A review of odonatology in freshwater applied ecology and conservation science

Jason T. Bried[1,3] **and Michael J. Samways**[2,4]

[1]Department of Integrative Biology, Oklahoma State University, Stillwater, Oklahoma 74078 USA
[2]Department of Conservation Ecology and Entomology, Stellenbosch University, Matieland 7602 South Africa

Abstract: The academic study of dragonflies and damselflies (odonatology) is well established, but relatively limited attention has been given to odonates in the context of applied ecology and conservation science. We used the Web of Science™ and Odonatological Abstract Service (ISSN 1438-0269) to capture trends in primary literature, characterize study features (habitats, life stages, etc.), identify research themes, and suggest future directions for odonatology in freshwater applied ecology and conservation science. We found no papers in this area prior to 1980, and 411 papers from 1980 through 2013. Nearly 75% of these papers were recent (since 2005) and >40% were very recent (since 2010). We identified several broad and overlapping research themes: 1) model taxa, 2) tools and indicators, 3) odonate-centered work, and 4) methodological issues and improvements (field sampling, data modeling/simulation, conservation/landscape-scale genetics). We found more reliance on field-based observational approaches than experiments and model-driven exercises, although the number of papers using model-driven exercises is rapidly increasing. We found a strong focus on adult stages, odonate assemblages, the Odonata as a whole, and studies of particular species. We identified research priorities in areas such as ecological valuation and management, monitoring and assessment, climate change and landscape planning, concordance with other taxa, effects of urbanization, data modeling/simulation, and rare-species ecology and conservation. To help establish an identity and facilitate communication, we suggest naming this diverse realm "applied odonatology". We think applied odonatology has a good future for a range of topics from conservation genetics and population ecology to assessments of anthropogenic impacts and the conservation of biodiversity.
Key words: dragonflies, assessment, climate change, monitoring, landscape planning, freshwater health, biodiversity conservation

The academic study of dragonflies and damselflies (odonatology) is well established. However, relatively few odonatologists work outside of taxonomy and systematics, behavioral ecology, evolutionary ecology, and other prominent areas of classical research. The major books (Corbet 1999, Córdoba-Aguilar 2008), treatises (e.g., Corbet 1980, Stoks and Córdoba-Aguilar 2012), and flagship journals of odonatology reveal a productive legacy, but also relatively limited attention to matters of applied ecology and conservation science. For example, <5% of the 275 papers published during 2009–2013 in *Odonatologica* and the *International Journal of Odonatology* are clearly relevant to applied ecology or conservation science. Nevertheless, the relatively few odonatologists working in this area and researchers based in other fields who often or sometimes use odonates as principal study subjects are making important contributions.

A growing body of dragonfly-related research deals with the study or use of odonates in the context of freshwater applied ecology and conservation science. No general review of odonatology has been done in this broad context, although detailed reviews have been made of relevant subject areas (e.g., Hassall and Thompson 2008). Our purpose was to review the odonatological literature for studies related to applied ecology and conservation science, and to provide a formal synthesis and baseline for assessing advances in freshwater applied science and conservation via odonates. Rather than diving deeply into any particular subject area, we tried to cover many different areas and provide a general map of the diverse field. We excluded nonscientific topics, such as odonates in ecotourism, culture, and symbolism, and environmental education, despite the importance of these areas to public awareness and conservation (Primack et al. 2000, Lemelin 2007). We also did not consider the extensive work in odonate faunistics as being inherently applied, even though faunistic efforts provide essential information for assessments of conservation status and niche mod-

E-mail addresses: [3]bried@okstate.edu; [4]samways@sun.ac.za

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eling. Our goal was to reach out to odonatologists and the broader freshwater-science community seeking tools and model taxa with which to address pressing issues in the realm of applied ecology and conservation science (Strayer 2006).

METHODS

We extracted odonatology literature stored in the Web of Science™ by querying TOPIC: (dragonfl* OR damselfl* OR Anisoptera OR Zygoptera OR Odonata) AND YEAR: (1900–1980 at 5-y intervals, 1980–2013 annually). We searched for primary literature (international peer-reviewed journals) that appeared to meet the criteria for applied ecological or conservation science, as defined by the aims, scope, and content of several leading journals (e.g., *Aquatic Conservation: Marine and Freshwater Ecosystems*, *Biological Conservation*, *Insect Conservation and Diversity*, *Journal of Applied Ecology*). We assessed each candidate paper and categorized it relative to the 17 subject areas listed in Table 1. The small number of applied/conservation papers that did not clearly fit at least one of the main subject headings were classified as Miscellaneous. We excluded purely faunistic or nonscientific surveillance investigations and the many studies in which results were reported for odonates but that did not explicitly target odonates (e.g., Gee et al. 1997, Maxted et al. 2000, King and Richardson 2007). However, we did count studies of broader issues that used odonates and other taxa as model or target groups (e.g., Siegfried 1993, Richter et al. 1997, Palmer 1999, Le Viol et al. 2009, Rosset et al. 2013, 2014).

We used the Odonatological Abstract Service (ISSN 1438-0269) to expand the Web of Science search results. The Odonatological Abstract Service, published by the International Dragonfly Fund in cooperation with the Worldwide Dragonfly Association, is an ongoing effort to compile odonate-related publications (in any language) using Google® searches, publisher databases, alerts from Google and publishers, and a correspondence network of odonatologists. This repository contains the world's largest collection of odonate-related literature, including items from primary and regional/domestic journals, museum bulletins, government reports and technical series, conference abstracts and proceedings, theses and dissertations, and other sources. We viewed titles, keywords, abstracts, and compiler annotations of all primary literature available from 1997 (when the abstract service began) through 2013, and stopped at the June 2014 issue. We avoided papers in recently launched open-access journals because of concerns about credibility (Bohannon 2013). The complete service was accessed using a fully searchable database built and maintained by M. Schorr (International Dragonfly Fund).

Table 1. Major odonatology research areas in freshwater applied ecology and conservation science using the Web of Science™ (1980–2013) and Odonatological Abstract Service (1997–2013), with the total number of articles from international peer-reviewed journals (No. papers) and frequently associated topics. Categories are not mutually exclusive; many entries were classified under 2 or 3 subject areas (see Appendix S1).

Subject area	No. papers	Key research topics
Biocontrol	16	Mosquitos, rice pests
Conservation status	23	Priority species, status ranks, vulnerability, Red Lists
Disturbance and threats		
Climate change	38	Range shifts, phenologic shifts
Invasives	19	Introduced fish, zebra mussels, *Acacia* trees
Urbanization	13	City landscapes, gradients of human development, secondary habitats
Other	65	Agroecology, forestry, altered vegetation
Diversity and distributions	36	Biodiversity, biogeography, hotspots
Ecological management	34	Habitat creation, recovery, remediation, restoration
Genetics	36	Conservation genetics, landscape-scale genetics
Landscape ecology	39	Movement and dispersal, metapopulations and metacommunities, fragmentation
Methods and modeling	49	Field surveys, genetic methods, climate and niche modeling
Monitoring and assessment		
Indicators	57	Pollution, climate change, diversity, ecological condition, fluctuating asymmetry
Other	44	Bioassessment, index applications, population and community trends
Planning and valuation	47	Reserve selection/design, species recovery plans, secondary habitats
Pollution and toxicology	60	Agriculture/pesticides, heavy metals, developmental instability
Rare species ecology	26	Autecology, habitat requirements, population trends
Miscellaneous	6	Various topics

For each paper we recorded the year, journal name, geographic location, study type, major habitat, life stage, community vs species focus, general research theme (described below in 'General research themes'), and up to 3 subject areas (see Table 1) based on perceived relevance. The categories in several information fields were not mutually exclusive, and many papers fit into >1 category. We left fields blank when the information was lacking or ambiguous in the abstract or not logically or scientifically applicable—e.g., the habitat type in laboratory studies and in some modeling exercises. Geographic location was the study location (when applicable and discernible) or the location of the corresponding author's institution. We viewed the full-text articles as needed, using an extensive library of >13,200 portable document files compiled by M. Schorr, journals in library holdings, and interlibrary loan service at Oklahoma State University.

All database searches were conducted by one of us (JTB), and all the numbers and figures reported in our paper are best interpreted as minimum estimates. The 2nd author (MJS) checked the various classifications for 30% of the selected papers and did not find any disagreements. We focused on primary literature because the full text is more readily available than for gray literature and to capture a globally representative cross-section of the broadest trends shaping applications and conservation in odonatology. We acknowledge that regional variation exists in research priorities, and we recognize that a vast amount of information on odonates is contained in domestic/regional journals and other gray literature (M. Schorr, personal communication).

RESULTS

We found no applied ecological or conservation science entries (searching primary literature only) in the Web of Science and Odonatological Abstract Service prior to 1980 (searching at 5-y intervals starting from 1900), and 411 papers in the annual search from 1980 through 2013 (Appendix S1). International peer-reviewed journal articles constituted ~35% of the total English-language entries (~8800) in the Odonatological Abstract Service. We treated several journal special series with an applied/conservation theme as single records. The number of new papers per year generally increased during the 34-y period (Fig. 1). Nearly 75% of papers appeared after 2005 and >40% after 2010.

Research characteristics of the 411 papers are given in Appendix S1. Here we provide an overview. The first clear records of applied ecology or conservation science (Moore 1980, Garrison and Hafernik 1981) focused on population ecology, habitat requirements, and threat factors of 2 rare damselfly species, and were followed by 6 more papers during the 1980s (Fig. 1). At this time, odonates began to feature prominently in some areas (e.g., aquatic toxicology), but contributions were lacking in newer applied research areas, such as climate change, invasive species, conservation genetics, urbanization, and restoration ecology. Conservation-status assessments, including regional and global Red Lists, became more frequent during the 1980s and 1990s, as did evaluations of odonates for use in biocontrol of mosquitos (e.g., Miura et al. 1990, Sebastian et al. 1990). Total contributions increased steadily into the 2000s (Fig. 1), but the percentage of papers on applied ecology and conservation science remained low (<5%).

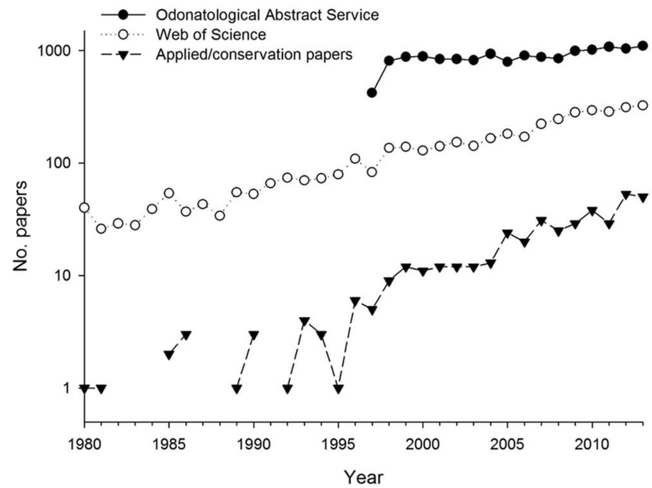

Figure 1. Cumulative odonate literature (papers in international peer-reviewed journals, excluding recently launched open-access journals) in the realm of applied ecology and conservation science based on the Web of Science™ (1980–2013) and complete Odonatological Abstract Service (1997–2013). We found no odonate papers on applied ecology or conservation science before 1980.

Empirical, observation-based research has been more common than experiments (Fig. 2A), suggesting a prevalence of fieldwork, although experimental manipulations and laboratory trials occur regularly in odonate-based biocontrol and ecotoxicology (e.g., Hardersen et al. 1999, Singh et al. 2003). The growing number of modeling and simulation efforts, although a small fraction overall (Fig. 2A), is a significant addition to the experiments and observational approaches in odonatology. Attention to conservation genetics and landscape-scale genetics has increased greatly over the past decade.

Studies were done most frequently at ponds or wetlands, least frequently at lakes, and with intermediate frequency at rivers and streams (Fig. 2B). This pattern was partly driven by the breeding habitats of target species. Adult and larval stages were used far more frequently than eggs and exuviae (Fig. 2C), which were surveyed more often in combination with other stages (6 and 23 papers, respectively) than alone (2 and 6 papers). Last, a community-level

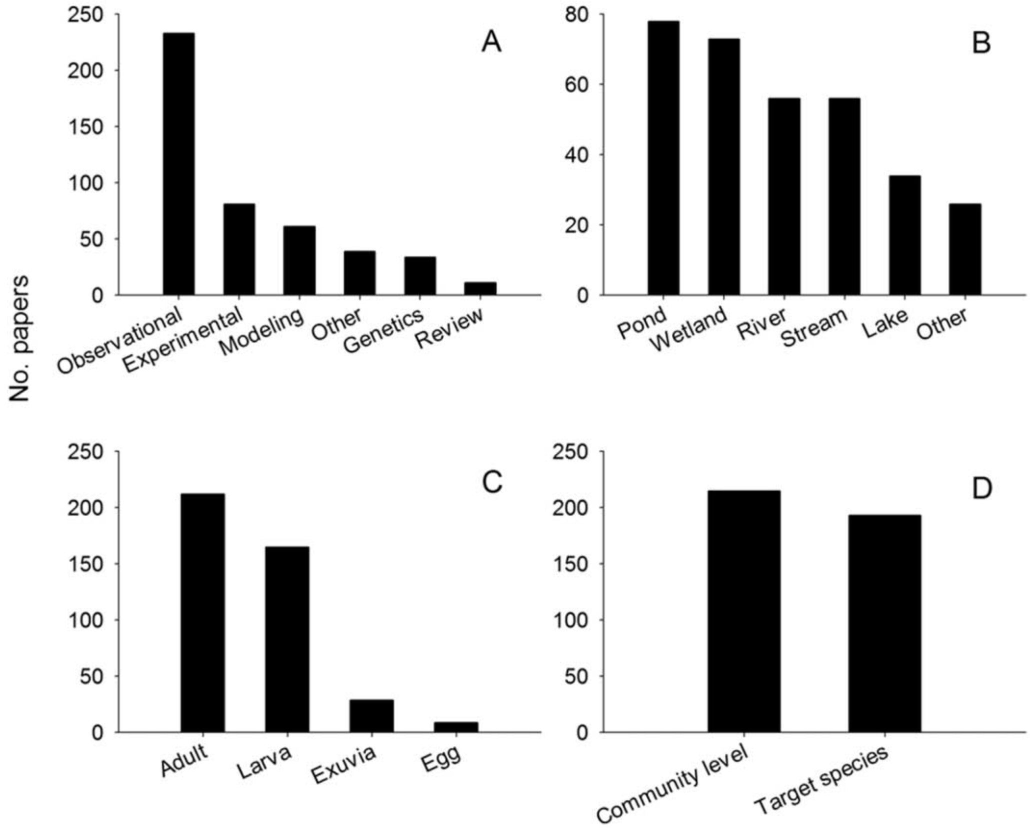

Figure 2. Distributions of study types (A), major habitats (B), life stages (C), and community vs species focus (D) in odonatology application and conservation science based on entries in the Web of Science™ (1980–2013) and complete Odonatological Abstract Service (1997–2013). In panel A, most 'other' papers were focused on assessments of conservation status. In panel B, 'other' papers included miscellaneous study habitats, such as springs, ditches, uplands, and phytotelmata. About 10% of the wetland studies were done in rice paddies, and ~5% of the pond studies involved artificial mesocosms.

focus was at least as common as target-species research, with 215 vs 186 papers, respectively (Fig. 2D).

GENERAL RESEARCH THEMES

We propose several research themes broadly defined as: 1) odonates as model organisms, 2) tools and indicators, 3) odonate-centered work, and 4) methodology (as a primary or secondary focus) (Table 2). Odonate-centered work comprised the largest number of database entries (173 primary publications) followed by tools and indicators (154), model organisms (104), and methods (59, ~50 with primary focus on methods or modeling). The categories are not mutually exclusive, and at least 18.5% of the 411 papers fit in multiple themes. In the discussion below, we cite articles published before 2014 as numerals and list them in Appendix S2.

Odonates as model taxa

Authors of papers in this category used odonates as principal subjects in studies designed to address broader problems in applied ecology and conservation science. Odonates are excellent models with which to test ideas, problems, and theory in applied landscape and community ecology. For example, they have been used to address questions about genetics, life history, and movement dynamics in human-dominated heterogeneous landscapes (9, 18, 48, 51, 56, 104, 105, Feindt et al. 2014, Harms et al. 2014, Suhonen et al. 2014). Other applications include the study of metapopulation and metacommunity dynamics in patchy or changing environments (16, 82, 99), partitioning variation in community responses among natural and anthropogenic drivers (65, 82), and testing predictions or implications of island biogeographic theory for biodiversity conservation (17, 83, 86, 121, Heiser et al. 2014).

This category also includes studies of odonate behavior in the context of major environmental stressors, such as predicting how pesticides, invasive species, and climate change may alter growth or predator–prey interactions (47, 96, 102, 112, 119). Many experimental studies of tadpole antipredator defense were done with odonate larvae as the model predator, and some investigators explicitly incorporated applied perspectives, such as pollution stress and invasion biology (55, 103, 108, 109, 118).

Table 2. General research themes for odonatology in freshwater applied ecology and conservation science. Subject areas correspond to Table 1. Values in parentheses are the percentage of papers in that subject area across the 4 categories (using single-category papers only).

Category	Main subject areas
1. Model taxa for applied ecology and conservation science	Climate change (64%), landscape ecology (53%)
2. Tools and indicators for conserving other taxa and systems	Indicators (93%), biocontrol (93%)
3. Odonate-centered, concern for species and their habitats	Rare species ecology (91%), conservation status (86%)
4. Method issues and improvement	Methods and modeling (93%)

More broadly, authors of these studies used odonates to help test whether predators modify the effects of nutrients/contaminants or invasive species on aquatic communities (116, 123). Odonates have good potential as model systems for aquatic toxicology (Stoks et al. 2015), including the transfer of toxic materials to higher taxa or across the land–water boundary (1, 106). As mid-level consumers with complex life histories, odonates may have a key role in trophic cascades addressed from the perspective of invasive species (92), local habitat alteration (62), and large-scale environmental change (98).

Other types of research done with odonates as model taxa include studies of biologically based selection and design of reserves (81, 85); shifts in phenology, distribution, and diversity in response to modern climate change (27, 36, 45, 115, Li et al. 2014); and planning of reserve networks under future climate scenarios (Bush et al. 2014a). The line between model taxa and tools/indicators (next section) may blur in these studies.

Odonates as tools and indicators

Studies that most clearly belong in this category are those that were done to develop or test odonate-based indices for freshwater monitoring and evaluation, such as the Dragonfly Biotic Index (38, 87) and a habitat association index for river–floodplain systems (11, 20, Chovanec et al. 2014). More broadly, odonates often are viewed as indicators or sentinels of environmental change and perturbation to freshwaters (52, 74, 80, 117). For example, indicator studies may use odonate mortality levels and developmental instability to assess pesticides and habitat alteration (e.g., 2, 5, 34, 107) and the potential transfer of contaminants to higher taxa and terrestrial systems (e.g., 1, 40, 49). Most evidence supporting odonates as indicators currently is context-specific and related to particular stressors or water-quality variables rather than to general ecological condition of freshwaters and surrounding landscapes (Kutcher and Bried 2014).

Odonates may be used as indicators for monitoring habitat creation, improvement, and restoration (8, 22, 50, 59) or as a focal group in prioritization schemes, identification of biodiversity hotspots, and assigning value to natural areas for inclusion in parks or protected areas (e.g., 6, 12, 64, Hart et al. 2014). Odonates also can be used when evaluating biodiversity in secondary or man-made aquatic habitats (e.g., 61, 99) or may have potential as a cross-taxon surrogate to represent broader freshwater diversity patterns (13, 19, 25, 32, 38, 94, 122). Many other potential uses of odonates as indicators, such as in conservation genetics applied to environmental monitoring (26) or when delineating protective buffer zones adjacent to habitat patches (29), have received little attention.

Scientific consideration of odonates for biocontrol continues to be common and probably is the best example of using odonates as agents of ecological services to humans (54). Much of the research on using odonates for biocontrol takes place in India and is focused on mosquitos (21, 35, 110), but odonate-based pest control has been evaluated in other contexts (3, 15, 46). Authors of recent reviews in biocontrol have highlighted the predatory capacity of odonates and called for further research (37, 63). Another example of service provided by odonates is conservation work driven by nonscientists but built on scientific underpinnings (e.g., 10, 14).

Odonate-centered research

Research in this category generally does not reach broader conclusions and implications for other taxa (including humans) or for ecosystem health and functioning. Instead, the studies are intrinsically motivated and targeted at particular species or assemblages (e.g., 60, 70), covering topics, such as rankings of conservation status, threat assessments, distributions and vulnerability, levels of endemism, and conservation genetics. Recent accomplishments include broad status assessments and prioritization schemes across regions, nations, continents, and the globe (e.g., 31, 33, 57, 67, 69, 93, 124, White et al. 2015). At the same time, finer-grained status rankings (e.g., 120) recognize the need to account for local rarity patterns and the logistical/jurisdictional realities of implementing conservation actions. Threat assessments may range from particular aspects of odonate biology (e.g., 89) to use of broad ecological patterns to guide conservation and management plans (e.g., 39). Odonatologists have studied odonate responses to a variety of anthropogenic threats, such as forestry and agriculture (e.g., 7, Koch et al. 2014), mining (e.g., 78), aquatic invasions (e.g., 4, 58), boating (e.g., Hall et al. 2015), and urbanization (e.g., Monteiro-Júnior et al. 2014). Many odonate-centered projects have focused on the genetics or ecology of rare and declining species (e.g., 72, 114, Dolný et al. 2014, Monroe and Britten 2014), and certain species of concern, such as *Coenagrion mercuriale* in Europe, *Hemiphlebia mirabilis* in Australia, *Mortonagrion hirosei* in Japan, and *Somatochlora hineana* in the USA, have received considerable attention.

Methodology

The importance of methodology is strongly appreciated throughout the biological sciences, as exemplified by numerous textbooks (e.g., 76) and journals, such as *Methods in Ecology and Evolution*. We found 49 papers focused largely or exclusively on methods and modeling (Table 1). Authors of such papers view methods as a means to an end and as an end in itself and strive to develop new methods, improve existing ones, or evaluate alternatives. Papers in this category often are specifically about methods for studying odonates, but broader methods issues can be addressed using odonates (e.g., 79, 95, Yoshioka et al. 2014).

Papers in this category tend to address genetic methods, field methods, and data modeling/simulation approaches. With regard to genetics, applications have ranged from developing genetic markers for conservation and population studies of vulnerable species (e.g., 24, 88) to new statistical approaches for quantifying landscape genetic structure (113). Other examples include nonlethal tissue sampling for protected species (28, 73), comparing genetic vs field estimates of population size and dispersal rates (42, 43), efficacy of DNA extraction from museum-archived material (44), and DNA barcoding to identify population boundaries and conservation units (53).

Field-methods research deals with principles of study design (sample size, representativeness, stratification, etc.), sampling logistics, statistical efficiency (minimizing variance), and observation biases. For example, investigators have evaluated line–transect distance sampling (30) and mark–recapture estimates of dispersal and population size (41, 101, Harms et al. 2014). Others have assessed the utility of exuvial sampling for sensitive species (23), the trade-offs of sampling different life stages (75, 90, 97), and empirical guidelines for cost-effective field surveys (91).

Researchers are active in building and validating odonate habitat and niche models, which are being used increasingly for predicting climate-induced range shifts and life-history alterations (66, 84, 111, Bush et al. 2014b). As odonate species distribution modeling becomes more mainstream, critical evaluations of ecological assumptions and model accuracy will be needed (68, 100, Collins and McIntyre 2015). Modeling the factors that control variation in probability of species detection deserves greater attention in odonatology (90). Controlling for imperfect detectability is important for estimating occupancy and abundance from standardized field surveys and may help investigators exploit extensive opportunistic data (71, 77, 125).

CONCLUSIONS AND RESEARCH PRIORITIES

Applied ecology and conservation science involving odonates has undoubtedly been shaped by greater popular and scientific awareness for insect conservation in general (Samways 1994, 2005, 2007, Bassett et al. 2009, New 2012). However, despite significant progress, the literature of odonatology in freshwater applied ecology and conservation science is sparse relative to the literature in behavioral ecology, sexual selection, morphological and molecular systematics, and other prominent areas (see Córdoba-Aguilar 2008). Our broad circumscription in Table 2 recognizes the intrinsic and utilitarian value of odonates and the importance of underlying methods. Research in applied ecology and conservation science tends to be more interdisciplinary and integrative than basic research, especially in studies of model taxa and tools/indicators where odonates usually are not the ultimate concern. These themes help place odonatology into the wider context of freshwater applied ecology and conservation science.

The results of our literature review indicate that descriptive or comparative observational approaches are used more than natural or manipulative controlled experiments and modeling approaches, but the use of modeling is increasing rapidly and can help compensate for deficiencies in purely observational studies, such as imperfect detectability. Experiments in odonatology have relied more heavily on larvae (easier to manipulate than adults) and particular species, whereas the observational approach seems to favor adult stages and species assemblages. Wetlands appear to be popular study habitats, but we caution that the term *wetlands* is often misused to refer to aquatic systems that are not bogs, marshes, swamps, or other true wetland types (Mitsch and Gosselink 2007). Moreover, investigators may have sampled wetland habitats within an encompassing aquatic system (e.g., a lake-fringe wetland) and named the habitat type according to the sampled area and not the larger habitat complex.

Our review suggests several research areas that would benefit from more attention. These are areas where odonates could make a substantial contribution, both as subjects in their own right and as tools or models for other taxa and ecological systems. The general priorities include, but are not limited to:

- Environmental change: synergies between climate change and landscape/habitat alteration, geographical range shifts, assisted dispersal strategies (Hoegh-Guldberg et al. 2008, Loss et al. 2011); e.g., How resilient are odonates to climate change?

- Reserve/natural area planning: protected area buffer zones, development of large-scale reserve networks, spatiotemporal congruence with other taxa; e.g., How well do Biosphere Reserves function? Are odonates surrogates for freshwater biodiversity?
- Ecological valuation and management: cost–benefit analyses of management interventions (sensu Morlando et al. 2012), ecological services including biocontrol of mosquitos and agricultural pests, value of natural vs created habitats, value of secondary habitats; e.g., Are rare or threatened species conserved in secondary habitats? Can odonates be used more widely for biocontrol of mosquitoes and, if so, how might the habitat (such as rice paddies) be modified to accommodate them?
- Urbanization and development: value of urban ponds for conservation of odonates, importance of riparian corridors in urban settings, road ecology; e.g., Is there a certain number, size distribution, or spatial distribution of ponds and wetlands that will maximize odonate diversity in urban settings? Are riparian zones important connectivity features in developed areas? Are odonates as threatened as butterflies by roads? Do we assume that all roads are barriers/obstacles, or are roads with low traffic volume flight corridors?
- Monitoring and modeling: community-level trends analysis (could use hierarchical occupancy models; DeWan and Zipkin 2010), estimating species tolerance values (to pollution or anthropogenic stress in general), consequences of native and nonnative species invasions, tracking restoration progress based on habitat potential (Bried et al. 2014, Chovanec et al. 2014), field validation of distribution model predictions, accounting for imperfect and varying detection probability, inferences from extensive citizen-science data sets; e.g., Can dragonfly-based ecological integrity indices be applied at large spatial scales (a pan-African Freshwater Health Assessment based on the Dragonfly Biotic Index is being done now)? Which odonate metrics (e.g., community structure vs ecological traits) work best, and do odonates add value to the Ephemeroptera, Plecoptera, Trichoptera trio of sentinels? Can citizen scientists be involved in recording particularly sensitive species?
- Field methods: optimal sampling design (site vs survey replication tradeoff), survey effort guidelines (frequency, duration, seasonal placement), interchangeability of major life stages (mature adults, tenerals, exuviae, larvae), criteria to extract locally autochthonous (resident) species in adult surveys; e.g., Can we establish universal procedures?
- Rare species ecology and conservation: brood size estimation, prediction of extinction risk (Population Viability Analysis), captive rearing and species reintroduction, conservation/landscape-scale genetics; e.g., Can we afford to address key threats to certain odonate species (fine-filter conservation) or should we operate only at the community and ecosystem levels (coarse-filter)?

Odonates have inherent strengths for use in freshwater applied ecology and conservation science, including ontogenetic linkage of aquatic and terrestrial systems, sensitivity to thermal conditions and water pollution in general, rapid response to large-scale environmental change, complex trophic interactions, keystone status in some ephemeral or fishless systems, and charisma to engage popular interest. We propose that dragonflies and damselflies are valuable as model taxa, tools and indicators, and subjects in their own right. We suggest referring to the academic study or science-based usage of odonates in the realm of applied ecology and conservation science as *applied odonatology*, a convenient name representing a diverse yet distinctive subset of odonatology. As research accumulates in priority subject areas, applied odonatology will require targeted reviews and meta-analyses to synthesize the important trends and facilitate further advancement. We think applied odonatology has a good future for a range of topics from conservation genetics and population ecology through to assessing anthropogenic impacts and the conservation of biodiversity.

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LITERATURE CITED

Basset, Y., B. A. Hawkins, and S. R. Leather. 2009. Visions for insect conservation and diversity: spanning the gap between practice and theory. Insect Conservation and Diversity 2:1–4.

Bohannon, J. 2013. Who's afraid of peer review? Science 342:60–65.

Bried, J., T. Tear, R. Shirer, C. Zimmerman, N. Gifford, S. Campbell, and K. O'Brien. 2014. A framework to integrate habitat monitoring and restoration with endangered insect recovery. Environmental Management 54:1385–1398.

Bush, A., V. Hermoso, S. Linke, D. Nipperess, E. Turak, and L. Hughes. 2014a. Freshwater conservation planning under climate change: demonstrating proactive approaches for Australian Odonata. Journal of Applied Ecology 51:1273–1281.

Bush, A. A., D. A. Nipperess, D. E. Duursma, G. Theischinger, E. Turak, and L. Hughes. 2014b. Continental-scale assessment of risk to the Australian Odonata from climate change. PLoS ONE 9:e88958.

Chovanec, A., M. Schindler, J. Waringer, and R. Wimmer. 2014. The Dragonfly Association Index (Insecta: Odonata)—A tool for the type-specific assessment of lowland rivers. River Research and Applications (in press). doi:10.1002/rra.2760

Collins, S., and N. E. McIntyre. 2015. Modeling the distribution of odonates: a review. Freshwater Science 34:1144–1158.

Corbet, P. S. 1980. Biology of Odonata. Annual Review of Entomology 25:189–221.

Corbet, P. S. 1999. Dragonflies: behavior and ecology of Odonata. Cornell University Press, Ithaca, New York.

Córdoba-Aguilar, A. (editor). 2008. Dragonflies and damselflies: model organisms for ecological and evolutionary research. Oxford University Press, Oxford, UK.

DeWan, A. A., and E. F. Zipkin. 2010. An integrated sampling and analysis approach for improved biodiversity monitoring. Environmental Management 45:1223–1230.

Dolný, A., F. Harabiš, and H. Mižičová. 2014. Home range, movement, and distribution patterns of the threatened dragonfly *Sympetrum depressiusculum* (Odonata: Libellulidae): a thousand times greater territory to protect? PLoS ONE 9: e100408.

Feindt, W., O. Fincke, and H. Hadrys. 2014. Still a one species genus? Strong genetic diversification in the world's largest living odonate, the Neotropical damselfly *Megaloprepus caerulatus*. Conservation Genetics 15:469–481.

Garrison, R. W., and J. E. Hafernik. 1981. Population structure of the rare damselfly, *Ischnura gemina* (Kennedy) (Odonata: Coenagrionidae). Oecologia (Berlin) 48:377–384.

Gee, J. H. R., B. D. Smith, K. M. Lee, and S. Wyn Griffiths. 1997. The ecological basis of freshwater pond management for biodiversity. Aquatic Conservation: Marine and Freshwater Ecosystems 7:91–104.

Hall, A. M., S. J. McCauley, and M.-J. Fortin. 2015. Recreational boating, landscape configuration, and local habitat structure as drivers of odonate community composition in an island setting. Insect Conservation and Diversity 8:31–42.

Hardersen, S., S. D. Wratten, and C. M. Frampton. 1999. Does carbaryl increase fluctuating asymmetry in damselflies under field conditions? A mesocosm experiment with *Xanthocnemis zealandica* (Odonata: Zygoptera). Journal of Applied Ecology 36:534–543.

Harms, T. M., K. E. Kinkead, and S. J. Dinsmore. 2014. Evaluating the effects of landscape configuration on site occupancy and movement dynamics of odonates in Iowa. Journal of Insect Conservation 18:307–315.

Hart, L. A., M. B. Bowker, W. Tarboton, and C. T. Downs. 2014. Species composition, distribution and habitat types of Odonata in the iSimangaliso Wetland Park, KwaZulu-Natal, South Africa and the associated conservation implications. PLoS ONE 9: e92588.

Hassall, C., and D. J. Thompson. 2008. The impact of environmental warming on Odonata: a review. International Journal of Odonatology 11:131–153.

Heiser, M., L. Dapporto, and T. Schmitt. 2014. Coupling impoverishment analysis and partitioning of beta diversity allows a comprehensive description of Odonata biogeography in the Western Mediterranean. Organisms Diversity and Evolution 14:203–214.

Hoegh-Guldberg, O., L. Hughes, S. McIntyre, D. B. Lindenmayer, C. Parmesan, H. P. Possingham, and C. D. Thomas. 2008. Assisted colonization and rapid climate change. Science 321: 345–346.

King, R. S., and C. J. Richardson. 2007. Subsidy-stress response of macroinvertebrate community biomass to a phosphorus gradient in an oligotrophic wetland ecosystem. Journal of the North American Benthological Society 26:491–508.

Koch, K., C. Wagner, and G. Sahlén. 2014. Farmland versus forest: comparing changes in Odonata species composition in western and eastern Sweden. Insect Conservation and Diversity 7:22–31.

Kutcher, T. E., and J. T. Bried. 2014. Adult Odonata conservatism as an indicator of freshwater wetland condition. Ecological Indicators 38:31–39.

Lemelin, R. H. 2007. Finding beauty in the dragon: the role of dragonflies in recreation and tourism. Journal of Ecotourism 6:139–145.

Le Viol, I., J. Mocq, R. Julliard, and C. Kerbiriou. 2009. The contribution of motorway stormwater retention ponds to the biodiversity of aquatic macroinvertebrates. Biological Conservation 142:3163–3171.

Li, F., Y.-S. Kwon, M.-J. Bae, N. Chung, T.-S. Kwon, and Y.-S. Park. 2014. Potential impacts of global warming on the diversity and distribution of stream insects in South Korea. Conservation Biology 28:498–508.

Loss, S. R., L. T. Terwilliger, and A. C. Peterson. 2011. Assisted colonization: integrating conservation techniques in the face of climate change. Biological Conservation 142:92–100.

Maxted, J. R., M. T. Barbour, J. Gerritsen, V. Poretti, N. Primrose, A. Silva, D. Penrose, and R. Renfrow. 2000. Assessment framework for mid-Atlantic coastal plain streams using benthic macroinvertebrates. Journal of the North American Benthological Society 19:128–144.

Mitsch, W. J., and J. G. Gosselink. 2007. Wetlands. 4th edition. John Wiley and Sons, New York.

Miura, T., R. M. Takahashi, and R. J. Stewart. 1990. Estimation of absolute numbers of damselfly nymphs (Odonata: Coenagrionidae) by dipper sampling in California rice fields with seasonal, spatial distributions and vegetation association. Journal of the American Mosquito Control Association 6:490–495.

Monroe, E. M., and H. B. Britten. 2014. Conservation in Hine's sight: the conservation genetics of the federally endangered Hine's emerald dragonfly, *Somatochlora hineana*. Journal of Insect Conservation 18:353–363.

Monteiro-Júnior, C. S., L. Juen, and N. Hamada. 2014. Effects of urbanization on stream habitats and associated adult dragonfly and damselfly communities in central Brazilian Amazonia. Landscape and Urban Planning 127:28–40.

Moore, N. W. 1980. *Lestes dryas* Kirby—a declining species of dragonfly (Odonata) in need of conservation: notes on its status and habitat in England and Ireland. Biological Conservation 17:143–148.

Morlando, S., S. J. Schmidt, and K. LoGiudice. 2012. Reduction in Lyme disease risk as an economic benefit of habitat restoration. Restoration Ecology 20:498–504.

New, T. R. (editor). 2012. Insect conservation: past, present and prospects. Springer, Dordrecht, The Netherlands.

Palmer, M. A. 1999. The application of biogeographical zonation and biodiversity assessment to the conservation of freshwater habitats in Great Britain. Aquatic Conservation: Marine and Freshwater Ecosystems 9:179–208.

Primack, R., H. Kobori, and S. Mori. 2000. Dragonfly pond restoration promotes conservation awareness in Japan. Conservation Biology 14:1553–1554.

Richter, B. D., D. P. Braun, M. A. Mendelson, and L. L. Master. 1997. Threats to imperiled freshwater fauna. Conservation Biology 11:1081–1093.

Rosset, V., J. P. Simaika, F. Arthaud, G. Bornette, M. J. Samways, B. Oertli, and D. Vallod. 2013. Comparative assessment of scoring methods of the conservation value of biodiversity in ponds and small lakes. Aquatic Conservation: Marine and Freshwater Ecosystems 23:23–36.

Rosset, V., S. Angélibert, F. Arthaud, G. Bornette, J. Robin, A. Wezel, D. Vallod, and B. Oertli. 2014. Is eutrophication really a major impairment for small waterbody biodiversity? Journal of Applied Ecology 51:415–425.

Samways, M. J. 1994. Insect conservation biology. Chapman and Hall, London, UK.

Samways, M. J. 2005. Insect diversity conservation. Cambridge University Press, Cambridge, UK.

Samways, M. J. 2007. Insect conservation: a synthetic management approach. Annual Review of Entomology 52:465–487.

Sebastian, A., M. M. Sein, M. M. Thu, and P. S. Corbet. 1990. Suppression of *Aedes aegypti* (L.) (Diptera: Culicidae) using augmentative release of dragonfly larvae (Odonata: Libellulidae) with community participation in Yangon, Myanmar. Bulletin of Entomological Research 89:223–232.

Siegfried, B. D. 1993. Comparative toxicity of pyrethroid insecticides to terrestrial and aquatic insects. Environmental Toxicology and Chemistry 12:1683–1689.

Singh, R. K., R. C. Dhiman, and S. P. Singh. 2003. Laboratory studies on the predatory potential of dragonfly nymphs on mosquito larvae. Journal of Communicable Diseases 35:96–101.

Stoks, R., S. Debecker, K. D. Van, and L. Janssens. 2015. Integrating ecology and evolution in aquatic toxicology: insights from damselflies. Freshwater Science 34:1032–1039.

Stoks, R., and A. Córdoba-Aguilar. 2012. Evolutionary ecology of Odonata: a complex life cycle perspective. Annual Review of Entomology 57:249–265.

Strayer, D. L. 2006. Challenges for freshwater invertebrate conservation. Journal of the North American Benthological Society 25:271–287.

Suhonen, J., E. Korkeamäki, J. Salmela, and M. Kuitunen. 2014. Risk of local extinction of Odonata freshwater habitat generalists and specialists. Conservation Biology 28:783–789.

White, E. L., P. D. Hunt, M. D. Schlesinger, J. D. Corser, and P. G. deMaynadier. 2015. Prioritizing Odonata for conservation action in the northeastern USA. Freshwater Science 34:1079–1093.

Yoshioka, A., Y. Miyazaki, Y. Sekizaki, S. Suda, T. Kadoya, and I. Washitani. 2014. A “lost biodiversity” approach to revealing major anthropogenic threats to regional freshwater ecosystems. Ecological Indicators 36:348–355.