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Big things come in small packages: why limnologists should care about small ponds

Grandes coisas vêm em pequenos embrulhos: por que limnólogos devem se preocupar com pequenos lagos

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Abstract: There is a substantial, and increasing, body of evidence that small ponds are critically important in diverse landscapes around the world by providing habitat, processing carbon, and mediating hydrological and nutrient fluxes to other larger surface waters (rivers, lakes, coastal). They are also among the most abundant surface water bodies in many areas. In an urbanizing planet, ecosystem services provided by ponds may become even more important. However, they have been historically neglected by limnologists and including them in global analyses can still be problematic. We propose that more limnologists should include small ponds in research programs; and we argue that these are also ideal systems for teaching the next generation of limnologists as well as for engaging the public.

Keywords: aquatic habitat; carbon cycling; nutrient retention; urban aquatic systems.

Resumo: Existem várias evidências de que as pequenas lagoas de água doce são muito importantes em diversas paisagens ao redor do mundo, fornecendo habitat, processando carbono e controlando fluxos hidrológicos e de nutrientes para águas superficiais maiores (rios, lagos e águas costeiras). As pequenas lagoas estão entre os recursos hídricos de superfície mais abundantes em muitas áreas do mundo. Em nosso planeta com intensa urbanização, os serviços ecossistêmicos fornecidos pelas lagoas pequenas podem se tornar ainda mais importantes. No entanto, eles têm sido historicamente negligenciados pelos limnólogos e a forma como incluí-los em análises globais ainda é problemática. Nós propomos que mais limnólogos deveriam incluir pequenas lagoas em programas de pesquisa; e sugerimos que estes ecossistemas são também ideais para ensinar a próxima geração de limnólogos, bem como envolver o público.

Palavras-chave: habitat aquático; ciclagem de carbono; retenção de nutrientes; ecossistemas aquáticos urbanos.

Natural and artificial water bodies smaller than 10 ha in surface area (=ponds) are abundant in many landscapes (Downing et al., 2006), ecologically important and historically ignored by limnologists. However, these ubiquitous features should be more highly valued in our field. We believe that limnology will benefit from renewed focus on these systems which, because of their sheer abundance provide valuable ecological services such as critical habitat, increased regional biodiversity, hydrologic benefits associated with retaining surface waters on the landscape, improvement of surface water quality and likely important hot spots of carbon transformations and possibly carbon sequestration (Céréghino et al., 2014;

Downing et al., 2008). Additionally, ponds provide an underutilized resource in teaching and training of the next generation of limnologists.

What is a pond? There are no clear quantitative characteristics of what constitutes a pond except that they are small (typically <10 ha), shallow and filled with freshwater. Biologists working in ponds have long recognized that they are ecologically different from other types of freshwater systems such as lakes and reservoirs. They may be permanent or seasonal, and they may be created as a direct result of human action or may occur due to a range of natural processes (Oertli et al., 2005). Some definitions include maximum depth criteria (Oertli et al., 2000); many ponds have relatively large areas where the entire water column is within the photic zone.

Does it really matter if we call something a pond or a lake? The size-distribution of the Earth's lakes is highly skewed toward many small lakes vs. few large lakes and many ecosystem processes are known to scale with size (Cael & Seekell, 2016). Søndergaard et al. (2005) found that nutrient concentrations were unaffected by lake size among 800 water bodies spanning a size range of .01 to 4200 ha. Water body size affects diversity for some groups of organisms more than others (Oertli et al., 2002; Søndergaard et al., 2005), but to our knowledge there is no universally accepted ecological threshold for distinguishing a "pond" from a lake or reservoir. Stratification is widely recognized as an important physical characteristic of lakes, affected by surface area and depth (Gorham & Boyce, 1989). However, variation in thermal stratification has been unaccounted for in many past studies (Coloso et al., 2011) and shallow lakes and ponds have complex stratification patterns (Branco & Torgersen, 2009). Treating them as well-mixed as has often been done in the literature may lead to erroneous results. For these and other reasons discussed in the sections that follow, limnologists may wish to consider including smaller water bodies that have been traditionally excluded from limnological studies.

1. Ponds Are Abundant

Estimates by Downing et al. (2006) suggested that the area of lakes and ponds up to 10 ha may be as high as 30% of the global total standing water area; more recent evidence suggests that more conservative estimates may be appropriate (Seekell et al., 2013; Verpoorter et al., 2014). Even though the question has long interested researchers, understanding how many lakes (and ponds) there are globally and how big they are is still an area of active investigation. Recent inventories using high-resolution satellite imagery omit ponds smaller than 0.2 ha in size (2000 m^2) because they are difficult to verify (Verpoorter et al., 2014), although even the very smallest of these (less than 0.1 ha) may have important roles in ecosystem processes (Holgerson & Raymond, 2016).

Our estimates will undoubtedly continue to improve, but small lakes/ponds appear to be numerically the most abundant among both natural and constructed lentic water bodies as well as hotspots for biogeochemical activity, leading some to argue that small aquatic systems may be among the most important, but largely ignored, ecosystems in the world (Downing, 2010). In some geographic areas, the prevalence of ponds is well-documented. For example, small farm ponds are now the dominant lentic ecosystem in the Great Plains of the United States (Huggins et al., 2011) and are common in the Cerrado region of Brazil (Bichsel et al., 2016). The inclusion of small water bodies in more research programs around the world will lead to an increased understanding of how many there are, how big they are, and what role they play in ecosystems.

2. Ponds Provide Important Habitat

Ponds are increasingly understood as an important factor for maintaining regional biodiversity and stability and published papers on these systems have increased quickly in the past decade (Downing, 2010). For example, the European Pond Conservation Network has conducted five international conferences aimed at expanding the understanding and valuing of pond ecosystems (Oertli et al., 2005). This society has contributed significantly to our understanding of ponds and has focused primarily on the habitat and biodiversity services which they contribute. Ponds provide essential inland freshwater habitat for animals and plants and foster maintenance of high regional biodiversity in addition to numerous other societal services.

Ponds have clearly been shown to have enormous value for amphibians (Beja & Alcazar, 2003; Knutson et al., 2004), invertebrates (Cayrou & Céréghino, 2005; Friday, 1987; Williams, 1997), and other groups of organisms (Davies et al., 2016; Sebastián-González et al., 2010). Soomets et al. (2016) demonstrated that ponds constructed for amphibians also serve as habitat for many other important species. Connected networks of ponds are viewed as essential to long-term regional stability by providing corridors for species migrations in response to climate change (Céréghino et al., 2014).

Urban ponds may be important for maintaining regional biodiversity in landscapes that have been highly modified by humans and may not follow the general pattern of reduced taxonomic richness in urban environments that has been shown for terrestrial or stream habitats (Hill et al., 2017). A similar conclusion was reached by Hassall & Anderson (2015) who showed that urban stormwater ponds in Canada have similar macroinvertebrate species richness as nearby unmanaged wetlands. The importance of ponds to pollination and pollinators, affecting important groups such as syrphids and bees as well as food crops such as strawberries was recently demonstrated (Stewart et al., 2017). The authors discuss additional habitat complexity in an environment that includes ponds, as well as the fact that some pollinators have aquatic larvae, as potential contributors to the observed results.

Pond ecosystems in Brazil have been studied to understand habitat and biodiversity services. Permanent man-made ponds up to one ha in size are present in high density (3.9 ponds/km^2) in the agricultural landscapes of the Cerrado of central Brazil (Goiás, BR) and represent important landscape features for maintenance of regional biodiversity (Marco et al., 2014). Shallow ponds provide habitat for tadpoles in an Atlantic rainforest fragment in Pernambuco, Brazil (Andrade et al., 2014). These systems are highly used by numerous species and therefore of likely importance to population stability.

3. Ponds Are Important in Global Carbon Dynamics

The importance of small water bodies to water-related ecosystem services in general should not be overlooked, and carbon cycling, in particular, may be dominated by processes occurring in them (Biggs et al., 2017; Downing, 2010). Ecological interactions between benthic and riparian habitats should be strongest in small and shallow lakes because the perimeter: area ratio generally increases as surface area and depth decrease (Schindler & Scheuerell, 2002). Inland waters (such as ponds) do not simply pass carbon from the land to the sea, but rather processing that occurs in them may be very significant in terms of the global carbon cycle (Cole et al., 2007). While many small natural wetlands have been lost in many areas during the last two centuries (Dahl, 1990), the number of small farm impoundments continues to rise (Smith et al. 2002). Small lentic water bodies (such as ponds) are the most numerous inland water body type in many landscapes (Downing et al., 2006; Smith et al., 2002) and modeling efforts predict that they may be extremely significant in biogeochemical cycles (Downing et al., 2008).

Ponds serve as sites for long-term burial of carbon in sediments. Organic carbon (OC) burial was evaluated in 40 small impoundments in an area of the U.S. that is one of the most intensive agricultural regions of the world (Downing et al., 2008). Estimates of sediment volume accumulation, dry bulk density, and sediment organic matter content in the watersheds were used to estimate sediment OC deposition and burial over the last century. OC burial rates were found to be generally higher for smaller and more productive impoundments. Empirical data regarding carbon burial and release of carbon from sediments for ponds in different areas of the world under varying landscape regimes and climatic conditions would be valuable in understanding the contribution of ponds to carbon retention on the landscape.

The weight of evidence from many studies indicates that lakes and reservoirs as a whole, are net sources of inorganic carbon to the atmosphere (Ask et al., 2012; Cole et al., 2000; Hanson et al., 2003; Raymond et al., 2013; Rubbo et al., 2006; Sand-Jensen & Staehr, 2007, 2009; Staehr et al., 2010, 2012). However, there is well-documented temporal and spatial variation both within and among lakes, and lakes can be net sources of carbon dioxide to the atmosphere some years and net sinks other years (Finlay et al., 2009) or seasons (Laas et al., 2012). Net ecosystem production (NEP) has been less studied in very small inland water bodies such as ponds; determining if they behave the same way as larger lakes and reservoirs, and quantifying variability would further our understanding of the role of the smallest of inland water bodies in carbon cycling. Ponds also are of likely importance in contributions of CO_2 and CH_4 to the atmosphere but are not always effectively represented in global estimates. Recently Holgerson & Raymond (2016) show that very small ponds (<1000 m^2) comprise only 8.6% of area represented by ponds and lakes but account for 15.1% of CO_2 and 40.6% of CH_4 emissions from these sources. Using the data provided by Holgerson &

Raymond (2016), Deemer et al. (2016) show that C-equivalent emissions from ponds may be similar to cumulative releases from reservoirs for CH_4 and higher for CO_2. Additionally, they show that the trophic status of the water body impacts emission rates, with higher rates seen for more eutrophic systems. This could explain the high contribution of ponds to the emission estimates since the smaller ponds tend to be more eutrophic than larger water bodies (Marco et al., 2014).

4. Ponds Likely Serve to Retain Water and Nutrients on The Landscape

The role of small water bodies on the cumulative ecosystem services of hydrology (Bedford, 1996) and water quality (Whigham & Jordan, 2003; Marton et al., 2015) has been less broadly evaluated than for habitat and carbon dynamics. However, given their enormous abundance on the landscape and emerging evidence of their function as biogeochemical reactors, it is possible that they play important and unappreciated roles here too. The fifth conference of the European Pond Conservation Network held in 2012 had numerous presentations highlighting the sustainable solutions ponds can provide in removing diffuse pollutants such as sediments, nitrogen and phosphorus from surface waters (Céréghino et al., 2014). Downing (2010) emphasizes the urgent need to understand patterns and fluxes of nutrients, metals and toxins in small water bodies.

Marton et al. (2015) and Cohen et al. (2016) recently reviewed the importance of small, geographically isolated wetlands (GIW) as biogeochemical reactors on the landscape for various regions of the USA. Both reviews were developed in response to recent supreme court decisions in the USA that will likely reduce federal protection for these systems. While human made ponds were not evaluated, these ponds share many of the key morphometric factors identified as important by Marton et al. (2015) including small size, large shoreline-volume ratio, position and abundance within the landscape. They conclude that despite lack of persistent surface water connectivity to larger bodies of water, these small GIWs are an integral part of landscape level hydrologic and biogeochemical processing and play significant roles in maintaining the integrity of large water features. This conclusion is supported by the work in Central Texas, USA which concludes that ponds and other small water features that occupy a higher position in the landscape relative to larger bodies of water mitigate sediment and nutrient loading by watersheds (Prochnow et al., 2007).

Forbes et al. (2012) demonstrated that small, rainfed wetland depressions and their associated watersheds capture 40% of precipitation falling on the coastal plain landscape around Galveston Bay, Texas, USA. While these coastal prairie wetlands (CPW) are natural features of the landscape, they appear to function hydrologically much like small ponds do in other watersheds. The CPW's studied retained most of the water they received. Because "flow-through" events were rare, these small aquatic features very strong sinks for inorganic N and P (>90% retention) and significant sinks for organic forms of N and P (55-70% retention). While discharge from these systems to coastal waters was rare, they contribute as much as half the organic C load to Galveston Bay. This landscape function of small natural wetlands has recently been extended to constructed wetlands (CW; Tournebize et al., 2017). They show that CW in agricultural watersheds are important sinks for nutrients and pesticides. They further propose that CWs area equivalent to 1% of the upstream drainage area would be effective at reducing nutrient and pesticide levels coming from agriculture landscape. Importantly, these landscape services could result in lower levels of nutrients flowing to coastal waters that contribute to coastal eutrophication. While accurate estimates of areal coverage by small ponds has been slowed by detection limits of traditional remote sensing techniques (see Downing et al., 2006; Holgerson & Raymond, 2016) it is likely that pond area often exceeds the 1% threshold and many agriculture ponds are constructed high in the watershed in the direct vicinity of human-induced disturbances.

5. Ponds Provide an Easily Available Environment for Teaching and Research

We believe that ponds can be effectively used not only to teach students specializing in aquatic sciences but also to educate the general public about water-related issues. Science educators are now keenly aware of the benefits of inclusive learning. Efforts to incorporate outdoor learning into formal learning experiences by focusing on place-based water environments may have powerful impacts on students (McDowell et al., 2014). Ponds are ubiquitous in the urban environment and may maintain many of the key attributes that make them valuable ecosystems. Ponds are ideal outdoor science laboratories to teach about benthic invertebrates, algae, shoreline plants, zooplankton and possibly even some fish communities. It is our observation that many parks, zoos, botanical gardens and other areas have easily accessible ponds that could be used for aquatic science education. In a study examining what motivates teachers to use various nature settings for environmental education (EE), rivers, ponds and marshes were identified by teachers as appropriate settings for EE that their students would enjoy visiting (Simmons, 1998). However, teachers expressed need for training to feel confident in teaching in these areas, and this is a role that limnologists could assist in as part of science outreach efforts. Additionally, leading environmental education organizations such as Project WET (Water Education for Teachers) have developed many educational modules that could be easily used in pond systems to teach the public, some of which are available in Portuguese.

Finally, from a basic scientific perspective, ponds offer limnologists something we all have mostly learned to live without- replication! While conducting studies on multiple lakes or reservoirs is probably resource and cost prohibitive for most efforts, that is not so for ponds. For example, the study of coastal prairie wetlands mentioned previously utilized data from 12 separate wetlands, six of which were monitored for 18 months (Forbes et al., 2012). An ongoing study in our lab is currently evaluating NEP at two times of the year in 30 constructed ponds in Central Texas (Mullins, unpublished data). The usefulness and value of constructing and maintaining mesocosm facilities has been an integral part of many limnologic stations, and we have something very similar available all over the world in the form of ponds. Small coastal lakes in Brazil, for example, exhibit variability over a relatively small geographic area for important limnological variables including pCO2, pH, salinity and dissolved organic carbon which may respond to external factors such as rainfall (Marotta et al., 2010).

In summary, we believe that limnologists should more highly value and prioritize research on ponds and related small water bodies on the landscape. These abundant, accessible and ecologically important areas offer numerous opportunities for research and education that have been undervalued for far too long. Limnologists in Brazil have a unique opportunity to provide important and currently unavailable data on how these small water bodies contribute to some of the key global questions of our day including carbon cycling and maintenance of biodiversity.

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