3: An international comparison of patterns of change in pond numbers

Country	Region	Dates	Pond change (%)	Annual change (%)	Primary source	Cited in
UK (pre-1998)	Huddersfield	1985-1997	-31	-2.6	37	95
	North Leicestershire	1934-1979	-60	-1.33	152	95
	Bedfordshire	1910-1981	-82	-1.15	152	95
	Sussex	1977-1996	-21	-1.1	153	95
	London region	1870-1984	up to -90	-0.79	154	95
	Huntingdonshire	1890-1980	-56	-0.68	152	95
	Cheshire	1870-1993	-61	-0.5	155	95
	Essex (selected areas)	1870-1989	-55 to -69	-0.46 to -0.58	156	95
	Cambridgeshire	1840/90-1990	-68	-0.45 to -0.68	157	95
	Leicestershire	1840/90-1990	-60	-0.40 to -0.60	157	95
	Durham	1840/90-1990	-41	-0.27 to -0.41	157	95
	Clwyd	1840/90-1990	-32	-0.21 to -0.32	157	95
	Midlothian	1840/90-1990	-23	-0.15 to -0.23	157	95
	Edinburgh	1840/90-1990	-6	-0.04 to -0.06	157	95
	England and Wales	1880-1920	-57.5	-1.41	158	95
	Britain	1990-1996	-7.4	-1.23	159	95
	Great Britain	1900-1990	-75	-0.78	160	95
UK (post-1998)	Great Britain	1998-2007	+12.5	1.39	99	99
	England	1998-2007	+18.3	2.03	99	99
	Scotland	1998-2007	+5.5	0.6	99	99
	Wales	1998-2007	+16.9	1.88	99	99
Sweden		1914-1970	-55	-1.0	161	162
Netherlands		1900-1989	-90	-1.0	163	162
Denmark		1868-1974	-67	-0.6	Briggs (unpub)	162
Germany	N Rhine Westphalia	1963-1986	>-40	>-1.7	164	162
	Berlin Sud	1880-1980	-81	-0.8	165	162
Poland	Wielopolska	1890-1941	-56	-1.1	166	162
Brazil		1905-2005	-90	-9.0	167	168

Further Reading/Resources

Faeth, Stanley H, Saari, Susanna, and Bang, Christofer (Jul 2012) Urban Biodiversity: Patterns, Processes and Implications for Conservation. In: eLS. John Wiley & Sons Ltd, Chichester. http://www.els.net [doi: 10.1002/9780470015902.a0023572]

Patterson, Trista M (Dec 2011) Ecosystem Services. In: eLS. John Wiley & Sons Ltd, Chichester. http://www.els.net [doi: 10.1002/9780470015902.a0021902]

Sharitz, Rebecca R, and Batzer, Darold P (Sep 2009) Wetland Communities. In: eLS. John Wiley & Sons Ltd, Chichester. http://www.els.net [doi: 10.1002/9780470015902.a0020461]

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