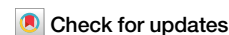


<https://doi.org/10.1038/s44185-026-00124-x>

Vietnamese Odonata: bridging global biodiversity, ecological, and conservation gaps in a changing world

Quoc Toan Phan¹, Huy Ngoc Nguyen² & Khuong V. Dinh^{3,4}✉

Vietnam is a global hotspot, hosting 493 Odonata species, with ~95% evaluated by the IUCN. Odonata species play vital ecological roles in aquatic and terrestrial ecosystems; yet, they face escalating threats from climate change, habitat loss, and pollution. Adult taxonomy has dominated research; yet, critical eco-evolutionary, ecotoxicological, and conservation studies are lacking. This synthesis of 200 years of Vietnamese Odonata research bridges knowledge gaps, offering insights into tropical ecosystem vulnerability in a changing world. We propose an integrative framework scalable to all aquatic invertebrates and understudied tropical regions to advance research and conservation: (1) enhance larval and adult taxonomy and phylogeny using morphology, DNA barcoding (COI gene), and whole genome sequencing for ecologically important, critically endangered or rare species; (2) implement monitoring programmes with eDNA metabarcoding, remote sensing, automated imaging, and citizen science to track distributions, phenology, and traits; (3) conduct eco-evolutionary and ecotoxicological studies with multi-omics to elucidate mechanisms underlying ecophysiology and evolutionary responses; and (4) apply machine learning to project distributions and responses to environmental changes. This framework aligns with global biodiversity and sustainability policy agendas, including the Convention on Biological Diversity and SDGs 14: Life Below Water, and 15: Life on Land, and offers actionable solutions for protecting vulnerable ecosystems.

Dragonflies and damselflies (Odonata) are among the earliest flying insects on Earth^{1,2}. They exhibit a hemimetabolous life cycle with eggs that are mostly laid in the water, but some species can also lay eggs or even pro-larvae on tree branches³, followed by long, multiple larval stages living in the water, and the adults are terrestrial^{2,4}. In aquatic ecosystems such as lakes, rivers, streams, rice fields, and aquaculture ponds, damselfly and dragonfly larvae are important intermediate predators that prey upon various small invertebrates such as mosquito larvae, daphnids, polychaetes, oligochaetes, small fish, and amphibian tadpoles (Fig. 1)^{2,5,6}. This predatory behavior positions them as potential biocontrol agents for vector-borne disease vectors, such as mosquitoes⁷. Concurrently, odonate larvae are also an important food source for many fish species⁸. As predators, odonate larvae have significant implications for the food web dynamics and agricultural and aquaculture systems, such as fish rearing and amphibian populations, which can potentially affect aquaculture yields⁹.

In terrestrial environments, odonate adults serve as a critical conduit for transferring aquatic-derived nutrients, particularly omega-3 fatty acids (ω 3),

to terrestrial food webs, supporting a range of insectivorous taxa, including adult amphibians, birds, and bats (see Fig. 1, refs. 8,10,11). This nutrient transfer is ecologically significant, as ω 3 are essential for avian reproduction, chick development, and migratory success^{12,13}. However, dragonflies and damselflies can also act as vectors for transferring contaminants such as pharmaceuticals and endocrine disruptors, facilitating their movement from aquatic to terrestrial ecosystems, where they may accumulate in terrestrial predators (Fig. 1, see also e.g., ref. 14). This dual role underscores the importance of odonates in mediating both beneficial nutrient dynamics and potential ecological risks in cross-ecosystem interactions.

Vietnam is considered the center of biodiversity for dragonflies and damselflies¹⁵. A total of 493 dragonfly and damselfly species have been recorded to June 2024 (see Supplementary Table 1). A growing concern is the impact of climate change and other human activities on the Vietnamese Odonata, yet the majority of studies have primarily focused on adult taxonomy (see Supplementary Note 2), with sparse data on distributions and ecological roles.

¹Center for Entomology & Parasitology Research, School of Medicine and Pharmacy, Biology & Pharmacy, Duy Tan University, Da Nang City, Vietnam. ²Center for Environmental Intelligence, VinUniversity, Vinhomes Ocean Park, Gia Lam District, Hanoi, Vietnam. ³Department of Biosciences, University of Oslo, Oslo, Norway.

⁴Nha Trang University, Nha Trang City, Vietnam. ✉e-mail: van.k.dinh@ibv.uio.no

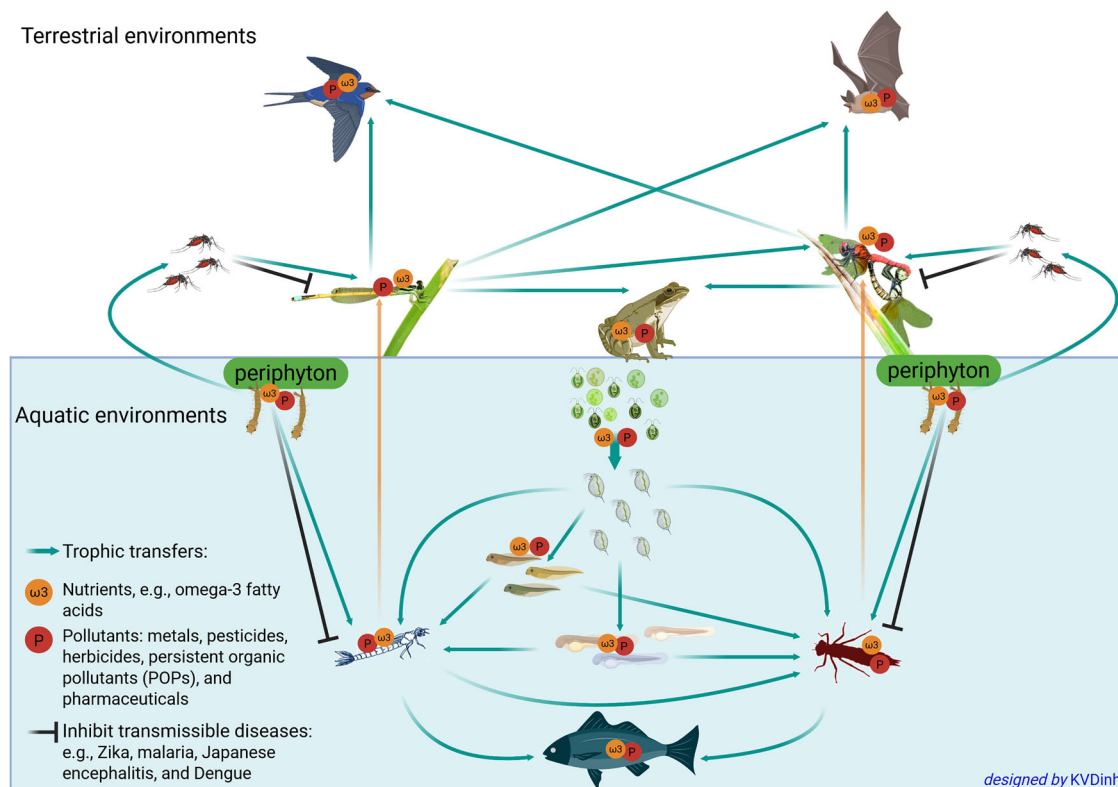


Fig. 1 | A conceptual diagram illustrating the central role of dragonflies and damselflies in Vietnam and other tropical ecosystems. Dark cyan arrows indicate a dual role of odonates in transferring energy, nutrients (such as omega-3 fatty acids – $\omega 3$), and pollutants (P); black lines show that vector-borne diseases are inhibited by odonate larvae and adults; orange arrows represent the emergence of odonates from

larvae to become adults, carrying both nutrients and pollutants from aquatic to terrestrial ecosystems. Photo credits: the damselfly larva © Duong Phuong; dragonfly larva © Phylopic. Photos of damselfly and dragonfly adults were taken by the first author, Phan QT. All other icons and the figure are created using a Biorender license to Khuong V. Dinh. Photos are not to scale.

This review positions Vietnamese Odonata as a model to bridge these global gaps, synthesising their taxonomy, distribution, and conservation status while assessing climate and human impacts across ecosystems, with parallels to Southeast Asian countries and other tropical regions. The hyperdiversity of tropical ecosystems, including those in Vietnam, is predicted to collapse due to warming in conjunction with other anthropogenic stressors, such as pollutants, invasive species, and habitat loss^{16,17}. However, we lack baseline biodiversity and ecological assessments to guide conservation and further pathways for nature recovery or nature-based solutions. Vietnam's vulnerability, marked by a 0.62 °C temperature rise since 1960 and massive environmental problems, especially in the past two decades^{18,19}, potentially amplifies this crisis.

In this context, we propose an integrative framework for advancing Vietnamese Odonata taxonomy and phylogeny, systematic monitoring programs, ecological, evolutionary, and environmental studies using advanced technologies such as environmental DNA (eDNA) metabarcoding, omics techniques, high throughput imaging systems, and citizen science, to comprehensively predict responses to environmental changes. These methodologies are critical innovations tailored to Southeast Asia's challenges: eDNA enables non-invasive detection of cryptic or rare Odonata taxa in remote, fragmented habitats, facilitating large-scale biomonitoring where traditional surveys are challenging^{20–22}. Citizen science empowers community-driven data collection to overcome resource limitations, but local capacity, and engage diverse stakeholders in conservation efforts. By highlighting the novelty and urgency of this approach in Vietnam's understudied odonate research, this framework provide tangible pathways to concrete outcomes: the combination of traditional and targeted survey, citizen science with genomic and eDNA tools will generate baseline data distributional and phylogenetic data for prioritizing endemic hotspots; integrating monitoring and omics experiments will quantify stressor

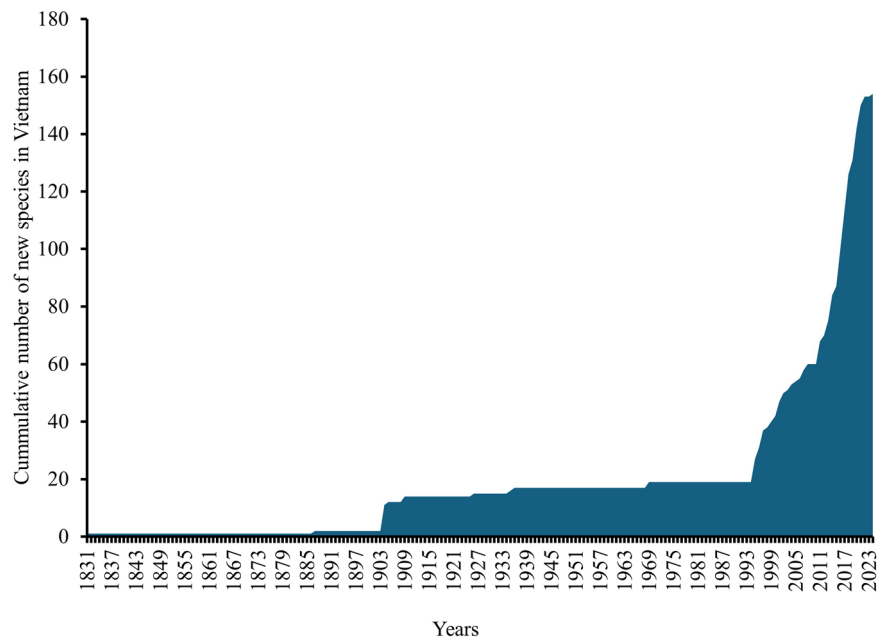
responses to inform targeted conservation strategies such as habitat corridors or population thresholds; and alignment with frameworks like the Convention on Biological Diversity and SDGs 14: Life Below Water, and 15: Life on Land will enable Vietnam's contributions to global assessment, fostering scalable solutions for tropical invertebrate conservation in a changing world.

History of taxonomic studies on Vietnamese Odonata

The taxonomy of Odonata in Vietnam has a rich history spanning nearly two centuries (see more details in Supplementary Note 2), marked by the first description of *Aristocypha fulgipennis* (Guérin, 1831). The taxonomic studies of Vietnamese Odonata before the 1980s were limited and often plagued by inaccuracies. For example, Martin²³ recorded some damselflies such as *Anisopleura lestoides* (Selys, 1853) from Tonkin (northern Vietnam), yet Hämäläinen and Karube²⁴ did not find *Anisopleura* specimens in Martin's collection. Current records confine *A. lestoides* to India and Nepal, *E. bocki* to Sumatra²⁵. From 1975 to 2015, research on Odonata in Vietnam expanded significantly, especially since 1995 (Fig. 2), but was primarily led by international researchers with contributions from a limited number of Vietnamese scientists. This period marked progress in species discovery with a clear geographic bias toward northern Vietnam (Supplementary Table 1) but underscored the need for broader geographic coverage and ecological data to complement taxonomic efforts. Since 2015, at least 70 new species have been discovered in Vietnam (Fig. 2, see also details in Supplementary Table 2). This period marked a shift toward more systematic surveys, with detailed species checklists compiled for specific national parks and nature reserves, particularly in central and southern Vietnam, enhancing regional biodiversity records (Supplementary Note 2).

Taxonomy of odonate larvae in Vietnam has recently gained attention, with several studies describing the final instar or stadium larvae to refine

Fig. 2 | Cumulative discoveries of Odonata species in Vietnam (1831–2024). A total of 154 new species were described over approximately 200 years (See Supplementary Table 2 for the details of species and years of discoveries), accounting for 31.2% (154/493) of the total recorded species diversity to date (Supplementary Table 1). The graph highlights an accelerating rate of descriptions since 1995, reflecting intensified surveys in biodiversity hotspots and the potential for further undescribed taxa in understudied regions, such as the Central Highlands.



species identification and phylogenetic understanding. For example, the final instar larva of *Anotogaster klossi* Fraser, 1919 has recently been described and compared with its congeners²⁶ (see also Supplementary Table 3 for a full list of all studies on the taxonomy of Odonata larvae in Vietnam). These studies enhance the taxonomic resolution and provide foundational data for ecological, evolutionary, and ecotoxicological research on larval stages, which dominate the aquatic phase of Odonata life cycles and serve as sensitive indicators of aquatic ecosystem health (see following sections).

Despite these advancements in the taxonomy of Odonata in Vietnam, many regions have little or no information on species records. Ongoing efforts by odonatologists continue to drive the discovery of new species, particularly in the mountainous regions, highlighting the high biodiversity of species and habitats in these regions, comparable to other tropical mountain forests, such as the Colombian Western Andes²⁷. There is growing concern that numerous species may face extinction before they can be identified and named²⁸. Advanced methodologies, such as deep hierarchical Bayesian learning²⁹, offer promising tools for identifying unknown species, thereby supporting a more thorough assessment of Odonata species diversity in Vietnam.

Distribution of Odonata species in Vietnam

Among 493 odonate species in Vietnam, only 15% (e.g., species in the families Libellulidae, Chlorocyphidae, Coenagrionidae) exhibit widespread distributions across the country, characterised as generalist species capable of occupying diverse habitats. 138 species are recorded from a single site or location (province), confined to a specific region or microhabitats, especially mountainous streams, or wetlands (Fig. 3, see Supplementary Table 1 for details). This pronounced localisation may be explained by (1) a high diversity of specialised microhabitats in fragmented landscapes^{30,31} and/or (2) uneven survey efforts or incomplete samplings. Further research, including data on dispersal rates, colonization–extinction dynamics, gene flow, or species turnover across habitat patches, is needed to test this hypothesis and confirm the role of such ecological processes in shaping these distributions. To address these knowledge gaps, there is an urgent need to expand systematic surveys across poorly studied regions of Vietnam to build local research capacity. Citizen science platforms such as iNaturalist, Global Biodiversity Information Facility (GBIF), offer potential for populating distribution databases (see Supplementary Table 4 for citizen science-derived observation tallies across regions in eleven Southeast Asian countries). Citizen science

initiatives in Thailand and Singapore enhance monitoring efforts and support conservation assessments^{32–34}.

Habitat loss and fragmentation, driven by human disturbances (see more details in section “Potential impacts of human activities on the Vietnamese and tropical Odonata”), likely reduce patch connectivity, limiting dispersal and increasing extinction risks in isolated populations^{35,36}. Tropical odonates with low dispersal abilities, such as Zygoptera species, are particularly sensitive to habitat fragmentation, as their metapopulations rely on closely spaced, high-quality patches (e.g., shade streams^{37,38}). Reduced genetic diversity in small, isolated populations exacerbates vulnerability, limiting adaptive potential to climate change and anthropogenic disturbances^{39–41}.

Generalist species, such as *Pantala flavescens* (Fabricius, 1798), *Acisoma panorpoides* Rambur, 1842, *Brachydiplax chalybea* Brauer, 1868, *Crocothemis servilia* (Drury, 1773), *Orthetrum sabina* (Drury, 1770), *Diplacodes trivialis* (Rambur, 1842), *Ischnura senegalensis* (Rambur, 1842), *Agriocnemis femina* (Brauer, 1868), *Copera marginipes* (Rambur, 1842), may have broader thermal performance curves and higher dispersal capacities, enabling them to colonize ponds, reservoirs in human-modified landscapes^{42,43}. These species likely maintain robust metapopulations through high patch occupancy and frequent colonisation, even in fragmented or degraded habitats^{42,44}. In contrast, species with highly localised, specialised, and less abundant are under extreme threats from climate change and human activities, yet remain understudied^{39–42,45}.

Phenology of Vietnamese Odonata

Vietnam’s extensive latitudinal range, spanning approximately 15 degrees, creates significant climatic variation between its northern and southern regions, influencing phenology, or the seasonal life cycle patterns of odonate species. In southern Vietnam, characterised by a tropical monsoon climate, the phenology of odonate species is likely influenced by the alternating wet and dry seasons, with drought being a significant factor. Precipitation patterns in Vietnam are marked by high variability on annual and interdecadal scales, rendering long-term trends challenging to discern. Nationally, the mean annual rainfall has increased by 2.1% since 1960; however, reductions in rainfall have been noted in the northern and southern parts of the Central Highlands. At a subnational level, central regions have experienced increased precipitation, while northern and southern regions have seen declines⁴⁶. Climatic phenomena such as El Niño and La Niña continue to exert a significant influence on precipitation trends⁴⁷.

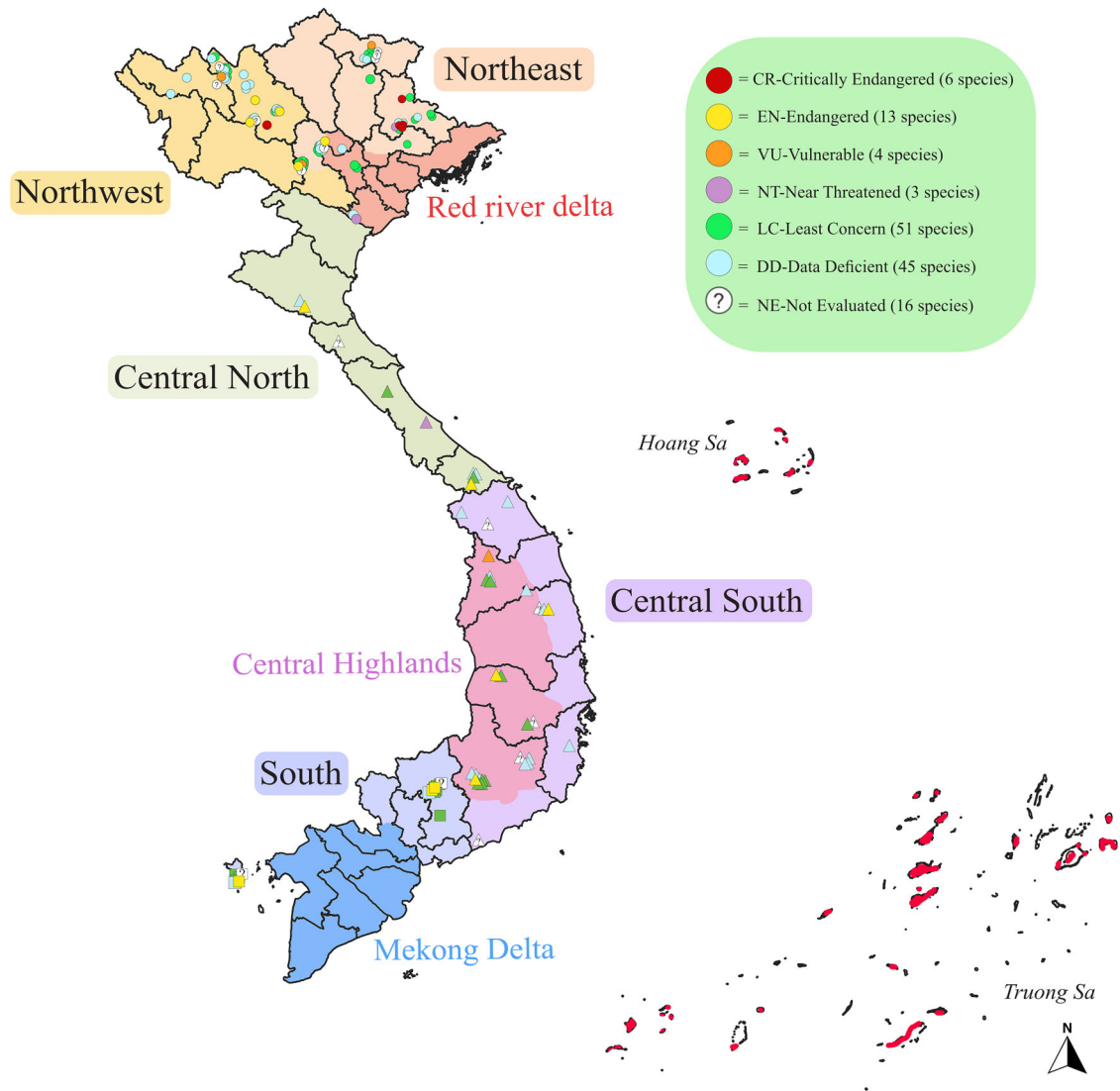


Fig. 3 | The map of dragonfly and damselfly species recorded in a single location or province in different sub-climate regions in Vietnam, alongside their IUCN Red List conservation statuses. A comprehensive list of these species with recorded locations is provided in Supplementary Table 5.

Prolonged droughts of the dry season, e.g., in the southern parts of the Central Highlands (see Fig. 2), a biodiverse plateau region in south-central Vietnam, renowned for its montane forests, endemic flora, and fauna⁴⁸, are expected to act as a critical limiting factor, influencing reproductive cycles, larval development, and adult emergence. Reduced water availability in temporary ponds can limit breeding sites, forcing species to accelerate larval development or risk desiccation. Such acceleration may result in trade-offs, reducing adult body size and fecundity, which could potentially compromise population persistence^{4,49}. These dynamics could be particularly relevant for species such as *Agriocnemis nana* (Laidlaw, 1914), *Ceragrion indochinense* Asahina, 1967, *Rhyothemis plutonia* Selys, 1883, and *Aethriamanta gracilis* (Brauer, 1878) inhabiting the Central Highlands of Vietnam, for example, swamps in Yok Don National Park (Fig. 4). Those unable to complete development before habitats dry may face population declines or even extirpation, as observed in analogous tropical systems in Africa⁵⁰.

Conversely, northern Vietnam, spanning regions from Tuyen Quang to Hue, exhibits a subtropical climate with pronounced seasonal variations. Summer temperatures can reach over 40 °C across these areas (see section “Potential impacts of climate change on Vietnamese and tropical Odonata”), while high-elevation zones occasionally experience snowfall during winter. Such climate extremes impose significant constraints on odonate life cycles,

especially species inhabiting elevated regions in the Northeastern and Northwestern mountains, such as *Aristocypha chaoi* (Wilson 2004), *Indocypha katharina* (Needham, 1930), *Atrocalopteryx atrocyana* (Fraser, 1935), *Atrocalopteryx auco* Hämäläinen, 2014⁵¹, *Atrocalopteryx laosica* Fraser, 1933, *Atrocalopteryx melli* (Ris, 1912), *Priscagrion pinhyi* Zhou and Wilson, 2001, *Coeliccia hoanglienensis* Do, 2007, *Rhipidolestes chaoi* Wilson, 2004, *Rhipidolestes jucundus* Lieftinck, 1948, *Rhipidolestes owadai* Asahina, 1997, *Mesopodagrion tibetanum australe* (Yu and Bu, 2009), *Rhinocypha oreia* Hämäläinen and Karube, 2001⁵², *Megalestes micans* Needham, 1930, *Chlorogomphus albomarginatus* Karube, 1995, *Anotogaster chaoi* Zhou, 1998, *Somatochlora dido* Needham, 1930, *Sympetrum* spp., and *Libellula melli* Schmidt, 1948. These species must contend with substantial temperature fluctuations, ranging from intense summer heat, occasionally exacerbated by heatwaves, to winter, sometimes freezing, conditions. The lowest recorded temperature in Vietnam was −4.7 °C at Co Noi (Son La, January 1974). Prolonged cold spells, such as the 38-day event in 2008 (from January 13 to February 20), with temperatures dropping to −2 to −3 °C in high-altitude areas (Mau Son, Hoang Lien Son) in northern Vietnam. A widespread cold in winter of 2015–2016, with temperatures as low as −4.2 to −4.4 °C in Sa Pa and Mau Son, caused ice and snow in unprecedented locations such as Ba Vi (Hanoi) and Ky Son (Nghe An)⁴⁶. Previous studies in higher latitude regions have shown that odonate larvae in cold



Fig. 4 | Some common odonate species in a swamp in Yok Don National Park, Central Highlands, Vietnam. A *Rhyothemis triangularis* Kirby, 1889 (male), **B** *Rhyothemis plutonia* (male), **C** *Aethriamanta gracilis* (male), **D** *Ceriatagrion*

indochinense (a mating pair), **E** *Agriocnemis nana* (male), and **F** *Argiocnemis rubescens* Selys, 1877 (male). A swamp in the wet (**G**) and dry (**H**) seasons. Photos are not to scale. All photos were taken by the first author, Phan QT.

environments can enter diapause, a state of developmental arrest, when water temperatures drop below 8 °C^{2,53–55}. This adaptation enables survival through adverse conditions, particularly in mountainous regions with pronounced thermal variability.

Investigating cold tolerance in northern Vietnamese Odonata, especially in high-altitude ecosystems, offers a compelling avenue for research. Such studies could elucidate mechanisms of diapause, thermal plasticity, and potential northward range shifts in response to climate change. Comparative analyses with other taxa demonstrate similar poleward migrations driven by winter temperatures^{56,57}, including damselflies⁵⁸. For Odonata, understanding these dynamics is critical, as their aquatic larval stages and a terrestrial adult stage make them a sensitive indicator of environmental change⁴. Future research should prioritise longitudinal field studies and experimental approaches to model phenological shifts and predict ecological impacts of Vietnamese Odonata under different climate change scenarios.

Potential impacts of climate change on Vietnamese and tropical Odonata

Over the past six decades, Vietnam has experienced pronounced climatic shifts, including rising temperatures, altered precipitation patterns, and changes in cyclone frequency and intensity. According to the Ministry of Natural Resources and Environment (MONRE)⁴⁶, the mean annual

temperature across Vietnam has risen by 0.62 °C since 1960. This warming trend has been more pronounced in the dry season and southern regions, particularly in southern Vietnam and the Central Highlands, followed by the Northwest and the upland areas of North Central Vietnam. Between 1971 and 2010, the rate of warming averaged 0.26 °C per decade, with greater temperature increases observed during winter months compared to summer months (see Table 1)⁴⁶.

Extreme temperature events have also become more frequent. Since 1960, the occurrence of hot days (temperatures > 35 °C) has increased across all seasons, with the most substantial rise in hot days recorded between September and November. Conversely, the frequency of cold days (temperatures < 13 °C) has decreased significantly, with the most pronounced reductions occurring in December, January, and February (see Table 2)⁴⁶.

From 1961 to 2018, the annual average maximum temperature (Tx) increased by 0.2–2.1 °C across most regions, with the largest increases in the Red River Delta, southern Northeast, northern North Central Coast, and eastern South. Smaller increases occurred in the Northwest, South Central Coast, and the western Central Highlands. Conversely, Northwest and Central Highlands showed a reduction of 0.2–0.6 °C over 58 years.

Dragonflies and damselflies are of tropical origin¹ and are highly sensitive to ambient temperature fluctuations⁵⁹, raising hypotheses about how climate change could alter taxonomic, functional, and phylogenetic

Table 1 | Historical mean seasonal temperature increases in seven sub-climate regions in Vietnam over 61 years: 1958–2018 (Data source: Ministry of Natural Resources and Environment - MONRE⁴⁶, variances unavailable in the source report)

Climate regions	Winter (°C)	Spring (°C)	Summer (°C)	Autumn (°C)
Northwest	1.1	0.8	0.9	1.3
Northeast	1.0	0.8	0.8	1.1
Red River Delta	0.9	0.9	0.7	1.2
Central North	0.8	0.9	0.8	1.3
Central South	0.6	0.4	0.6	0.9
Central Highlands	1.3	0.7	1.0	1.4
South and the Mekong Delta	1.1	0.8	0.9	1.1

Table 2 | Observed annual hot and cold days in North Central and South Central Vietnam (Data source: Ministry of Natural Resources and Environment – MONRE⁴⁶)

Periods	Hot days (>35 °C)	Cold days (< 13 °C)
North Central Vietnam		
1960–2007	50–60	5–15 in El Niño years 10–20 in La Niña years
2009–2024	50–70 in ENSO and La Niña years 80–100 in El Niño years	5–10 in El Niño years 10–15 in La Niña years
South Central Vietnam		
1960–2007	40–50	0
2009–2024	40–60 in ENSO and La Niña years 70 in El Niño years	0

Values represent regional ranges from national meteorological records, highlighting historical extremes relevant to Odonata thermal exposures. Variances and site-specific details are unavailable in the source.

diversity of odonate species across space and time⁶⁰. For example, predictive models for tropical Odonata in Vietnam might integrate *ecological niche theory* to hypothesize environmental constraints⁶¹, *life history theory* to explore potential trade-offs, and *thermal performance theory* to predict physiological limits^{38,62,63}, though these frameworks remain untested in the Vietnamese context due to limited empirical data. Such models hypothesize that tropical odonate species could be particularly vulnerable to warming, as many appear to operate near their upper thermal limits^{62,64} and have often limited geographic ranges. Even small temperature increases might push them beyond hypothesised thermal optima or critical thermal maxima (CTmax). Supporting this hypothesis, a study in the Mexican tropics at ~19°N latitude reported CTmax values of 37–42 °C for odonates⁶⁵. No comparable data exist for Vietnamese species, but the increasing frequency of extreme heatwaves, such as record-high temperatures of 43.4 °C in April 2019⁶⁶, 44.1 °C on May 6, 2023, in Thuong Xuan, Thanh Hoa, and 44.2 °C on May 7, 2023, in Tuong Duong, Nghe An, highlight potential risks. According to the National Center for Hydro-Meteorological Forecasting⁶⁷, 102 weather stations across Vietnam recorded unprecedented high temperatures in April 2024, with three consecutive heatwaves. The average temperature was 2–4 °C higher than the same period in 2023. These trends underscore the need for Vietnam-specific studies to test whether odonates face a high risk under rapidly warming climates, especially during heatwaves.

Reduced body size at maturity is one of the universal responses of animals to a warming climate, consistently observed across diverse taxa⁶⁸. In dragonflies and damselflies, the relationship between body size and temperature along latitudinal gradients generally conforms to this

pattern, aligning with the rule⁶⁹. However, this relationship is modulated by ecological and physiological factors, notably changes in the voltinism or the number of generations per year⁷⁰. Increased temperatures can lead to higher voltinism, potentially intensifying selection pressures on body size and morphology^{41,70}. Accelerated life cycles in tropical odonate species are expected to be even more pronounced under warming, but we lack such studies for Vietnamese dragonflies and damselflies.

Warming also influences specific morphological traits in Odonata. For example, some species exhibit reduced wing size and flight muscles under elevated temperatures^{71,72}. These responses may impair flight performance and dispersal capacity^{72,73}, especially small-bodied tropical damselflies³⁸.

Climate warming drives species range shifts, a well-documented response in many taxa^{74–76}. Among insects, dragonflies and damselflies exhibit rapid northward range expansions, although a few odonate species do not show this trend^{74–76}. In Vietnam, only a few studies have investigated this topic. For damselflies, *Neurobasis chinensis* (Linnaeus, 1758), a species that has a core distribution in South-Central Vietnam, is projected to shift northward under warming scenarios⁷⁷. However, its northward range will be limited by high-altitude barriers, notably the Himalayan mountain range at elevations above 1200 m⁷⁷. Similarly, the dragonfly *Pantala flavescens* (Fabricius, 1798), a widely distributed species with a core distribution in northern Vietnam, is predicted to shift northeastward, with the Asian range centering in south-eastern China under future climate scenarios⁷⁸. These shifts, however, may be impeded by reduced flight performance in fragmented tropical landscapes, such as those affected by riparian forest loss³⁸, further challenging the adaptive capacity of tropical odonates to track warming climates⁷⁹.

A step further is determining species-at-risk under a warming climate, particularly with increasing frequency, duration, and severity of the heatwaves^{80,81}. This can be done by experimentally determining key physiological metrics, including thermal performance curves, critical thermal thresholds⁶³, and thermal safety margins⁸², which quantify the responses of all Vietnamese dragonflies and damselflies to temperature extremes, thereby assessing their vulnerability to climate warming and heatwaves based on the current and future projections⁸³. These metrics, combined with long-term monitoring of species distribution and abundance, temperature fluctuations, rain, drought, and pollutant exposure (see e.g., pesticides⁸⁴), enable mapping of species vulnerability to projected future climate scenarios (see Fig. 7). Integrating these physiological and ecological data will provide a robust framework for prioritising conservation efforts for Vietnam's Odonata under accelerating climate change.

Potential impacts of human activities on the Vietnamese and tropical Odonata

Habitat loss caused by deforestation, land use, and pollution from agriculture and agroforestry, altered hydrology, are major anthropogenic threats to odonate species, and more generally, invertebrates worldwide^{42,85,86}. Few available studies could provide some indications of how human activities may affect tropical damselflies and dragonflies in Southeast Asian countries.

Habitat loss, driven primarily by land use changes, represents the predominant factor contributing to the decline of the entomofauna^{85,87}, with over 40% of insect species facing extinction risk⁸⁷. In Vietnam and other Southeast Asian countries, deforestation is one of the major causes of habitat loss¹⁷, substantially affecting the species richness and abundance of both larvae and adults. Historically, deforestation was a serious problem in Vietnam, caused by wartime activities¹⁹, illegal or unsustainable logging¹⁷, expansion of agriculture⁸⁸, and aquaculture⁸⁹. These activities reduced primary forest cover from 43% of the country's land area in 1943⁹⁰ to a minimum of 25–31% in 1991–1993. Subsequently, national reforestation efforts increased forest cover to 32–37% by 1999–2001^{91,92}. However, the transition from primary tropical rainforest to secondary forests, often dominated by monoculture plantations such as coffee, tea, rubber, and timber, has profoundly altered habitats for many dragonfly and damselfly species. For example, *Rhinocypha oreia* is only found in Tam Dao National

Park, northern Vietnam⁵². Its population has declined due to deforestation and extremely high levels of tourism activities⁹³.

In other Southeast Asian countries, for example, Malaysia, a survey of 16 streams in Sabah showed that habitat disturbances negatively correlate with larval abundance and species richness of 49 species, while adults show no significant changes³⁵. The plantation of oil palm appears to have the strongest negative effect on damselfly larvae in nearby streams, resulting in their near absence due to four potential effects³⁵. Firstly, homogeneous oil palm plantations eliminate all low overhanging vegetation, particularly along waterways, which are essential for damselflies to rest and reproduce³⁵. The lack of shaded areas in oil palm forests makes the daytime temperature too warm for small-bodied damselflies, which could lead to competition from larger, sun-loving, cosmopolitan Anisoptera³⁵. The temperature in the cleared areas of oil palm forests is, on average, 5 °C higher than in primary forests⁹⁴. A daily temperature fluctuation of 9 °C in the oil palm forest is also more than twice as high as in primary forests⁹⁴. Other environmental factors, such as reduced pH, dissolved organic matter, and water levels, also negatively impact larval diversity in oil palm waterways⁹⁵.

Similarly, human-induced disturbances and the turnover from primary to secondary forests negatively affect the species composition, abundance, and functional diversity of 88 odonate species, particularly zygopteran forest specialists in tropical rainforests of East Kalimantan, Indonesia³⁷. Damselflies, especially forest specialists, are the most vulnerable group to burned forests in tropical regions, such as in Indonesia⁹⁶. It may take a decade for these species to recover from 50% to 98% of species richness⁹⁶.

The second major driver of ecological degradation is the pervasive contamination from pesticides and agrochemicals^{84,87,97}. Vietnam ranks among the regions with the highest risk of pesticide pollution globally⁸⁴. The excessive application of pesticides in Vietnamese agriculture⁹⁸ and agroforestry, poses great threats to odonate populations in natural water bodies such as wetlands, ponds, lakes, streams, and rivers^{99,100}. Many odonate species are highly specialised to adapt to these habitats. For example, species in the Central Highlands of Vietnam (e.g., Table 3) can be vulnerable to agrochemicals and excessive fertilisers from coffee production¹⁰¹. Pesticide exposures have been shown to disrupt odonate biology across multiple levels, from genes, physiology, immune responses, fitness-related traits, to natural populations and communities (reviewed in ref. 102). However, similar studies on the tropical dragonflies and damselflies in Vietnam are lacking.

In Southeast Asian countries, some evidence suggests complex ecological responses to agrochemical use. For example, in Seberang Perai, Malaysia, species diversity and individual abundance of dragonflies and damselflies were higher in rice plots applied with the herbicides propanil, quinclorac, molinate/propanil, 2,4-D amine, and bensulfuron than in the control plots¹⁰³. This increase may result from herbicide-induced decomposition of plant materials, which elevates organic matter availability, thereby enhancing food resources for odonate prey¹⁰³. Additionally, herbicides may reduce populations of odonate predators, such as fish and amphibians, thereby decreasing predation pressure on dragonfly and damselfly larvae.

Another important stressor is extensive hydropower dam construction that has profoundly altered the rivers, wetlands, and delta hydrological regimes, threatening biodiversity¹⁰⁴, potentially including odonate species. The impact of hydropower plants on odonate species has not been studied in Vietnam or other Southeast Asian countries, but similar studies have been conducted in other tropical regions. For example, across control and dam-impacted sites in the Brazilian Savanna, 1,128 odonate species were recorded, but small hydroelectric power (SHP) plants resulted in a decline of 25% species richness downstream due to altered water flow, pH, and turbidity¹⁰⁵. These changes impact larval development¹⁰⁵, especially sensitive Zygoptera species that have elongated body shapes, caudal lamellae respiration, conforming thermoregulation, and endophytic oviposition¹⁰⁶. It is crucial to investigate the direct impacts of these changes and how these are

compounded by intensive aquaculture and agriculture, and rapid urbanization in Vietnam.

Importantly, climate change, habitat loss, and pollution do not affect odonate species independently, but more likely, these stressors can interact and drastically increase the vulnerability of damselflies and dragonflies^{35,107–112}. For example, delayed effects of starvation and heatwaves may increase the vulnerability of damselfly larvae to pesticides¹⁰⁸. Similarly, a field study in 60 small waterways within oil palm plantations in Peninsular Malaysia showed that habitat loss from agroforestry combined with low pH and high sedimentation significantly reduced the diversity of tropical Odonata⁹⁵. These interactions underscore the urgent need for comprehensive studies to elucidate the cumulative effects of anthropogenic stressors on odonate populations and to inform effective conservation strategies.

Conservation of Vietnamese Odonata

Globally, 10–16% of dragonflies and damselflies are threatened with extinction, driven primarily by habitat loss, climate change, and pollution^{40,42}. In Vietnam, Odonata face similar pressures exacerbated by rapid urbanisation, deforestation, and wetland degradation. Of the 493 species recorded in Vietnam, 467 (~95%) have been assessed for their conservation status on the IUCN Red List of Threatened Species (Fig. 5), providing the first baseline for assessing their vulnerability.

The majority of assessed Vietnamese Odonata, 434 species (88%), including 112 or 81% of 138 single-location recorded species, are classified as Least Concern (LC), Data Deficient (DD) and Not Evaluated (NE) (Fig. 5). Least concern species may imply their abundance in the wild, yet this designation often masks the underappreciated ecological roles and conservation needs of these odonate species, which remain overlooked in broader biodiversity protection efforts. The Least Concern classification for some species may also be misleading, as it could reflect insufficient data rather than true population stability, particularly for species in fragmented habitats (e.g., Central Highlands). The high proportion of DD and NE species, given that ~95% of Vietnam's Odonata are IUCN-evaluated, indicates a lack of ecological and population data beyond taxonomic identification. A total of 60 species are listed as threatened or near-threatened (Fig. 5), including 20 Vulnerable (VU), 13 Near Threatened (NT), 20 Endangered (EN), and 7 Critically Endangered (CR) species. Additionally, 95 species (19.3%) are Data Deficient (DD) (Fig. 5), highlighting significant knowledge gaps in their distribution, population trends, and taxonomic status.

Endemic and rare species are particularly at risk. For example, *Euphaea sanguinea* (VU), *Coellicia coronata* (VU), *C. diomedea* (NT), *C. mattii* (VU), *C. schorri* (VU), *Megalestes australis* (VU), are only found in some specific localities in Central Vietnam and the Central Highlands^{113,114}. Critically Endangered and Endangered species, such as *Archineura maxima* (CR), *Atrocalopteryx auco* (CR), *Paracercion ambiguum* (CR), *Coellicia hayashii* (EN), *Coellicia curua* (EN), *Coellicia natgeo* (EN), *Matticnemis doi* (CR), are known from single or highly localised sites in Vietnam^{51,115–119}, making them exceptionally vulnerable to habitat disturbances. Notably, *Archineura maxima*, known only from a single female collected in 1904, has no recent records and may be extinct¹²⁰, underscoring the urgency of targeted surveys.

Effective conservation strategies must adopt an inclusive approach, integrating considerations of species diversity, the vital ecosystem services provided by odonate species, and their phylogenetic heritage within targeted ecosystems⁵⁰.

Roadmap for Odonata research in Vietnam with applications to tropical regions

Taxonomy and systematics

Most studies on the Vietnamese dragonflies and damselflies focus on adult taxonomy, often providing some basic descriptions of new species and their associated habitats or localities. Larval stages constitute the most substantial and persistent knowledge gap in Vietnamese Odonata research and must be treated as a core priority within any forward-looking research roadmap. Of the 493 species currently recognized from Vietnam, larval stages have been

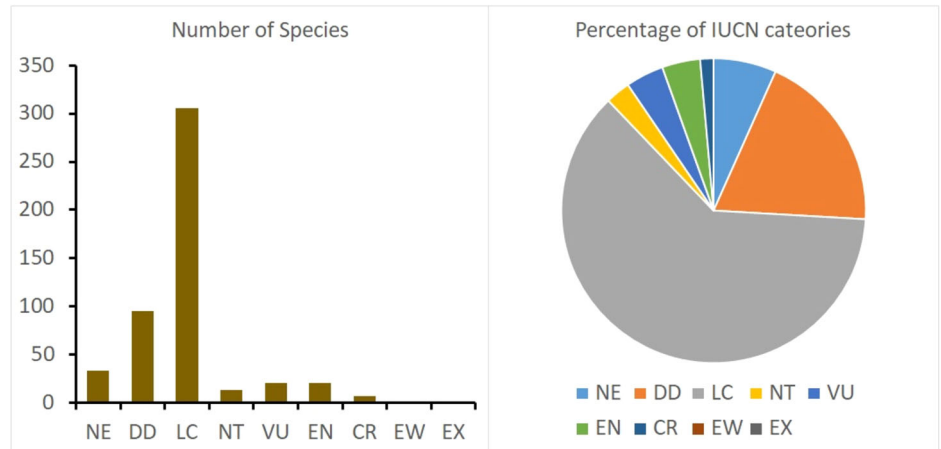
Table 3 | Some specialised odonate species associated with streams in the Central Highlands of Vietnam, based on 15 years of field observations by the first author (Phan QT)

Species in streams in the Central Highlands	Distributions
<i>Euphaea hirta</i> Hämäläinen & Karube, 2001 ⁵²	Lam Dong (Bao Loc; Nam Nung; Bidoup Nui Ba), Dak Lak (Chu Yang Sin; Nam Kar), Dong Nai (Vinh An; Cat Tien)
<i>Euphaea sanguinea</i> Kompier & Hayashi, 2018	Đak Lak (Chu Yang Sin), Lam Dong (Nam Nung; Ta Dung; Bao Loc)
<i>Rhinocypha seducta</i> Hämäläinen & Karube, 2001 ⁵²	Gia Lai (Kon Chu Rang NR), Quang Ngai (Chu Mom Ray; Mang Den, Kon Plong), Dak Lak (Chu Yang Sin), Lam Dong (Di Linh; Bao Loc; Dong Nai Thuong; Bu Gia Map), Dong Nai (Cat Tien)
<i>Coelliccia coronata</i> Kompier, Dow & Steinhoff, 2020 ¹¹⁷	Dak Lak (Chu Yang Sin), Lam Dong (Bao Loc; Nam Nung), Khanh Hoa (Hon Ba)
<i>Coelliccia diehlae</i> Phan & Bui, 2021	Gia Lai (K'Bang)
<i>Coelliccia duytan</i> Phan, 2017	Dak Lak (Chu Mom Ray)
<i>Coelliccia hayashii</i> Phan & Kompier, 2016 ¹¹⁵	Gia Lai (K'Bang)
<i>Coelliccia lecongcoi</i> Phan, 2019	Quang Ngai (Ngoc Linh), Gia Lai (Kon Ka Kinh)
<i>Coelliccia lephuocdieui</i> Phan, Ngo & Bui, 2020	Gia Lai (Kon Ka Kinh)
<i>Coelliccia mattii</i> Phan & Kompier, 2016 ¹¹⁵	Dak Lak (Chu Yang Sin), Lam Dong (Bao Loc; Da Lat; Nam Nung), Khanh Hoa (Hon Ba)
<i>Coelliccia schorri</i> Phan & To, 2019	Gia Lai (K'Bang; An Toan), Da Nang (Song Thanh; Tay Giang)
<i>Coelliccia suoitia</i> Dow, 2016	Lam Dong (Da Lat; Bidoup Nui Ba; Bao Loc)
<i>Prodaseura doisuthepensis</i> Hoess, 2007	Gia Lai (K'Bang; An Toan), Quang Ngai (Chu Mom Ray; Kon Plong), Dak Lak (Chu Yang Sin), Lam Dong (Bao Loc), Khanh Hoa (Hon Ba), Dong Nai (Cat Tien)
<i>Prodaseura hoffmanni</i> Kosterin, 2015	Quang Ngai (Kon Plong), Dak Lak (Chu Yang Sin), Dak Nong (Nam Nung), Lam Dong (Bao Loc; Da Lat; Bidoup Nui Ba; Bu Gia Map), Dong Nai (Cat Tien)
<i>Podolestes pandanus</i> Wilson & Reels, 2001	Dak Lak (Ea H'leo)
<i>Indolestes cyaneus</i> (Selys, 1862)	Gia Lai (Kon Ka Kinh), Quang Ngai (Kon Plong), Da Nang (Tay Giang)
<i>Platylestes platystylus</i> (Rambur, 1842)	Dak Lak, Lam Dong (Lac Duong), Dong Nai (Cat Tien)
<i>Indocnemis marijanmatoki</i> Phan, 2018 ¹¹⁴	Khanh Hoa (Hon Ba), Gia Lai (K'Bang)
<i>Drepanosticta hansruealii</i> Phan, 2021	Lam Dong (Bao Loc; Ham Thuan Nam)
<i>Protosticta binhi</i> Phan, To, Trinh & Dinh, 2019 ¹⁸	Gia Lai (K'Bang; An Toan)
<i>Protosticta linnaei</i> Van Tol, 2008	Dak Lak (Chu Yang Sin)
<i>Protosticta proboscis</i> Kompier, 2016	Lam Dong (Bao Loc)
<i>Sarasaeschna minuta</i> Asahina, 1986	Lam Dong (Da Lat)
<i>Asiagomphus kosterini</i> Kompier, 2018	Quang Ngai (Kon Plong), Lam Dong (Bidoup - Nui Ba)
<i>Burmagomphus schneideri</i> Do, 2011 ¹²⁶	Gia Lai (K'Bang)
<i>Macrogomphus annulatus</i> (Selys, 1854)	Lam Dong (Da Lat)
<i>Microgomphus juritzai</i> Karube, 2000	Dak Lak (Ea H'Leo), Lam Dong (Bao Loc; Nam Nung)
<i>Leptogomphus baolocensis</i> Karube, 2001	Lam Dong (Bao Loc; Nam Nung)
<i>Stylogomphus delicatus</i> Kompier, 2017	Lam Dong (Bao Loc)
<i>Stylogomphus inglisi</i> Fraser, 1922	Dak Lak (Ea H'leo)
<i>Chlorogomphus caloptera</i> Karube, 2013	Lam Dong (Da lat; Bao Loc, Bao Lam), Khanh Hoa (Hon Ba)
<i>Chlorogomphus hoaian</i> Phan & Karube, 2022	Quang Ngai (Ngoc Linh; Chu Mom Ray; Kon Plong), Gia Lai (Kon Ka Kinh; An Toan)
<i>Chlorogomphus serratus</i> Karube, Katatani & Phan, 2024	Lam Dong (Lac Duong)
<i>Chlorogomphus vani</i> Phan & Karube, 2022	Đak Lak (Chu Yang Sin)
<i>Epopthalmia frontalis</i> Selys, 1871	Lam Dong (Bao Loc)
<i>Macromia calliope</i> Ris, 1916	Quang Ngai (Kon Plong)
<i>Macromia chaiyaphumensis</i> Hämäläinen, 1985	Lam Dong (Bao Loc)
<i>Macromia cydippe</i> Laidlaw, 1922	Lam Dong (Bao Loc)
<i>Hemicordulia tenera</i> Lieftinck, 1930	Lam Dong (Da Lat; Bao Loc)
<i>Risiolebia dohrni</i> (Kruger, 1902)	Lam Dong (Bao Loc)

described for only 158 species (32%), with markedly lower coverage in Zygoptera (22%: 48/217 species) than in Anisoptera (40%: 110/276 species) (Supplementary Table 1). These results summarize larval knowledge available for species occurring in Vietnam and draw largely on regional Southeast Asian material (e.g., Thailand¹²¹), reflecting the strong ecological continuity of odonate larval habitats across the region. Coverage remains highly uneven among families, ranging from relatively well-documented

groups such as Libellulidae (59%: 47/79 species) and Macromiidae (79%: 15/19 species) to severely underrepresented families, including Devadattidae, Rhipidolestidae, Argiolestidae, and Priscagrionidae, for which no larvae have yet been described. Even among taxonomically diverse and ecologically important families, larval knowledge remains limited, including Gomphidae (28%: 24/86 species), Aeshnidae (28%: 15/53 species), Platynemididae (15%: 9/61 species), and Chlorogomphidae (13%: 3/24 species).

Fig. 5 | The conservation status of odonate species in Vietnam according to the International Union for Conservation of Nature (IUCN). NE Not Evaluated, DD Data Deficient, LC Least Concern, NT Near Threatened, VU Vulnerable, EN Endangered, CR Critically Endangered, EW Extinction in the Wild, and EX Extinct.



Larval morphology provides phylogenetic, taxonomic, and evolutionary information that is largely independent of adult characters, and a long-standing bias toward adult stages continues to constrain integrative systematics^{122,123}. Within Vietnam, larval taxonomy remains at an early stage, although recent descriptions of final instar or stadium larvae have refined species identification and phylogenetic understanding across families (Supplementary Note 3 and Supplementary Table 3). Expanding larval descriptions based on tropical Asian freshwater systems, and explicitly linking larvae to adults through rearing and molecular approaches, should therefore be regarded as a strategic priority equivalent to adult-based taxonomy, COI barcoding, and phylogenomics.

Taxonomic challenges persist across several families due to morphological complexity, limited genetic data, and varying levels of research effort. In particular, the family **Aeshnidae** includes species with poorly resolved identities and limited diagnostic precision. For example, Karube documented the presence of *Periaeschna magdalena* Martin, 1909, in Bach Ma National Park¹²⁴. Subsequent rigorous morphological analyses reclassified these specimens as *P. yazhenae* Xu, 2012¹²⁵, based on the absence of the diagnostic "T" mark on the frons, a defining feature of *P. magdalena*¹²⁵. Similarly, family **Gomphidae** are highly diverse in Vietnam, yet many taxa (e.g., *Sieboldius gigas* (Martin, 1904)²³, and *Megalogomphus sommeri* Selys, 1854¹²⁶; or *Orientogomphus circularis* (Selys, 1894), and *Orientogomphus naninus* (Förster, 1905)¹²⁷) remain inadequately revised, with uncertain species boundaries. In contrast, the superfamily **Calopterygoidea** has been relatively well studied, providing a more stable taxonomic framework and thus a useful comparison. In addition, the high diversity of families **Coenagrionidae** and **Libellulidae** poses major challenges, as many species are superficially similar and require integrative approaches for reliable delimitation.

For most, if not all, of 107 newly described or new record species (21.7% of total species), genetic analyses are needed to confirm whether some of these are distinct species or ecotypes, as polymorphism is prevalent in Odonata¹²⁸. Body and wing coloration are often essential morphological characteristics for species identification, but many species undergo dramatic color changes during maturation, complicating taxonomic assessments. For example, the bluish damselfly *Coeliccia cyanomelas* Ris, 1912 males exhibit three synonyms in three forms: *Coeliccia mingxiensis* Xu, 2006—an early mature form with yellow, curved antehumeral stripes, *Coeliccia wilsoni* Zhang and Hou, 2011—an intermediate-mature form with a large yellowish antehumeral stripe, and *Coeliccia sexmaculata* Wang, 1994—a young mature form with pale blue, rounded antehumeral stripes (see Fig. 6). Similarly, *Coeliccia mattii* males display four different body color patterns across their adult stage (see Fig. 5, ref. 129).

Whole-genome sequencing (WGS) offers transformative potential for resolving taxonomic uncertainties, elucidating evolutionary relationships, and uncovering the genomic basis of phenotypic diversity in Odonata^{128,130}.

By providing high-resolution genomic data, WGS clarifies species boundaries and phylogenetic relationships (e.g., *Ischnura elegans* (Vander Linden, 1820), ref. 128), but this method is constrained by high costs, substantial bioinformatic requirements, and limited local infrastructure. To date, none of the odonate species in Vietnam has had its genome fully sequenced. To enhance practical conservation efforts, WGS can be complemented by more accessible genomic approaches, such as DNA barcoding, restriction-site associated DNA sequencing (RADseq), or transcriptomics, which provide valuable resolution for species identification and population genetics at lower cost. Integrating WGS with these methods as part of a broader genomic toolkit will support accurate biodiversity assessments and prioritising conservation efforts for Vietnam's endemic and threatened odonate species, such as the critically endangered *Archineura maxima*¹²⁰ or *Atrocalopteryx auco* (a strikingly patterned endemic damselfly restricted to a few highland streams⁵¹). This parallels recent genomic approaches to iconic Vietnamese species like the Saola *Pseudoryx nghetinhensis* Dung, Giao, Chinh, Tuoc, Arcander, MacKinnon, 1993¹³¹.

Ecological, evolutionary, and ecotoxicological studies

Long-term monitoring programmes. Climate change and other anthropogenic stressors are driving macrogeographical and ecological shifts in species on Earth, including dragonflies and damselflies^{74,76,132}. Consequently, it is imperative to map the distribution, habitat connectivity, and range shifts of Vietnamese odonate species and populations under climate change. Such efforts will enhance global assessments of species range shifts in response to climate change, with significant applications for biological conservation. To this end, long-term, standardised monitoring programs are essential for statutory bioassessments of species and trait diversity across Vietnam (Fig. 7), especially targeting those in the highly specialised habitats, e.g., in the Central Highlands (Table 3). These programs would provide comprehensive data for assessing how climate change and human activities, addressing a critical gap in tropical and Asian biodiversity assessments, which remain severely underrepresented in global assessments (see e.g., refs. 85,133). Indeed, a global assessment of invertebrate biodiversity in over 72,000 lotic sites across 45 nations and 6 continents revealed that equatorial regions suffer the highest percentage (41–61%) of impaired sites¹³⁴.

Our knowledge of the ecology, evolution, ecotoxicology, and environmental monitoring of dragonflies and damselflies in Vietnam and other Southeast Asian and the entire Global South countries is extremely limited. In Vietnam, only study of Hoang et al.¹³⁵ used larvae of four families: Gomphidae, Coenagrionidae, Amphipterygidae, and Libellulidae as indicators to study habitat suitability for 30 macroinvertebrate families in the Du River in Northern Vietnam. We lack fundamental knowledge about the larval growth, development, life cycle, reproduction, behaviours, flying performance, ecophysiology, and sensitivity of most, if not all, odonate

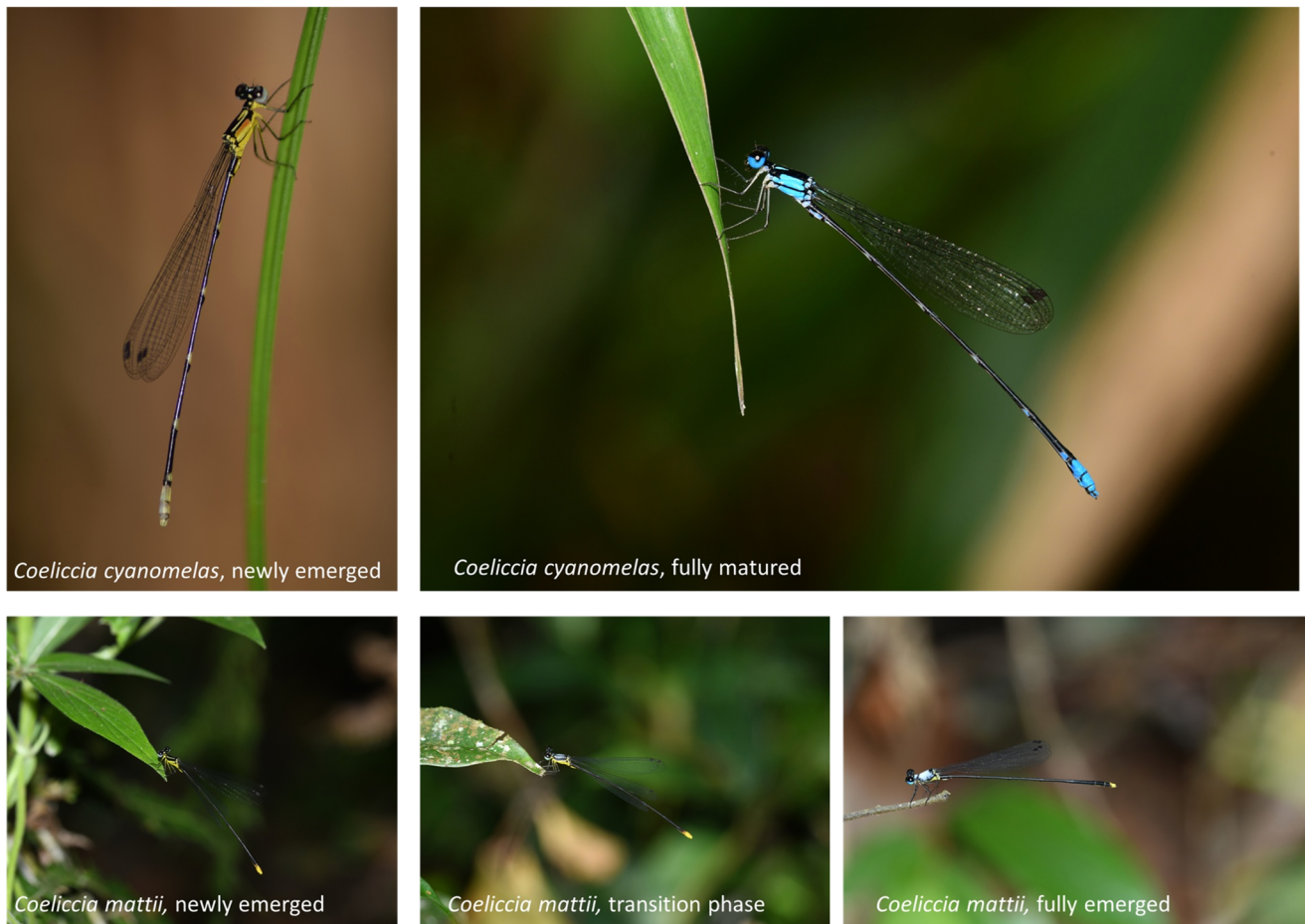


Fig. 6 | Polymorphisms in male damselflies of two selected species in Vietnam. Not all male forms of these species have been recorded in Vietnam. Photos of *Coelliccia cyanomelas* from Bach Ma National Park, Hue City, and *Coelliccia mattii*

from Nam Nung Nature Reserve, Lam Dong. Photos are not to scale. All photos were taken by the first author, Phan QT.

species to human-induced stressors such as global warming, heatwaves, precipitation changes, pollution, and habitat disconnectivity.

Odonata larvae play a central role in freshwater ecology (see Fig. 1) and represent a critical but underutilized resource for biomonitoring and conservation in Vietnam and across tropical regions. In freshwater ecosystems, odonate larvae are sensitive to changes in water quality, hydrology, substrate composition, and riparian structure (see section “Potential impacts of human activities on the Vietnamese and tropical Odonata”). Larval traits, habitat specificity, and life-history strategies provide ecological information such as respiratory modes (e.g., rectal vs. external caudal gills), microhabitat specialization (burrowing, clinging, or sprawler morphologies), feeding guilds and trophic position, voltinism and developmental duration, and tolerance to flow regime, sediment load, and dissolved oxygen conditions^{122,123}. These traits cannot be inferred reliably from adult records alone. In tropical regions, where taxonomic gaps or ecological biases may limit traditional Ephemeroptera, Plecoptera, and Trichoptera (EPT)-based indices, odonate larvae offer essential complementary indicators of ecosystem integrity, as already demonstrated in regional assessments from South and Southeast Asia^{121,136}. These traits suggest that Odonata larvae can be effectively integrated into national freshwater monitoring frameworks by targeting investments in larval taxonomy and ecology, expanded reference DNA libraries linking larvae and adults, and the development of trait-based ecological classifications¹⁰⁶. Including larval ecology in the research agenda will address a critical scientific deficit and enhance the applied value of Odonata research for conservation planning, water management, and biodiversity policy in Vietnam and comparable tropical regions⁴².

The absence of long-term time-series data on species composition and abundance introduces substantial uncertainty into ecological risk assessments, hindering the development of robust conservation strategies. To address these challenges, Vietnam must prioritise the establishment of systematic, long-term bioassessment programs. These programs should integrate advanced monitoring techniques (see below) alongside quantitative metrics of species diversity, niche differentiations, population dynamics, and habitat connectivity to elucidate the synergistic effects of climate change and anthropogenic pressures on odonate communities. By aligning with global biodiversity monitoring frameworks, such initiatives will contribute to a more equitable representation of tropical ecosystems in international conservation efforts, ultimately supporting the resilience of vulnerable species and ecosystems.

Together with monitoring programs, ecological, evolutionary, and ecotoxicological experiments are critical for evaluating the adaptability of tropical odonate species and populations to climate change and other anthropogenic stressors (Fig. 7). Ecological experiments frequently utilise damselfly larvae to assess their sensitivity, adaptability, and recovery from exposure to stressors such as warming, pollutants, and invasive species¹⁰². In contrast, adult odonates are employed to investigate reproductive behaviours, including mating competition, and flight performance, which serves as a proxy for dispersal capacity and movement dynamics in heterogeneous, human-dominated landscapes⁴⁴. Research must account for seasonal variations in species diversity, including range shift and migration, as well as physiological responses to environmental changes⁵⁷.

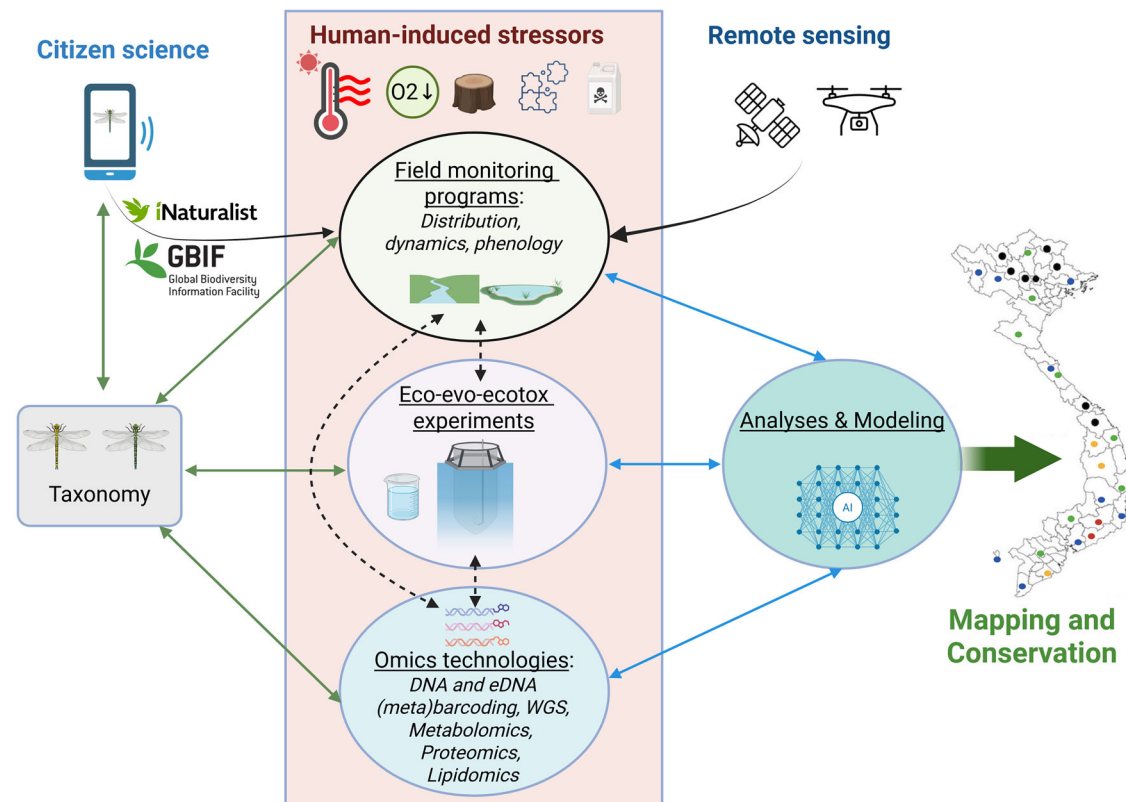


Fig. 7 | The framework outlines taxonomical, biodiversity, ecological, evolutionary, and ecotoxicological research on odonate species in Vietnam. Human-induced stressors (left to right): warming and heatwaves, deoxygenation, deforestation, habitat fragmentation, and pollutants. Key methodologies including field monitoring programmes using standardised sampling techniques along with citizen science (upper left) and remote sensing (satellites and drones – upper right), Eco-evo-ecotox experiments = ecological, evolutionary and ecotoxicological experiments; omics technologies (eDNA = environmental DNA, WGS = whole genome sequencing); and AI = artificial intelligence; Solid arrows indicate direct data and information flows among components (e.g., citizen science observations contributing to

GBIF and field monitoring, or remote sensing informing spatial analyses and distribution mapping). Dashed arrows represent cross-disciplinary integration and iterative feedback, highlighting how experimental results, omics data, and taxonomic validation reciprocally inform hypothesis generation, monitoring design, and mechanistic understanding. Outputs from analyses and modeling, including machine learning and artificial intelligence, support spatial mapping, forecasting, and conservation prioritisation. On the map, different coloured dots = different odonate species, while dots of the same colour = different populations of the same species. The Vietnamese map was created by the first author, Phan QT. The icons and diagram were created in Biorender.com license to Khuong V. Dinh.

Integrative tools and strategies for advancing Odonata research, monitoring, and conservation

eDNA metabarcoding - A non-invasive tool for Odonata monitoring.

Environmental DNA (eDNA) metabarcoding can provide a transformative and non-invasive approach to monitoring biodiversity by extracting DNA from environmental samples, such as water from rivers, lakes, or wetlands, to detect species presence via genetic markers¹³⁷. This technique involves extracting and amplifying DNA and sequencing specific gene regions, such as the cytochrome c oxidase I (COI) gene, enabling simultaneous identification of multiple species, providing a cost-effective and efficient alternative to traditional morphological surveys¹³⁷. This method seems to be particularly valuable in remote or densely vegetated areas where conventional sampling is challenging. In Vietnam, where habitat loss and pollution threaten odonatan populations, eDNA is particularly valuable for tracking species distributions and population dynamics in remote or densely vegetated areas where conventional sampling is challenging.

The success of eDNA applications critically depends on the completeness and curation quality of the DNA barcode reference library for Vietnamese Odonata. Our compilation in Supplementary Table 1 reveals that, of Vietnam's 493 recorded Odonata species, 279 (56.6%) have at least one publicly available COI barcode in GenBank, while 214 (43.4%) remain unbarcoded, disproportionately affecting data-deficient and endemic lineages in under-surveyed central highlands. Coverage is uneven across

families (e.g., 84% for Coenagrionidae [37/44 species], 66% for Platycnemididae [35/59 species], 73% for Libellulidae [58/79], 36% for Gomphidae [31/87], 49% for Aeshnidae [27/52], and 51.9% combined for Chlorocyphidae/Euphaeidae [23/39]) and suborders (58% for Zygoptera [125/216] vs. 54% for Anisoptera [151/277]), underscoring priorities for under-represented groups like threatened dragonflies.

Limitations in detecting odonate species, such as rapid DNA degradation in tropical climates and incomplete reference databases, require localised validations and methodological improvements¹³⁸. To strengthen the Vietnamese reference library, a realistic roadmap includes prioritising endemisms and threatened taxa (e.g., via focused expeditions in karst and highland hotspots), adopting standardized operating procedures (SOPs) for sampling and sequencing, and mandating deposition in national collections like the Vietnam National Museum of Nature. Framing eDNA metabarcoding as dependent on this robust barcode backbone will enhance its actionability for conservation. Integrating eDNA metabarcoding with traditional surveys can enhance monitoring programmes, supporting the conservation of Odonata and broader freshwater biodiversity. This approach offers scalable solutions for biodiversity assessment in Vietnam's rapidly changing ecosystems.

Advancing to whole genome sequencing (WGS) - Unlocking mechanistic insights. WGS can provide deeper phylogenetic resolution and elucidate the mechanisms underlying evolutionary, ecological, and

behavioral responses to climate change and anthropogenic stressors such as habitat pollution¹³⁹. WGS can identify genes and pathways linked to flight performance, muscle efficiency, and energy metabolism, shedding light on the genetic underpinnings of dispersal capacity¹³⁰. For Vietnamese odonates, this could inform predictions about their ability to colonise new habitats or retreat to refugia as temperatures rise. WGS can uncover genetic mechanisms of resilience, such as detoxification genes (e.g., enzymes cytochrome P450 and glutathione S-transferases) that confer resistance to pollutants (see, e.g., in *Anopheles* mosquitoes¹⁴⁰). Understanding these mechanisms can guide habitat management strategies to mitigate anthropogenic impacts. WGS, combined with epigenomic analyses, can reveal how environmental changes such as temperature, pollution (e.g., metals, pesticides, pharmaceuticals, microplastics), and habitat degradations influence gene expression through DNA methylation or histone modifications. This is particularly relevant for odonates, which exhibit phenotypic plasticity in traits like larval development rates or adult colorations¹²⁹. Understanding WGS and epigenetic mechanisms can clarify how Vietnamese odonates cope with climate- and human-driven habitat changes.

Lipidomics - bridging aquatic-terrestrial energy flows. Analysing the lipidomes of Odonata is crucial for understanding the energy reserve, which shows a positive correlation with the flying performance to disperse in fragmented habitats or for range shift under global warming (e.g., in *Coenagrion* species^{141,142}). Furthermore, by examining the lipid composition, we can quantify the abundance and type of fatty acids, especially omega-3 such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are essential for terrestrial animals, including birds, bats, and riparian spiders. Odonata, rich in EPA and DHA, serve as critical prey for these small predators, transferring essential fatty acids from aquatic to terrestrial ecosystems, supporting their physiological functions and reproduction^{11,13}. Such research informs conservation strategies by emphasizing the importance of preserving aquatic insect populations to sustain both aquatic and terrestrial food webs. Like WGS, lipidomics also faces analytical costs and expertise gaps, but its integration into multi-omics frameworks promises holistic strategies for Odonate in Vietnam, from molecular mechanisms to ecosystem responses and resilience.

Local citizen science networks - crowdsourcing spatial insights. Local citizen science harnesses community-driven data collection by integrating smartphone camera systems with taxonomic information and platforms such as “iNaturalist” or Global Biodiversity Information Facility (GBIF) (see Fig. 7). These platforms are already contributing significantly to mapping species distribution and phenology of Odonata in Vietnam and Southeast Asia, with iNaturalist and GBIF hosting a rapidly growing volume of georeferenced odonate records that provide valuable baseline data for species distribution, phenology, and conservation assessments (Supplementary Table 4), demonstrate the effectiveness of social media and citizen science platforms in capturing large-scale distributional data for dragonflies and damselflies, offering a model for Vietnam. These tools enable accurate species identification and georeferenced data submission, significantly enhancing spatial and temporal monitoring of odonate distributions and phenological shifts (e.g., refs. 32,42,143). By standardizing data collection protocols and providing training on species identification, these networks can generate robust datasets to track ecological responses to climate change and anthropogenic stressors, supporting evidence-based conservation strategies for Odonata and broader freshwater biodiversity.

Remote sensing and automated imaging (e.g., refs. 144,145) can provide high-resolution environmental data to model habitat suitability and detect anthropogenic stressors like habitat degradation and pesticide contamination.

Machine learning and artificial intelligence - predictive frontiers. Finally, machine learning algorithms, e.g., random forest or

convolutional neural network, applied to all types of datasets, offer predictive power for species distribution modeling, particularly evolutionary responses to environmental changes. These tools are especially critical for odonate research in Vietnam’s challenging mountainous and tropical environments, where harsh weather, rugged terrain, and seasonal flooding often impede traditional field experiments and observational studies, thus necessitating an innovative, data-driven approach to advance conservation and toxicological assessments of Odonata.

Recommendations

The rich diversity of Vietnam’s 493 Odonata species, coupled with their ecological significance as bioindicators and vulnerability to climate change and habitat loss, underscores the urgent need for innovative research and conservation strategies. This review is the first to synthesise 200 years of Vietnamese Odonata research, highlighting critical data gaps, and proposes a multidisciplinary framework to advance Odonata research. This framework is scalable to all aquatic invertebrates, such as crustaceans and insects (e.g., Ephemeroptera, Plecoptera, and Trichoptera) and understudied tropical regions (e.g., Southeast Asia, Congo Basin, and Amazon Basin) for biodiversity research and conservation. The following recommendations provide a roadmap to bridge ecological and conservation gaps, aligning with the UN Sustainable Development Goals (SDGs 13: Climate Action, 14: Life Below Water, and 15: Life on Land) and the Global Biodiversity Framework’s (GBF) 30 × 30 target to protect 30% of ecosystems by 2030, providing a model for global biodiversity conservation.

1. **Enhance both larval and adult taxonomy, phylogeny, and ecology using integrated morphology and genomic tools:** Develop comprehensive inventories integrating basic ecological data, encompassing larval habitat preferences, life history traits, phenology, and larval-adult habitat connections, which are vital for elucidating distribution patterns, assessing vulnerabilities, and informing conservation strategies. Furthermore, leveraging WGS and phylogenetic analyses can resolve taxonomic uncertainties, such as polymorphisms in the genus *Coeliccia*, resolve uncertainties in families like Gomphidae and Aeshnidae, and clarify species boundaries for the 107 newly described species since 1975. These advancements will enhance the accuracy of biodiversity assessments, addressing the taxonomic bias that currently limits ecological insights.
2. **Establish long-term monitoring programmes:** Implement standardised bioassessment programmes that combine regular field samplings of larvae and adults with eDNA metabarcoding, remote sensing, and citizen science to track distribution gaps (e.g., addressing 138 single-site records), species diversity, population dynamics, and habitat connectivity. Furthermore, it is critically important to apply quantitative analyses, e.g., generalized mixed models for abundance trends, spatial autocorrelation metrics for connectivity, and time-series regressions for phenological shifts, to detect statistically significant changes and forecast vulnerability under climate change scenarios and human impacts.
3. **Prioritize genome research:** Conduct WGS and epigenomic analyses to resolve taxonomic uncertainties, identify adaptive traits, and understand responses to environmental changes.
4. **Integrate multidisciplinary approaches:** combine ecological, evolutionary, and ecotoxicological experiments, high-throughput omics, and machine learning to holistically project large-scale and long-term odonate responses to climate change and anthropogenic stressors.
5. **Align with global frameworks:** Ensure monitoring programmes contribute to international biodiversity assessments, addressing the underrepresentation of tropical ecosystems.
6. **Enhance capacity building:** develop training programs for researchers and citizens to support advanced monitoring and conservation efforts.

By advancing these research domains, Vietnamese Odonata can bridge global ecological and conservation gaps, providing a model for understanding and protecting tropical biodiversity in a changing

world¹⁶. This integrated approach not only addresses Vietnam-specific challenges, such as habitat loss and climate-driven range shifts, but also offers a scalable blueprint for global Odonatology, entomology, and invertebrate zoology. It provides policymakers with actionable tools, such as standardised monitoring and capacity building, to safeguard tropical ecosystems under increasing environmental pressure, ensuring resilience in a changing world.

Received: 15 July 2025; Accepted: 2 February 2026;

Published online: 01 April 2026

References

- Kohli, M. et al. Evolutionary history and divergence times of Odonata (dragonflies and damselflies) revealed through transcriptomics. *iScience* **24**, 103324 (2021).
- Corbet, P. S. *Dragonflies: Behavior and Ecology of Odonata* (Cornell University Press, 1999).
- Dayananda, H. S. K. & Kitching, R. L. Ovo-viviparity in the Odonata? The case of *Heliocypha perforata* (Zygoptera: Chlorocyphidae). *Int. J. Odonatol.* **17**, 181–185 (2014).
- Stoks, R. & Cordoba-Aguilar, A. Evolutionary ecology of Odonata: a complex life cycle perspective. *Annu. Rev. Entomol.* **57**, 249–265 (2012).
- Johnson, D. M. Behavioral ecology and larval dragonflies and damselflies. *Trends Ecol. Evol.* **6**, 8–13 (1991).
- Jonsson, M., Johansson, F., Karlsson, C. & Brodin, T. Intermediate predator impact on consumers weakens with increasing predator diversity in the presence of a top-predator. *Acta Oecol. Int. J. Ecol.* **31**, 79–85 (2007).
- Ramlee, S., Norma, R. & Mohd, S. A. Odonata nymphs as potential biocontrol agent of mosquito larvae in Malaysia. *Southeast Asian J. Trop. Med. Public Health* **53**, 426–435 (2022).
- Acorn, J. *Damselflies of Alberta: Flying Neon Toothpicks in the Grass* (University of Alberta, 2004).
- Folorunso, L., Falaye, A. & Ajani, E. Predatory size of dragonfly (*Palpopleura lucia* (Drury, 1773)) Nymphs on Guppy (*Poecilia reticulata* (Peters, 1859)). *J. Fish. Aquat. Sci.* **9**, 483 (2014).
- Nyffeler, M., Şekercioğlu, ÇH. & Whelan, C. J. Insectivorous birds consume an estimated 400–500 million tons of prey annually. *Sci. Nat.* **105**, 47 (2018).
- Twining, C. W. et al. Integrating the bright and dark sides of aquatic resource subsidies: a synthesis. *Ecol. Lett.* **28**, e70109 (2025).
- Twining, C. W., Brenna, J. T., Hairston, N. G. Jr & Flecker, A. S. Highly unsaturated fatty acids in nature: what we know and what we need to learn. *Oikos* **125**, 749–760 (2016).
- Twining, C. W., Shipley, J. R. & Winkler, D. W. Aquatic insects rich in omega-3 fatty acids drive breeding success in a widespread bird. *Ecol. Lett.* **21**, 1812–1820 (2018).
- Previšić, A., Vilenica, M., Vučković, N., Petrović, M. & Rožman, M. Aquatic insects transfer pharmaceuticals and endocrine disruptors from aquatic to terrestrial ecosystems. *Environ. Sci. Technol.* **55**, 3736–3746 (2021).
- Kalkman, V. J. et al. In *Freshwater Animal Diversity Assessment* (eds Balian E. V., Lévêque C., Segers H., & Martens K.) 351–363 (Springer Netherlands, 2008).
- Barlow, J. et al. The future of hyperdiverse tropical ecosystems. *Nature* **559**, 517–526 (2018).
- Sodhi, N. S., Koh, L. P., Brook, B. W. & Ng, P. K. L. Southeast Asian biodiversity: an impending disaster. *Trends Ecol. Evol.* **19**, 654–660 (2004).
- Dinh, K. V. Vietnam's fish kill remains unexamined. *Science* **365**, 333–333 (2019).
- Truong, K. N. & Dinh, K. V. Agent orange: half-century effects on the Vietnamese wildlife have been ignored. *Environ. Sci. Technol.* **55**, 15007–15009 (2021).
- Schmidt, K. J., Soluk, D. A., Maestas, S. E. M. & Britten, H. B. Persistence and accumulation of environmental DNA from an endangered dragonfly. *Sci. Rep.* **11**, 18987 (2021).
- Cairns, J., Baird, I. R. C., Johnson, F., Noble, L. & Glamore, W. Detecting *Petalura gigantea*: Novel eDNA method and water balance modelling insights enable improved catchment management and conservation outcomes. *Ecohydrology* **18**, e70013 (2025).
- Uche-Dike, R. et al. Integrating eDNA and community science to monitor urban Odonata diversity. *Insect Conserv. Divers.* <https://doi.org/10.1111/icad.70006> (2025).
- Martin, R. Liste des Neuroptères de l'Indo-Chine: Odonates. *Pavie A Mission Pavie Indo Chine* **3**, 1879–1895 (1904).
- Hämäläinen, M. & Karube, H. Description of *Anisopleura bipugio* sp. nov. from southern Vietnam (Odonata: Euphaeidae). *Tombo. Acta Odonatol. Japonica* **55**, 51–55 (2013).
- Dow, R. A. e. T163775A138283056 (International Union for Conservation of Nature, 2020).
- Keetapithchayakul, T. S., Kim, J., Lam, N. B. V. & Phan, Q. T. Description of the larva of *Anotogaster klossi* Fraser, 1919 (Odonata, Cordulegastroidea, Cordulegastridae), with a note on the known larvae of the genus *Anotogaster* Selys, 1854. *Zootaxa* **5632**, 349–363 (2025).
- Novelo-Gutiérrez, R., Londoño, G. A., Cordero-Rivera, A., Flórez-VC, S.-H. J. & Bota-Sierra, C. The importance of tropical mountain forests for the conservation of dragonfly biodiversity: a case from the Colombian Western Andes. *Int. J. Odonatol.* **24**, 233–247 (2021).
- Costello, M. J., May, R. M. & Stork, N. E. Can we name Earth's species before they go extinct?. *Science* **339**, 413–416 (2013).
- Badirli, S. et al. Classifying the unknown: insect identification with deep hierarchical Bayesian learning. *Methods Ecol. Evol.* **14**, 1515–1530 (2023).
- Hanski, I. & Ovaskainen, O. The metapopulation capacity of a fragmented landscape. *Nature* **404**, 755–758 (2000).
- Bried, J. T., Alves-Martins, F., Brasil, L. S. & McCauley, S. J. in *Dragonflies and Damselflies: Model Organisms for Ecological and Evolutionary Research* 233–246 (Oxford University Press, 2023).
- Moore, M. P. et al. Sex-specific ornament evolution is a consistent feature of climatic adaptation across space and time in dragonflies. *Proc. Natl. Acad. Sci. USA* **118**, e2101458118 (2021).
- Fajenblat, M. et al. Leveraging massive opportunistically collected datasets to study species communities in space and time. *Ecol. Lett.* **28**, e70094 (2025).
- Ngiam, R. W. J. & Cheong, L. F. The dragonflies of Singapore: an updated checklist and revision of the national conservation statuses. *Nat. Singap.* **9**, 149–163 (2016).
- Luke, S. H. et al. The impacts of habitat disturbance on adult and larval dragonflies (Odonata) in rainforest streams in Sabah, Malaysian Borneo. *Freshw. Biol.* **62**, 491–506 (2017).
- Rodríguez-Tapia, G., Rocha-Ortega, M. & Córdoba-Aguilar, A. An index to estimate the vulnerability of damselflies and dragonflies (Insecta: Odonata) to land use changes using niche modeling. *Aquat. Insects* **41**, 254–272 (2020).
- Dolný, A., Harabiš, F., Bárta, D., Lhota, S. & Drozd, P. Aquatic insects indicate terrestrial habitat degradation: changes in taxonomical structure and functional diversity of dragonflies in tropical rainforest of East Kalimantan. *Tropical Zool.* **25**, 141–157 (2012).
- De Marco Júnior, P., Batista, J. D. & Cabette, H. S. R. Community assembly of adult odonates in tropical streams: an ecophysiological hypothesis. *PLoS ONE* **10**, e0123023 (2015).
- Urban, M. C. Accelerating extinction risk from climate change. *Science* **348**, 571–573 (2015).
- Clausnitzer, V. et al. Odonata enter the biodiversity crisis debate: the first global assessment of an insect group. *Biol. Conserv.* **142**, 1864–1869 (2009).

41. Hassall, C. & Thompson, D. J. The effects of environmental warming on Odonata: a review. *Int. J. Odonatol.* **11**, 131–153 (2008).
42. Samways, M. J. et al. Scientists' warning on the need for greater inclusion of dragonflies in global conservation. *Insect Conserv. Divers.* **18**, 1–20 (2025).
43. Termaat, T. et al. Distribution trends of European dragonflies under climate change. *Divers. Distrib.* **25**, 936–950 (2019).
44. Bried, J. T. & Samways, M. J. A review of odonatology in freshwater applied ecology and conservation science. *Freshw. Sci.* **34**, 1023–1031 (2015).
45. Williams, S. E., Shoo, L. P., Isaac, J. L., Hoffmann, A. A. & Langham, G. Towards an integrated framework for assessing the vulnerability of species to climate change. *PLoS Biol.* **6**, e325 (2008).
46. MONRE. 253 (Vietnam Natural Resources, Environment and Mapping Publishing House, 2020).
47. Gobin, A., Nguyen, H., Pham, V. & Pham, H. Heavy rainfall patterns in Vietnam and their relation with ENSO cycles. *Int. J. Climatol.* **36**, 1686–1699 (2016).
48. Sterling, E. J. & Hurley, M. M. Conserving biodiversity in Vietnam: applying biogeography to conservation research. *Proc. Calif. Acad. Sci.* **56**, 98 (2005).
49. Stearns, S. C. *The Evolution of Life Histories* (Oxford University Press, 1998).
50. Suhling, F., Schenk, K., Padeffke, T. & Martens, A. A field study of larval development in a dragonfly assemblage in African desert ponds (Odonata). *Hydrobiologia* **528**, 75–85 (2004).
51. Hämäläinen, M. *Atrocalopteryx auco* spec. Nov. from Vietnam, with taxonomic notes on its congeners (Odonata: Calopterygidae). *Zootaxa* **3793**, 561–572 (2014).
52. Hämäläinen, M. & Karube, H. *Rhinocypha oreia* spec. Nov., a new damselfly from Vietnam (Odonata: Chlorocyphidae). *Zoologische Mededel.* **75**, 405–408 (2001).
53. Nilsson-Örtman, V., Stoks, R., De Block, M. & Johansson, F. Generalists and specialists along a latitudinal transect: patterns of thermal adaptation in six species of damselflies. *Ecology* **93**, 1340–1352 (2012).
54. Nilsson-Örtman, V., Stoks, R., De Block, M. & Johansson, F. Latitudinal patterns of phenology and age-specific thermal performance across six Coenagrion damselfly species. *Ecol. Monogr.* **83**, 491–510 (2013).
55. Nilsson-Örtman, V., Stoks, R., De Block, M., Johansson, H. & Johansson, F. Latitudinally structured variation in the temperature dependence of damselfly growth rates. *Ecol. Lett.* **16**, 64–71 (2013).
56. Osland, M. J. et al. Tropicalization of temperate ecosystems in North America: The northward range expansion of tropical organisms in response to warming winter temperatures. *Glob. Change Biol.* **27**, 3009–3034 (2021).
57. Dinh, K. V. et al. Winter is coming: Interactions of multiple stressors in winter and implications for the natural world. *Glob. Change Biol.* **29**, 6834–6845 (2023).
58. Carbonell, J. A., Wang, Y.-J. & Stoks, R. Evolution of cold tolerance and thermal plasticity in life history, behaviour and physiology during a poleward range expansion. *J. Anim. Ecol.* **90**, 1666–1677 (2021).
59. Rocha-Ortega, M., Rodríguez, P., Bried, J. T., Abbott, J. & Córdoba-Aguilar, A. Why do bugs perish? Range size and local vulnerability traits as surrogates of Odonata extinction risk. *Proc. R. Soc. B* **287**, 20192645 (2020).
60. Cancellario, T. et al. Climate change will redefine taxonomic, functional, and phylogenetic diversity of Odonata in space and time. *npj Biodivers.* **1**, 1 (2022).
61. Chase, J. M. & Leibold, M. A. *Ecological Niches: Linking Classical and Contemporary Approaches* (University of Chicago Press, 2009).
62. Huey, R. B. & Kingsolver, J. G. Evolution of thermal sensitivity of ectotherm performance. *Trends Ecol. Evol.* **4**, 131–135 (1989).
63. Sinclair, B. J. et al. Can we predict ectotherm responses to climate change using thermal performance curves and body temperatures?. *Ecol. Lett.* **19**, 1372–1385 (2016).
64. Tewksbury, J. J., Huey, R. B. & Deutsch, C. A. Putting the heat on tropical animals. *Science* **320**, 1296–1297 (2008).
65. Castillo-Pérez, E. U., Suárez-Tovar, C. M., González-Tokman, D., Schondube, J. E. & Córdoba-Aguilar, A. Insect thermal limits in warm and perturbed habitats: Dragonflies and damselflies as study cases. *J. Therm. Biol.* **103**, 103164 (2022).
66. AFP. In *Barron's* (Dow Jones and Company, Inc., 2023).
67. AFP. In *The Straits Times* (ASIA, 2024).
68. Gardner, J. L., Peters, A., Kearney, M. R., Joseph, L. & Heinsohn, R. Declining body size: a third universal response to warming?. *Trends Ecol. Evol.* **26**, 285–291 (2011).
69. Mähn, L. A., Hof, C., Brandl, R. & Pinkert, S. Beyond latitude: temperature, productivity and thermal niche conservatism drive global body size variation in Odonata. *Glob. Ecol. Biogeogr.* **32**, 656–667 (2023).
70. Corbet, P. S., Suhling, F. & Soendgerath, D. Voltinism of Odonata: a review. *Int. J. Odonatol.* **9**, 1–44 (2006).
71. McCauley, S. J., Hammond, J. I. & Mabry, K. E. Simulated climate change increases larval mortality, alters phenology, and affects flight morphology of a dragonfly. *Ecosphere* **9**, e02151 (2018).
72. Tüzün, N., Op de Beeck, L., Oliariony, R., Van Dievel, M. & Stoks, R. Warming under seminatural outdoor conditions in the larval stage negatively affects insect flight performance. *Biol. Lett.* **14**, 20180121 (2018).
73. Swaegers, J. et al. Ecological and evolutionary drivers of range size in *Coenagrion* damselflies. *J. Evolut. Biol.* **27**, 2386–2395 (2014).
74. Hickling, R., Roy, D. B., Hill, J. K., Fox, R. & Thomas, C. D. The distributions of a wide range of taxonomic groups are expanding polewards. *Glob. Change Biol.* **12**, 450–455 (2006).
75. Chen, I. C., Hill, J. K., Ohlemuller, R., Roy, D. B. & Thomas, C. D. Rapid range shifts of species associated with high levels of climate warming. *Science* **333**, 1024–1026 (2011).
76. Parmesan, C. et al. Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* **399**, 579–583 (1999).
77. Liao, J. et al. Modeling and Prediction of the Species' Range of *Neurobasis chinensis* (Linnaeus, 1758) under Climate Change. *Biol. Basel* **11**, <https://doi.org/10.3390/biology11060868> (2022).
78. Liao, J. et al. Projected effects of climate change on species range of *Pantala flavescens*, a wandering glider dragonfly. *Biol.-Basel* **12**, 16 (2023).
79. Hill, J. K., Griffiths, H. M. & Thomas, C. D. Climate change and evolutionary adaptations at species' range margins. *Annu. Rev. Entomol.* **56**, 143–159 (2011).
80. Cheng, J. et al. Heatwaves and dengue outbreaks in Hanoi, Vietnam: New evidence on early warning. *PLoS Neglect. Trop. Dis.* **14**, <https://doi.org/10.1371/journal.pntd.0007997> (2020).
81. Ly, P. T., Ha, P. T., Van Tan, P. & Yen, V. T. Variability of heatwaves across Vietnam in recent decades. *Vietnam J. Earth Sci.* **45**, 517–530 (2023).
82. Pinsky, M. L., Eikeset, A. M., McCauley, D. J., Payne, J. L. & Sunday, J. M. Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature* **569**, 108–111 (2019).
83. Espagne, E. et al. Climate Change in Vietnam - Impacts and adaptation. *Agence Française. Dév.*, **612**, hal-05068881 (2021).
84. Tang, F. H. M., Lenzen, M., McBratney, A. & Maggi, F. Risk of pesticide pollution at the global scale. *Nat. Geosci.* **14**, 206–210 (2021).
85. Reid, A. J. et al. Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biol. Rev.* **94**, 849–873 (2019).
86. IPBES. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science - Policy Platform on Biodiversity and Ecosystem Services. 56 (IPBES, 2019).

87. Sánchez-Bayo, F. & Wyckhuys, K. A. G. Worldwide decline of the entomofauna: a review of its drivers. *Biol. Conserv.* **232**, 8–27 (2019).
88. Cochard, R., Ngo, D. T., Waeber, P. O. & Kull, C. A. Extent and causes of forest cover changes in Vietnam's provinces 1993–2013: a review and analysis of official data. *Environ. Rev.* **25**, 199–217 (2017).
89. Tinh, P. H. et al. Distribution and drivers of Vietnam mangrove deforestation from 1995 to 2019. *Mitig. Adapt. Strateg. Glob. Change* **27**, 29 (2022).
90. Na, H. R., Manno, J. P., Sonnenfeld, D. A. & Heisler, G. M. Governance of forests. *Routledge Handbook Environ. Soc. Asia* 303 (2014).
91. Meyfroidt, P., Phuong, V. T. & Anh, H. V. Trajectories of deforestation, coffee expansion and displacement of shifting cultivation in the Central Highlands of Vietnam. *Glob. Environ. Change Hum. Policy Dimens.* **23**, 1187–1198 (2013).
92. Meyfroidt, P. & Lambin, E. F. Forest transition in Vietnam and its environmental impacts. *Glob. Change Biol.* **14**, 1319–1336 (2008).
93. Phan, Q. T. *Vietnam Red List of Threatened Species. Rhinocypha Orea*. IS42 (Vietnam Academy of Science and Technology, 2023).
94. Hardwick, S. R. et al. The relationship between leaf area index and microclimate in tropical forest and oil palm plantation: Forest disturbance drives changes in microclimate. *Agric. For. Meteorol.* **201**, 187–195 (2015).
95. Ishak, M. et al. Physicochemical properties as driver of odonata diversity in oil palm waterways. *Front. For. Glob. Change* **4**, 613064 (2021).
96. Harrison, M. E. et al. Impacts of fire and prospects for recovery in a tropical peat forest ecosystem. *Proc. Natl. Acad. Sci. USA* **121**, <https://doi.org/10.1073/pnas.2307216121> (2024).
97. Beketov, M. A., Kefford, B. J., Schafer, R. B. & Liess, M. Pesticides reduce regional biodiversity of stream invertebrates. *Proc. Natl. Acad. Sci. USA* **110**, 11039–11043 (2013).
98. Normile, D. Vietnam turns back a 'tsunami of pesticides'. *Science* **341**, 737–738 (2013).
99. FAO. (Food and Agriculture Organization United States Rome, Italy, 2019).
100. Hoai, P. M., Sebesvari, Z., Minh, T. B., Viet, P. H. & Renaud, F. G. Pesticide pollution in agricultural areas of Northern Vietnam: case study in Hoang Liet and Minh Dai communes. *Environ. Pollut.* **159**, 3344–3350 (2011).
101. Ho, T. Q., Hoang, V.-N., Wilson, C. & Nguyen, T.-T. Eco-efficiency analysis of sustainability-certified coffee production in Vietnam. *J. Clean. Prod.* **183**, 251–260 (2018).
102. Stoks, R., Debecker, S., Dinh, K. V. & Janssens, L. Integrating ecology and evolution in aquatic toxicology: insights from damselflies. *Freshw. Sci.* **34**, 1032–1039 (2015).
103. Rawi, C. S. M., Al-Shami, S. A., Shah, A., Ahmad, A. H. & Man, A. Effects of herbicides on Odonata communities in a rice agroecosystem. *Toxicol. Environ. Chem.* **94**, 1188–1198 (2012).
104. Grumbine, R. E. & Xu, J. Mekong hydropower development. *Science* **332**, 178–179 (2011).
105. Klein, C. et al. The influence of small hydroelectric power plants on the richness and composition of Odonata species in the Brazilian Savanna. *Int. J. Odonatol.* **21**, 33–44 (2018).
106. Silva, L. F. R. et al. Functional responses of Odonata larvae to human disturbances in neotropical savanna headwater streams. *Ecol. Indic.* **133**, 108367 (2021).
107. Dinh, K. V. et al. Susceptibility to a metal under global warming is shaped by thermal adaptation along a latitudinal gradient. *Glob. Change Biol.* **19**, 2625–2633 (2013).
108. Dinh, K. V., Janssens, L. & Stoks, R. Exposure to a heat wave under food limitation makes an agricultural insecticide lethal: a mechanistic laboratory experiment. *Glob. Change Biol.* **22**, 3361–3372 (2016).
109. Dinh, K. V. et al. Interactive effects of warming and pollutants on marine and freshwater invertebrates. *Curr. Pollut. Rep.* **8**, 341–359 (2022).
110. Šigutová, H. et al. In *Dragonflies and Damselflies: Model Organisms for Ecological and Evolutionary Research* (eds Cordoba-Aguilar A., Beatty C., & Bried J.) 0 (Oxford University Press, 2023).
111. Orr, J. A. et al. Studying interactions among anthropogenic stressors in freshwater ecosystems: a systematic review of 2396 multiple-stressor experiments. *Ecol. Lett.* **27**, e14463 (2024).
112. Orr, J. A. et al. Towards a unified study of multiple stressors: divisions and common goals across research disciplines. *Proc. R. Soc. B* **287**, 20200421 (2020).
113. Karube, H. Vietnamese Odonata collected in 1992–2003 surveys (4) Synlestidae. *Tombo. Acta Odonatol. Japonica* **56**, 73–76 (2014).
114. Phan, Q. T., Kompier, T., Karube, H. & Hayashi, F. A synopsis of the Euphaeidae (Odonata: Zygoptera) of Vietnam, with descriptions of two new species of Euphaea. *Zootaxa* **4375**, 151–190 (2018).
115. Phan, Q. T. & Kompier, T. Description of two new species of *Coelliccia* from Vietnam (Odonata: Platycnemididae). *Zootaxa* **4196**, 407–414 (2016).
116. Phan, Q. T., Ngo, Q. P., Toan, T. C. & Tuan, V. A. Description of *Coelliccia natgeo* sp. nov. from Central Vietnam with keys to the males and females of the hayashii-group (Odonata: Zygoptera: Platycnemididae). *Zootaxa* **4896**, 096–104 (2020).
117. Kompier, T., Dow, R. A. & Steinhoff, P. O. Five new species of *Coelliccia* Kirby, 1890 from Vietnam (Odonata: Platycnemididae), and information on several other species of the genus. *Zootaxa* **4766**, 501–538 (2020).
118. Ning, X., Kompier, T., Yu, X. & Bu, W. *Paracercion ambiguum* sp. nov. from Lang Son, Vietnam (Zygoptera: Coenagrionidae). *Zootaxa* **4144**, 263–275 (2016).
119. Hämäläinen, M. *Platycnemis doi* sp. nov. from Huu Lien nature reserve in northern Vietnam (Odonata: Platycnemididae). *Int. J. Odonatol.* **15**, 223–228 (2012).
120. Hämäläinen, M. From *Echo maxima* to *Archineura maxima* - a slow taxonomic process (Odonata: Calopterygidae). *Not. Odonatol.* **8**, 156–201 (2015).
121. Novelo-Gutiérrez, R. & Sites, R. W. *The Dragonfly Nymphs of Thailand (Odonata: Anisoptera): An Identification Guide to Families and Genera* (Springer Nature, 2024).
122. Sutherland, L. N. et al. Zygoptera systematics: past, present, and future. *Insect Syst. Divers.* **9**, 5 (2025).
123. Ware, J. et al. Odonata systematics: past, present, and future: a review of the phylogenetic works in Anisoptera (dragonflies). *Insect Syst. Divers.* **9**, 9 (2025).
124. Karube, H. Vietnamese Odonata collected in 1992–2003 surveys (1) Aeshnidae. *Tombo. Acta Odonatol. Japonica* **47**, 1–11 (2004).
125. Xu, Q. *Periaeschna yazhenae* sp. nov. from Fujian, China (Odonata: Anisoptera: Aeshnidae). *Zootaxa* **3526**, 72–78 (2012).
126. Do, M. C. Notes on three species of gomphid dragonflies from Vietnam (Odonata: Gomphidae). *Int. Dragonfly Fund.* **36**, 1–9 (2011).
127. Phan, Q. T. & Ngo, Q. P. An updated the checklist of dragonflies and damselflies (Insecta: Odonata) of Phu Quoc National Park, southern Vietnam. *Int. J. Dragonfly Fund.* **175**, 1–18 (2023).
128. Willink, B. et al. The genomics and evolution of inter-sexual mimicry and female-limited polymorphisms in damselflies. *Nat. Ecol. Evol.* **8**, 83–97 (2024).
129. Phan, Q. T., Phu, N. Q., Bui, A. P., Le, H. S. & Nguyen, G. S. Notes on the changes in body color with age in male and female *Coelliccia mattii* Phan & Kompier, 2016 (Odonata: Zygoptera: Platycnemididae). *Int. Dragonfly Fund. Rep.* **2020**, 1–6 (2020).
130. Bybee, S. M. et al. Phylogeny and classification of Odonata using targeted genomics. *Mol. Phylogenet. Evol.* **160**, 107115 (2021).
131. Garcia-Erill, G. et al. Genomes of critically endangered saola are shaped by population structure and purging. *Cell*. <https://doi.org/10.1016/j.cell.2025.03.040> (2025).
132. Parmesan, C. Ecological and evolutionary responses to recent climate change. *Annu. Rev. Ecol. Evol. Syst.* **37**, 637–669 (2006).

133. Lawlor, J. A. et al. Mechanisms, detection and impacts of species redistributions under climate change. *Nat. Rev. Earth Environ.* **5**, 351–368 (2024).
134. Feio, M. J. et al. Fish and macroinvertebrate assemblages reveal extensive degradation of the world's rivers. *Glob. Change Biol.* **29**, 355–374 (2023).
135. Hoang, T. H., Lock, K., Mouton, A. & Goethals, P. L. Application of classification trees and support vector machines to model the presence of macroinvertebrates in rivers in Vietnam. *Ecol. Inform.* **5**, 140–146 (2010).
136. Kalkman, V. J. et al. Checklist of the dragonflies and damselflies (Insecta: Odonata) of Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka. *Zootaxa* **4849**, 1–84 (2020).
137. Altermatt, F. et al. Utilizing aquatic environmental DNA to address global biodiversity targets. *Nat. Rev. Biodivers.* **1**, 332–346 (2025).
138. Schwesig, K., Zizka, V., Scherber, C. & Hölzel, N. Comparing eDNA and transect methods for aquatic biodiversity assessment in lakes and ponds. *Mol. Ecol. Resour.* **25**, e14060 (2025).
139. Ioannidis, P. et al. Genomic features of the damselfly *Calopteryx splendens* representing a sister clade to most insect orders. *Genome Biol. Evol.* **9**, 415–430 (2017).
140. Lucas, E. R. et al. Genome-wide association studies reveal novel loci associated with pyrethroid and organophosphate resistance in *Anopheles gambiae* and *Anopheles coluzzii*. *Nat. Commun.* **14**, 4946 (2023).
141. Dinh, K. V. et al. Delayed effects of chlorpyrifos across metamorphosis on dispersal-related traits in a poleward moving damselfly. *Environ. Pollut.* **218**, 634–643 (2016).
142. Therry, L., Gyulavári, H. A., Schillewaert, S., Bonte, D. & Stoks, R. Integrating large-scale geographic patterns in flight morphology, flight characteristics and sexual selection in a range-expanding damselfly. *Ecography* **37**, 1012–1021 (2014).
143. Bried, J. T. et al. Towards global volunteer monitoring of odonate abundance. *BioScience* **70**, 914–923 (2020).
144. Jackson, M. C. et al. In *Advances in Ecological Research* (Elsevier, 2016).
145. Vo, T. et al. SuoiAI: Building a Dataset for Aquatic Invertebrates in Vietnam. *arXiv* <https://doi.org/10.48550/arXiv.2504.15252> (2025).

Acknowledgements

We thank Dr. Tosaphol Saetung Keetapichayakul, Duy Tan University, and Mr. Nguyen Tu Minh Hoang for their assistance during field trips.

Author contributions

K.V.D. developed the concepts and wrote the main manuscript text. Q.T.P. contributed to the taxonomy, distribution, and conservation status. H.N.N. contributed to climate data. All authors contributed to editing, reviewing, and revising the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s44185-026-00124-x>.

Correspondence and requests for materials should be addressed to Khuong V. Dinh.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2026