Benefits of Bats

With more than 1,400 species of bats worldwide, over 40 species in the U.S. alone, and in making up 25% of the world's total mammal population, these nocturnal flying creatures have quite a large footprint. As the Bat World Sanctuary (BWS) shares, "Consider this: if your day includes soap, shampoo, cosmetics, a toothbrush and toothpaste, coffee, margarine, paper or ink, cushions, wood furniture, fuel or lubricating fluids, sisal used to make rope and twine, timber, boats or canoes, ornamental trees, life saving medicines, air fresheners, candles, rubber, chewing gum, spices, vegetables, fruits, chocolate or even margaritas or beer, you are not only involved with bats, you are dependent upon bats."

Ecosystem Services

Bats, among other wildlife including birds and bees, provide important ecosystem services through pollination, management of pest populations, and contributing to plant resilience and productivity. The importance of bat species and their services cannot be understated. Bats are the only nocturnal insect predator in the U.S. and are one of two primary nocturnal pollinators (along with moths) — important roles for night-flowering plants and for farmers.

Bats are one of many under-appreciated pollinators, but bat pollination, technically known as chiropterophily, is integral for many wild and commercial tropical fruits. Pollination occurs when the bats feed from nectar and collect pollen in their fur that they then transport to numerous other flowers. Indeed, over 500 plants worldwide are completely or partially dependent on bat pollination. The next time you eat a guava, avocado, fig, peach, clove, cashew, or mango you might want to thank the bats.

Seed dispersal is another important service bats provide. "Some seeds will not sprout unless they have passed through the digestive tracts of a bat. Bats spread millions of seeds every year from the ripe fruit they eat... Fruit bats are responsible for 98% of the reforestation of the world's rain forests (the lungs of our planet). Without fruit bats we would lose entire forests without felling a single tree," BWS notes.

Bats' pest control services—relatively invisible because they do their insect marauding at night when humans are not watching—represent an excellent nontoxic, biological control for some agricultural pests, as well as for mosquitoes that may be human disease vectors. This highlights the public health benefits from bats, as they lower health care costs by reducing toxic pesticide use on chemical farms and in their ability to lower the rate of mosquito borne disease. Bats are also incredibly useful in the study of emerging viral diseases such as coronaviruses, and add an inherent, existential value to natural landscapes.

These organisms not only consume mosquitoes that can carry diseases, such as West Nile virus, Eastern equine encephalitis (EEE), Zika virus, malaria, dengue fever, yellow fever, and others, but their management of pests protects millions of dollars in agriculture. As declines in bat populations and other pollinators continue to occur, it is becoming increasingly clear that the ecosystem services provided by bats cannot be adequately replaced by human activities. These species are both integral to biodiversity as well as agricultural production.

Approximately 70% of bat species are insectivores, including pests that consume the crops we rely on for food. The two species of brown bats (the "big" and the "little") most common in the U.S. are voracious, consuming 3,000–7,000 insects per night. "Who needs pesticides when we have bats?," Bat Conservation International says. They continue: "Scientists estimate that insect-eating, or insectivorous, bats may save U.S. farmers roughly $23 billion each year by reducing crop damage and

limiting the need for pesticides. Most, on average, can eat up to half their body weight in insects, while pregnant or nursing mothers will consume up to 100 percent of their body weight each night." Adding to this, BWS states, "The 20 million bats that roost at Bracken Cave in Texas, eat 200 tons of insects each summer evening. They eat crop pests that cost farmers billions of dollars annually. Insect control by bats keeps down prices of fruits and vegetables in the market place."

ART PAGE FEATURE: Our thanks to Brad from Fairfax, CA, for sharing the above images from his photography series "Bats - Raspberry Pi with IMX462 sensor." *See more of his artwork featured on the Photography page!*

Bats and Pesticides

Bats are also considered an "indicator species," meaning that they interact with many elements of their environment and that their well-being is a barometer for the health of those ecosystems. While degradation of ecosystems is attributable to many factors, pesticide use accounts for an important element in harm to bats and overall biodiversity. Bats also tend to have only one offspring each year, making them vulnerable to the population impacts of negative reproductive effects caused by pesticides, because low reproductive rates require high adult survival rates to avoid population declines.

Because bats are unusually long-lived for animals their size—with lifespans ranging from 20 to 40 years—their bodies can accumulate pesticide residues over a lengthy period, exacerbating adverse effects associated with those pesticides that can accumulate in fatty tissue. Also, during migrations or winter hibernation (when their fat stores are metabolized), bats' consumption of large volumes of pesticide-contaminated insects can mean that these compounds may reach toxic levels in their brains — making them more susceptible to white-nose syndrome (WNS), a fungal disease that impacts several cave-dwelling bat species.

This invasive fungus (*Pseudogymnoascus destructans*), as highlighted in an article in the New York Times, has caused three species of bats in North America to be decimated by this syndrome, and bats with WNS have been confirmed in 40 states and nine Canadian provinces. WNS causes bats to behave uncharacteristically by waking up more frequently during the winter and flying during the day. These changes use up their limited fat reserves too quickly, leaving them debilitated. WNS has killed millions of bats since the introduction of the fungal disease in 2006. In just the first five years from onset, scientists estimated between five and seven million bats died as a result of WNS.

According to bat experts, as of 2023, 52% of bat species in North America are at risk of severe declines over the next 15 years. With the collapse of many bat populations from WNS, farmers turn to toxic chemicals to replace the ecosystem services bats usually provide. These chemicals, however, lead to ripples throughout the ecosystem and create a cyclic problem for bat species. By further suppressing their immune systems, it only adds to their susceptibility to WNS.

Additionally, when insect-eating bats encounter food exposed to pesticide treatments, the pesticides can diminish their ability to echolocate, causing them to travel on less established paths and frequently become lost while hunting. Preservation of habitats frequented by bats, including scrub and saguaro desert; deciduous, pine, and oak forests; and canyons, as well as their food sources within those environments, is imperative to protect the future of all bat species.

Resources

- Impacts of Pesticides on Wildlife
- Know Your Pollinators
- Impact of Pesticides on Pollinators
- Protecting Honey Bees and Wild Pollinators: What Can You Do?
- BEE Protective... for kids!
- Biodiversity
- Mosquito Management: Alternatives to Spraying

Scientific Studies

Species-specific aquatic habitat use predicts pesticide residues in feces of insectivorous birds and bats. (*Lorenz, S. et al. 2026*) Water bodies located in the agricultural landscape may face a substantial contamination by agrochemicals due to modern agricultural practice. Many insect species inhabiting these water bodies have a complex life-cycle with an aquatic phase as larvae and a terrestrial phase as winged adults when they serve as prey for many aerial insectivores, such as bats and birds. Thus, they may act as vectors, transferring pesticides from the water bodies into the terrestrial food webs. This transfer of pesticides from water to land via emerging insects is still poorly studied. This study investigated the contamination of feces from various insectivorous organisms with different foraging mode and aquatic habitat use, quantified by movement analysis. In total, we detected 16 current-use pesticide residues, two legacy compounds and six metabolites in the feces of three species which had a high selection strength towards aquatic habitats: barn swallow (Hirundo rustica), Western house martin (Delichon urbicum), and the common noctule bat (Nyctalus noctula). In contrast, no substances were detected in feces of European starling (Sturnus vulgaris), a species that uses rather terrestrial habitats and is known to feed on terrestrial insects. The fungicide prochloraz, used to combat fungal grain diseases, was the substance with the highest detection rate of 69% of all samples. Five of the substances detected (i.e., bixafen, diflufenican, dinoterb, prochloraz, simazine) are classified as critical in terms of their potential for bioconcentration and ten out of 18 substances are classified to be of concern for mammal short term dietary uptake. While the direct ecotoxicological effects on the organisms are unclear, our study is one of the first ones to infer the contamination pathway via emerging insects and to highlight that species-specific use of aquatic habitats increases pesticide exposure risk in insect-eating birds and bats in farmland.

Impact of Climate Change on Bats Involved in Biological Control. (*Russo, D. et al. 2025*) Climate change can disrupt predator–prey interactions in agricultural systems by altering species' physiology, distribution and behaviour. Temperature and precipitation changes may cause mismatches in resource timing, destabilising these dynamics. Such shifts can reduce natural pest control effectiveness, increasing reliance on chemical methods. Many bat species prey on arthropods and play a crucial role in pest control. Bats help to reduce pesticide use, saving farmers costs. However, climate change impacts bat distribution, reproduction and behaviour. Some species have shifted their ranges, while others face challenges like heat stress and drought, affecting survival and reproduction. These shifts may disrupt bat–pest interactions, creating mismatches between pest outbreaks and bat presence. Climate change also affects insect emergence and bat reproduction timing, potentially leading to pest outbreaks. Future research should monitor bat and pest dynamics, and predict climate change's impact on the important ecosystem services bats deliver.

The complex web between environmental disruption, pesticide use, and human health: lessons from the bat crisis. (*Silva, H. 2025*) The close relationship between environmental balance, biodiversity, and human health has long been a concern of science and public policy. Disruptions in ecosystems often trigger cascading effects that extend far beyond the original ecological imbalance, affecting

agricultural practices, food security, and public health. Understanding these interdependencies is essential, particularly in the face of growing environmental degradation, global health threats, and rising levels of scientific misinformation. Recent evidence demonstrates how the decline of bat populations due to fungal infections led to a dramatic increase in pesticide use and a corresponding rise in infant mortality in a specific region, even though all pesticide applications occurred within legal safety thresholds. The death of over two-thirds of the bat population, natural insect predators, resulted in intensified chemical pest control measures. This unexpected outcome illustrates how the loss of ecological agents can result in human health impacts through indirect mechanisms. In contexts where pesticide use is widespread and regulatory frameworks are weaker, such as in parts of Latin America, particularly Brazil and Central America, the potential for similar or worse consequences is high (Wesseling in Int J Occup Environ Health 7:287–294, 2001; Londres in Rede Bras Justiça Ambient Articul Nac Agroecol, 2012; do Dossiê in DOSSIÊ ABRASCO Um alerta sobre os impactos dos Agrotóxicos na Saúde Parte 1-Agrotóxicos, Segurança Alimentar e Saúde, 2017). The current scenario is further exacerbated by the global decline of pollinators like bees, which threatens agricultural productivity and food supply chains. These challenges are compounded by increased human encroachment on natural habitats, contributing to the emergence of zoonotic diseases, as observed in recent pandemics. Environmental disruptions, when met with poorly considered human interventions, may result in unintended and harmful effects on public health. The evidence reinforces the urgency of adopting integrated environmental and health policies based on scientific evidence and ecological understanding. Promoting ecological conservation and reducing dependence on chemical inputs are crucial not only for biodiversity preservation but also for protecting human lives, particularly those of the most vulnerable populations. This study argues that ecological collapse, pesticide dependency, and public health crises are inseparable dimensions of the Anthropocene, demanding integrated, cross-sectoral responses.

Habitat heterogeneity and food availability in beaver-engineered streams foster bat richness, activity and feeding. (*Moser, V. et al. 2025*) As ecosystem engineers, Eurasian beavers (Castor fiber) modify aquatic and terrestrial ecosystems, which can benefit the biodiversity and community composition of plant and animal species. However, in contrast to aquatic taxa, beaver engineering impacts on terrestrial taxa, like bats, are so far largely overlooked. While it has been shown that bats prefer beaver-engineered ecosystems, the reason for this choice is poorly understood. We hypothesized that this preference may be associated with beaver-related changes in habitat characteristics and food availability. To address this knowledge gap, we recorded bat species richness, activity and feeding activity in eight beaver-engineered ecosystems (pool) with paired control sites without beavers (control) along the same stream in Switzerland. In addition, we collected data on food availability (arthropods) with arthropod flight interception traps and characterized habitat suitability with deadwood volume and vegetation surveys, as well as assessing canopy heterogeneity based on different digital height models. The nighly bat species richness increased from four to five species between control and pool sites. Bat activity increased 1.6 times and bat feeding activity 2.3 times in beaver-engineered systems compared to controls. These increases in richness and activity were explained by higher volumes of standing deadwood, higher canopy heterogeneity and higher arthropod abundance in beaver systems compared to controls. Overall, the volume of standing deadwood, a critical resource for bat roosting and foraging, had a stronger effect on bat species richness than canopy heterogeneity or arthropod availability. Bat feeding guilds (short-, mid-, long-range echolocators) responded differently to beaver-engineered habitat changes, with edge-hunting mid-range species benefiting the most. Our findings suggest that beaver engineering created structurally diverse habitats that supported a broader range of bat species. By modifying both habitat structure and prey abundance, beaver engineering affected bat activity, richness, and feeding activity directly and indirectly. These changes operated across aquatic–terrestrial boundaries, highlighting the cross-ecosystem influence and ecological complexity of ecosystem engineering.

Ground cover promotes enhanced bat activity in high-value insular vineyards. (*Cistrone, L., Schofield, H. and Russo, D. 2025*) Vineyards represent a significant portion of global agricultural land. However, their conventional management, which relies on synthetic inputs and intensive cultivation, often reduces habitat complexity, impacting biodiversity and reducing ecosystem services such as pest control. Inter-row grass cover has been proposed as a management strategy to enhance biodiversity, but its effects on insectivorous bats – key providers of pest suppression – remain unexplored. We investigated the influence of inter-row grass cover on bat activity in the vineyards of Pantelleria (Italy), a Mediterranean island where agriculture must balance productivity with environmental sustainability. We conducted acoustic surveys across 18 vineyards, comparing bat activity between grass-covered and cleared inter-rows. We recorded 3240 bat passes from seven species, with Pipistrellus kuhlii being the most frequently detected. Our results indicate that inter-row grass cover significantly increases P. kuhlii activity, likely due to enhanced habitat complexity and prey availability. Plecotus gaisleri activity increased with vineyard area, suggesting better foraging conditions in larger vineyards. Species richness and the remaining bat species were unaffected by inter-row management. Maintaining inter-row grass cover can benefit P. kuhlii, the species most frequently hunting in Pantelleria vineyards, offering a potential win-win strategy for biodiversity and agricultural sustainability. To promote inter-row grass cover while minimising competition affecting vine growth and productivity, we recommend restricting mowing, weed removal, and hoeing to the vine base and planting basin while maintaining grass cover between rows. Rotational mowing, selecting native plants, and preserving hedgerows can enhance bat habitat. Mowing outside peak insect activity and engaging vineyard owners may further support biodiversity and productivity.

A Call to Protect Common Species: Bats as a Case Study. (*Russo, D. and Dechmann, D. 2025*) The ongoing biodiversity crisis highlights the need for targeted conservation efforts, yet the focus often remains on rare and endangered species. This overlooks the vital role of common species, which are the ecological backbone of ecosystems, supporting the stability and functioning of biodiversity. We argue that common species, especially their population dynamics and potential tipping points, are too often neglected and that their conservation is urgent. We illustrate this issue using bats (Chiroptera) as a model. This diverse mammalian order features key ecosystem service providers, including insectivores, pollinators, and seed dispersers. Bats are sensitive to anthropogenic pressures, and many species, including common ones, face population declines and the impact of ecosystem disruption. Research and conservation must urgently be expanded to include common species. Through case studies, we demonstrate how common bat species are indicators of environmental changes and the urgent need to monitor their populations. We provide recommendations for improving research, enhancing conservation policies, and adopting a more inclusive framework acknowledging the indispensable role of common species in ecosystem services and biodiversity.

Precision foraging: Bats in organic desert palm plantations hunt where it is most needed. (*Russo, D. et al. 2025*) Bats are crucial in suppressing pest arthropods in agroecosystems, contributing vitally to sustainable agriculture. However, the importance of bats in agriculture in extreme environments, such as deserts, has received far less attention. Date palm plantations represent one of the few productive systems in hyper-arid regions. We studied habitat use in an organic date palm plantation in the Arava Valley (Southern Israel) employing acoustic surveys to assess bat activity and foraging behaviour. According to our predictions, bats preferentially foraged in the plantation's most productive areas, with most of the 13 recorded species exhibiting significant activity in older, sheltered plots. Higher wind speeds correlated with decreased foraging across most species, but sheltered habitats often buffered this effect. While species richness remained stable across habitats, according to our prediction, activity levels varied according to habitat type and wind conditions. In general, bat activity increased in old productive plots in the plantation's core section and decreased elsewhere in response to strong winds. These results highlight the importance of maintaining older productive areas within the interiors of date palm plantations to support bat populations and enhance

their pest-suppressing roles. Management strategies should design wind-buffering plantations to protect critical bat foraging areas and provide water sources. As date palm plantations act as "oases" in unproductive landscapes, many bats likely travel significant distances to forage there. Protecting bat habitats on a large scale and prioritising multiscale conservation is crucial to preserving bats and their ecosystem services.

Bat diversity boosts ecosystem services: Evidence from pine processionary moth predation. (*Augusto, A., Raposeira, H., Horta, P., Mata, V., Aizpurua, O., Alberdi, A., Jones, G., Razgour, O., Santos, S., Russo, D., & Rebelo, H. 2024*) Coniferous forests contribute to the European economy; however, they have experienced a decline since the late 1990s due to an invasive pest known as the pine processionary moth, Thaumetopoea pityocampa. The impacts of this pest are increasingly exacerbated by climate change. Traditional control strategies involving pesticides have had negative effects on public health and the environment. Instead, forest managers seek a more ecological and sustainable approach to management that promotes the natural actions of pest control agents. This study aims to evaluate the role of bats in suppressing pine processionary moths in pine forests and examine how the bat community composition and abundance influence pest consumption. Bats were sampled in the mountainous environment of the Serra da Estrela in central Portugal to collect faecal samples for DNA meta-barcoding analysis. We assessed the relationship between a) bat richness, b) bat relative abundance, c) bat diet richness, and the frequency of pine processionary moth consumption. Our findings indicate that sites with the highest bat species richness and abundance exhibit the highest levels of pine processionary moth consumption. The intensity of pine processionary moth consumption is independent of insect diversity within the site. The highest occurrence of pine processionary moth presence in bat diets is primarily observed in species that forage in cluttered habitats. A typical predator of pine processionary moths among bats is likely to be a forest-dwelling species that specialises in consuming Lepidoptera. These species primarily use short-range echolocation calls, which are relatively inaudible to tympanate moths, suitable for locating prey in cluttered environments, employing a gleaning hunting strategy. Examples include species from the genera Plecotus, Myotis, and Rhinolophus. This study enhances our understanding of the potential pest consumption services provided by bats in pine forests. The insights gained from this research can inform integrated pest management practices in forestry.

High temporal resolution data reveal low bat and insect activity over managed meadows in central Europe. (*Dietzer, M. et al. 2024*) Increasing agriculture and pesticide use have led to declines in insect populations and biodiversity worldwide. In addition to insect diversity, it is also important to consider insect abundance, due to the importance of insects as food for species at higher trophic levels such as bats. We monitored spatiotemporal variation in abundance of nocturnal flying insects over meadows, a common open landscape structure in central Europe, and correlated it with bat feeding activity. Our most important result was that insect abundance was almost always extremely low. This was true regardless of management intensity of the different meadows monitored. We also found no correlation of insect abundance or the presence of insect swarms with bat feeding activity. This suggests that insect abundance over meadows was too low and insect swarms too rare for bats to risk expending energy to search for them. Meadows appeared to be poor habitat for nocturnal flying insects, and of low value as a foraging habitat for bats. Our study highlights the importance of long-term monitoring of insect abundance, especially at high temporal scales to identify and protect foraging habitats. This will become increasingly important given the rapid decline of insects.

To improve or not to improve? The dilemma of “bat-friendly” farmland potentially becoming an ecological trap. (*Russo, D. et al. 2024*) Conventional agriculture occupies a substantial portion of Earth’s terrestrial surface and adversely affects biodiversity through pesticide spread, mechanisation, and loss of spatial and temporal heterogeneity of farmed landscapes. Consequently, conventional agriculture has become a primary target of many restoration projects operating at various scales, from habitat to landscape. While these restoration efforts aim to increase farmland biodiversity and

promote the delivery of associated ecosystem services, unintended consequences may arise when important threats are not mitigated. For instance, animals may be led to make maladaptive choices, and lured to attractive sites with poor habitat quality (ecological traps), resulting in adverse effects on individual fitness and demography. We focus our review on European farmland as a case study because of its extensive presence on the continent and the particularly articulated legal framework regulating agriculture and biodiversity within the European Union. Europe's policy framework is dual-faced: one promotes farmland development regardless of management practices, while the other advocates for biodiversity protection measures that sometimes lack strong supporting evidence or overlook critical management aspects. Insectivorous bats contribute significantly to ecosystem service delivery through insectivory in agricultural landscapes, consuming large numbers of pest arthropods. However, when restoring habitats for bats in conventional farmland, potential unintended outcomes must be considered, particularly if restoration actions are not accompanied by mitigation of key threats. These threats include the persistent and widespread use of pesticides, road networks, the siting of wind turbines in farmed landscapes, and opportunistic predators, especially domestic cats. We argue that installing bat boxes and enhancing habitat and landscape features, such as increasing connectivity and diversity, potentially trap bats in attractive yet unsuitable environments if such threats are not mitigated. While environmental restoration in farmland is highly valued for supporting bat populations, it is crucial to avoid neglecting factors that could have the opposite effect, turning 'improved' farmland into a sink. Research is urgently needed to understand such potential unintended effects and inform farmland management and policymakers.

A bat a day keeps the pest away: Bats provide valuable protection from pests in organic apple orchards. (*Ancillotto, L., Borrello, M., Caracciolo, F., Dartora, F., Ruberto, M., Rummo, R., Scaramella, C., Odore, A., Garonna, A. P., & Russo, D. 2024*) Organic farming is an essential component of sustainable agriculture that can help maintain biodiversity in agricultural landscapes, providing benefits for both human well-being and environmental conservation. Recent studies have highlighted the vital role of insectivorous bats in farmland ecosystems in controlling pest insect populations. Our research focuses on the direct economic value of bat insectivory in woody crops, specifically in apple orchards affected by the codling moth Cydia pomonella. We conducted an exclusion experiment followed by an economic evaluation to estimate the impact of bat insectivory on crop damage and economic savings. Our results demonstrate that the presence of bats in apple orchards can significantly reduce the damage caused by C. pomonella, resulting in a 32.1% reduction in affected apple trees and a 50% reduction in the total weight of damaged apples per tree. This translates to estimated economic savings of 551 €/ha/y by reducing the need for insecticide applications and, consequently, minimizing the negative impacts of such chemicals on the environment and human health. Moreover, the presence of bats can lead to higher crop yields and protect the quality of the product, resulting in higher profits for farmers. Our findings highlight the critical role of bats in maintaining ecosystem services and provide valuable information for the sustainable management of farmland ecosystems.

The economic impacts of ecosystem disruptions: Costs from substituting biological pest control. (*Frank, E. 2024*) Scientists have long theorized that declines in biodiversity and continued degradation of ecosystem functioning would lead to meaningful negative impacts on human well-being. Quantifying those impacts is challenging because of the limited measurements available on wildlife and plant populations as well as the ethical and feasibility constraints involved with randomly manipulating ecosystems at scales that would allow for the testing of key theoretical predictions. This work makes a contribution to our understanding of the relationship between ecosystem functioning and human well-being by using a natural experiment—an occurrence resulting from unexpected changes in environmental conditions that approximates a randomized control trial. Specifically, I use the sudden emergence of a deadly wildlife disease in insect-eating bats—known as white-nose syndrome—to quantify the benefits from their provision of biological pest control. I validate previous

theoretical predictions that farmers respond by substituting bats with insecticides; however, because those are toxic compounds, by design, this substitution leads to higher human infant mortality rates in the areas affected by the bat die-offs.

Re-establishing historic ecosystem links through targeted species reintroduction: Beaver-mediated wetlands support increased bat activity. (*Hooker, J. et al. 2024*) Despite the global significance of wetlands, conservation strategies often fall short in preserving these ecosystems due to failures in incorporating processes that sustain the ecosystem functioning, hydrological dynamics, ecological processes, and biodiversity of wetlands. Nature-based solutions, such as the reintroduction of beavers, have emerged as effective tools for promoting wetland restoration. Whilst the impact of beavers on wetland restoration is well known, their broader influence on ecosystem health, particularly in modifying habitats for other species, remains inadequately understood. Here we assess the impact that habitat modification through the reintroduction of beavers has on bat populations. There were significantly greater activity levels within beaver-modified wetland habitats for multiple bat species, including higher activity levels of 393 % for Barbastella barbastellus and 313 % for Plecotus spp.. Additionally, we observed positive effects on bat populations in the woodland habitat surrounding beaver-modified wetland for certain taxa. In the face of escalating challenges posed by climate change and habitat loss, addressing biodiversity loss necessitates a shift toward ecosystem-centric mitigation measures. Our study demonstrates that the reintroduction of keystone species like beavers can re-establish historical facilitative links between aquatic and terrestrial food webs, highlighting the importance of such interventions in fostering the resilience and sustainability of entire ecosystems.

Pest suppression by bats and management strategies to favour it: a global review. (*Tuneu-Corral, C. et al. 2023*) Fighting insect pests is a major challenge for agriculture worldwide, and biological control and integrated pest management constitute well-recognised, cost-effective ways to prevent and overcome this problem. Bats are important arthropod predators globally and, in recent decades, an increasing number of studies have focused on the role of bats as natural enemies of agricultural pests. This review assesses the state of knowledge of the ecosystem services provided by bats as pest consumers at a global level and provides recommendations that may favour the efficiency of pest predation by bats. Through a systematic review, we assess evidence for predation, the top-down effect of bats on crops and the economic value of ecosystem services these mammals provide, describing the different methodological approaches used in a total of 66 reviewed articles and 18 agroecosystem types. We also provide a list of detailed conservation measures and management recommendations found in the scientific literature that may favour the delivery of this important ecosystem service, including actions aimed at restoring bat populations in agroecosystems. The most frequent recommendations include increasing habitat heterogeneity, providing additional roosts, and implementing laws to protect bats and reduce agrochemical use. However, very little evidence is available on the direct consequences of these practices on bat insectivory in farmland. Additionally, through a second in-depth systematic review of scientific articles focused on bat diet and, as part of the ongoing European Cost Action project CA18107, we provide a complete list of 2308 documented interactions between bat species and their respective insect pest prey. These pertain to 81 bat species belonging to 36 different genera preying upon 760 insect pests from 14 orders in agroecosystems and other habitats such as forest or urban areas. The data set is publicly available and updatable.

The Contribution of Desert-Dwelling Bats to Pest Control in Hyper-Arid Date Agriculture. (*Schäckermann, J. et al. 2022*) Over 40% of the Earth’s surface has been converted to agricultural use and agroecosystems have become important habitats for wildlife. In arid regions, intensive agriculture creates artificial oasis-like habitats due to their high irrigation inputs. Date production is one of the primary agricultural practices in the deserts of the Middle East and North Africa. Insectivorous bats are known to use agricultural areas, but the role of date plantations as their foraging habits and the

importance of insectivorous bats as date bio-pest control agents are still unknown. We assessed the role of date plantations as foraging habitats for local desert bat species by acoustically recording bat activity in conventional and organic date plantations in the southern Arava Valley, Israel. In addition, we captured bats in the plantations and collected feces for DNA metabarcoding analysis to investigate the presence of pest species in their diets. We found that 12 out of the 16 known species of bats in this region frequently used both conventional and organic date plantations as foraging habitats. Species richness was highest in the organic plantation with complex ground vegetation cover. Foraging activity was not affected by plantation type or management. However, bat species richness and activity increased in all plantations during summer date harvesting. Molecular analysis confirmed that bats feed on a variety of important date pests, but the particular pests consumed and the extent of consumption varied among bat species. Our results highlight a win–win situation, whereby date plantations are an important foraging habitat for desert bats, while bats provide bio-pest control services that benefit the date plantations. Therefore, date farmers interested in bio-pest control should manage their plantations to support local desert bat populations.

Cascading Effects of Birds and Bats in a Shaded Coffee Agroforestry System. (*Schmitt, L. et al. 2021*) Volant vertebrate insectivores, including birds and bats, can be important regulators of herbivores in forests and agro-ecosystems. Their effects can be realized directly through predation and indirectly via intraguild predation. This paper examines data from bird and bat exclosures in coffee farms in Chiapas, Mexico in order to determine their effect on herbivores. Arthropods were sampled in 32 exclosures (with 10 coffee plants in each) and their paired controls three times during 6 months. After 3 months, herbivore and spider abundance increased, underscoring the importance of both intertrophic predation between volant vertebrate insectivores and herbivores and intraguild predation between volant vertebrate insectivores and spiders. After 6 months, herbivore abundance increased in the exclosures, which is indicative of a direct negative effect of birds and bats on herbivores. We suggest that intraguild predation is important in this food web and that seasonality may change the relative importance of intraguild vs. intertrophic predation. Results suggest a dissipating trophic cascade and echo the growing body of evidence that finds birds and bats are regulators of herbivores in agro-ecosystems.

Bats provide a critical ecosystem service by consuming a large diversity of agricultural pest insects. (*Maslo, B. et al. 2021*) Biodiversity directly influences the delivery of multiple ecosystem services, most notably within agriculture. Projected future global demands for food, fiber and bioenergy will require enhancement of agricultural productivity, but favoring biodiversity-based ecosystem services generally remains underutilized in agricultural practice. In addition, agricultural intensification is a key driver of biodiversity loss. A significant obstacle preventing the adoption of ecologically sensitive practices is a lack of knowledge of the species delivering the services. Insectivorous bats have long been suggested to regulate insect pest populations and may be a critical component of biodiversity-based ecosystem services. Bats may also serve as agents of insect pest surveillance through environmental DNA (eDNA) monitoring approaches. However, the biological and economic importance of bats to agriculture remains under-quantified. Here we catalogued the dietary niche of two North American bats, little brown bat (Myotis lucifugus) and big brown bat (Eptesicus fuscus), through DNA metabarcoding of guano collected from seven roosting sites over a 26-week period. We measured the frequency of occurrence of known pest species in guano samples, compared interspecific differences in diet, and examined seasonal patterns in prey selection. Overall, we detected 653 unique prey species, 160 of which were known agricultural pests or disease vectors. Species diversity of prey species consumed varied by bat species and across the season, with big brown bats accounting for the majority of arthropod diversity detected. However, little brown bats consumed relatively more aquatic insects than big brown bats, suggesting that increased bat species richness in a landscape can amplify their net pest regulation service. Further, we hypothesized that detection probabilities of target insect pests would be higher in guano samples than in conventional survey methods. Multi-

survey occupancy modeling revealed significantly lower detectability in bat guano than in conventional monitoring traps, however, highlighting important tradeoffs in selection of survey methods. Overall, the results presented here contribute to a growing evidence base supporting the role bats play in the provisioning of biodiversity-based ecosystem services.

Insectivorous bats provide significant economic value to the Australian cotton industry. (*Kolkert, H. et al. 2021*) Insectivorous bats exert top-down pressure on pest insect populations in agricultural systems globally. However, few economic estimates exist of their value as pest control agents in many high value crops. We calculated the economic benefit of direct predation of insect pests by bats and the damage averted to cotton yield, a high value commodity crop in Australia. Using a combination of bat dietary studies, average daily energy requirements (estimated by field metabolic rate), prey energy content and acoustic data of bat feeding attempts in cotton crops, we show the direct value of insectivorous bats to the Australian cotton industry is likely between $99–126 ha−1 in dryland Bt-cotton and $286–361 ha−1 in irrigated Bt-cotton through the consumption of pest moth Helicoverpa armigera, amounting to $63.6 million annually. We estimate that a population of bats can remove between 77–119 t of moths from Australian cotton crops in an average year across the growing season. However, different bat species consume different insect pests, highlighting the need to conserve bat diversity in agroecosystems. These results provide further incentive for growers to manage non-crop bat roosting habitat to benefit from natural pest control in crops.

An appetite for pests: Synanthropic insectivorous bats exploit cotton pest irruptions and consume various deleterious arthropods. (*Cohen, Y. et al. 2020*) Conservation biological control (CBC) seeks to minimize the deleterious effects of agricultural pests by enhancing the efficiency of natural enemies. Despite the documented potential of insectivorous bats to consume pests, many synanthropic bat species are still underappreciated as beneficial species. We investigated the diet of Kuhl's pipistrelle (Pipistrellus kuhlii), a common synanthropic insectivorous bat that forages in urban and agricultural areas, to determine whether it may function as a natural enemy in CBC. Faecal samples of P. kuhlii were collected throughout the cotton-growing season from five roost sites near cotton fields located in a Mediterranean agroecosystem, Israel, and analyzed using DNA metabarcoding. Additionally, data on estimated abundance of major cotton pests were collected. We found that the diet of P. kuhlii significantly varied according to sites and dates and comprised 27 species of agricultural pests that were found in 77.2% of the samples, including pests of key economic concern. The dominant prey was the widespread cotton pest, the pink bollworm, Pectinophora gossypiella, found in 31% of the samples and in all the roosts. Pink bollworm abundance was positively correlated with its occurrence in the bat diet. Furthermore, the bats' dietary breadth narrowed, while temporal dietary overlap increased, in relation to increasing frequencies of pink bollworms in the diet. This suggests that P. kuhlii exploits pink bollworm irruptions by opportunistic feeding. We suggest that synanthropic bats provide important pest suppression services, may function as CBC agents of cotton pests and potentially contribute to suppress additional deleterious arthropods found in their diet in high frequencies.

Effects of imidacloprid, a neonicotinoid insecticide, on the echolocation system of insectivorous bats. (*Wu, C. et al. 2020*) Imidacloprid, a widely used neonicotinoid insecticide, has led to a decline in the honey bee population worldwide. An invertebrate insect prey with neonicotinoid toxicity can adversely affect insectivores, such as echolocating bats. The aim of the current study was to examined whether imidacloprid toxicity may interfere echolocation system such as vocal, auditory, orientation, and spatial memory systems in the insectivorous bat. By comparing the ultrasound spectrum, auditory brainstem-evoked potential, and flight trajectory, we found that imidacloprid toxicity may interfere functions in vocal, auditory, orientation, and spatial memory system of insectivorous bats (Hipposideros armiger terasensis). As suggested from immunohistochemistry and western blots evidences, we found that insectivorous bats after suffering imidacloprid toxicity may decrease vocal-related FOXP2 expressions in the superior colliculus, auditory-related prestin expressions in the cochlea, and the auditory-related otoferlin expressions in the cochlea and the inferior colliculus, and

cause inflammation and mitochondrial dysfunction-related apoptosis in the hippocampal CA1 and medial entorhinal cortex. These results may provide a reasonable explanation about imidacloprid-induced interference of echolocation system in insectivorous bats.

Pest control services provided by bats in vineyard landscapes. (*Muneret, O., et al. 2018*) Faced with current health and environmental challenges, viticulture is directly concerned with the need to reduce pesticide use. Natural pest control services provided by bats have been demonstrated in other crops and is regularly mentioned as a way to reduce pesticide use. However, the trophic link between bats and grape pests as well as the effect of pest presence on bat activities remain largely unknown. To investigate the functional role of bats in vineyard landscapes, we used two independent approaches. We monitored the activities of bats and of the European grapevine moth (Lobesia botrana) in 23 vineyards located in the Bordeaux region (France). In parallel, we developed DNA primers to examine bat faeces from two regions, Bordeaux and Burgundy, for the presence of the three main species of grapevine moths. Our results demonstrate that bats significantly increase their hunting activity when European grapevine moths are present in vineyards. In addition, our molecular analysis of the faeces provides robust evidence that at least 10 species of bats predate the three grapevine moth species. Our results therefore suggest that bats can be natural enemies of grape pests in vineyard landscapes. Further research is now needed to investigate the consequences of predation of pests by bats on crop production as well as the effect of some management options at both the local and landscape scale to increase the level of pest control services provided by bats.

Novel perspectives on bat insectivory highlight the value of this ecosystem service in farmland: Research frontiers and management implications. (*Russo, D., Bosso, L. and Ancillotto, L. 2018*) Bats are major consumers of arthropods, and there is ever growing evidence that they play a pivotal role in the fight against agricultural pests. However, relatively little research has addressed explicitly this important topic, and studies in temperate regions (especially European case studies) are infrequent. In the last few years, state-of-art molecular methods to identify prey remains in droppings and new experimental approaches to assess the actual magnitude of this ecosystem service have opened new perspectives in research. In this review, we discuss such aspects with an emphasis on temperate regions, and identify new research frontiers. These comprise: (1) detecting new bat species that consume pests, and further pest insects that bats might eat; (2) exploring sublethal effects of bat echolocation calls on tympanate moth pests; (3) getting a better understanding of bat predation over blood-sucking arthropods that parasitize livestock; (4) unveiling indirect effects of bat predation on plant pathogens; (5) implementing models to map the occurrence of bat insectivory and the potential to promote it; and (6) analyse bat droppings for active surveillance of arthropod pests and the diseases they carry. We also highlight that so-called “common” bat species, often neglected in conservation actions, are likely to provide the bulk of pest suppression in agroecosystems. All such aspects merit investigation and may lead to novel management practices aimed at conjugating bat conservation with economic and social sustainability of farming.

Effects of free-ranging cattle and landscape complexity on bat foraging: Implications for bat conservation and livestock management. (*Ancillotto, L., Ariano, A., Nardone, V., Budinski, I., Rydell, J., & Russo, D. 2017*) Traditional agropastoralism increases biodiversity by maintaining habitats whose existence depends on human practices as well as by providing wildlife, including bats, with key spatial and trophic resources. Bats in farmland are crucial predators of crop pests, thus offering an economically important ecosystem service. It seems possible that bats may also provide services by feeding on insects associated with livestock. We tested whether bats forage over cattle in a traditionally managed pastoral area of central Italy, i.e. setting the bases for providing pest control services. We found that small bat species (mostly Pipistrellus spp.) foraged preferentially over livestock, and that their activity increased, but then reached a plateau or slightly decreased, for progressively larger herds. Landscape complexity also led to an increase in bat activity over livestock. Since insects attracted to cattle at night typically include flies such as mosquitoes (Culicidae) and

biting midges (Ceratopogonidae), which are potentially harmful to cattle and may carry serious diseases, and that bats such as Pipistrellus spp. are important predators of such flies, we argue that bats may play a valuable pest-suppression role.

Imidacloprid toxicity impairs spatial memory of echolocation bats through neural apoptosis in hippocampal CA1 and medial entorhinal cortex areas. (*Hsiao, C. et al. 2016*) It has been reported that the decimation of honey bees was because of pesticides of imidacloprid. The imidacloprid is a wildly used neonicotinoid insecticide. However, whether imidacloprid toxicity interferes with the spatial memory of echolocation bats is still unclear. Thus, we compared the spatial memory of Formosan leaf-nosed bats, Hipposideros terasensis, before and after chronic treatment with a low dose of imidacloprid. We observed that stereotyped flight patterns of echolocation bats that received chronic imidacloprid treatment were quite different from their originally learned paths. We further found that neural apoptosis in hippocampal CA1 and medial entorhinal cortex areas of echolocation bats that received imidacloprid treatment was significantly enhanced in comparison with echolocation bats that received sham treatment. Thus, we suggest that imidacloprid toxicity may interfere with the spatial memory of echolocation bats through neural apoptosis in hippocampal CA1 and medial entorhinal cortex areas. The results provide direct evidence that pesticide toxicity causes a spatial memory disorder in echolocation bats. This implies that agricultural pesticides may pose severe threats to the survival of echolocation bats.

Pest control service provided by bats in Mediterranean rice paddies: linking agroecosystems structure to ecological functions. (*Puig-Montserrat, X. et al. 2015*) Pest control through integrated pest management systems stands as a very convenient sustainable hazard-free alternative to pesticides, which are a growing global concern if overused. The ability of the soprano pipistrelle bat (Pipistrellus pygmaeus) to control the rice borer moth (Chilo supressalis), which constitutes a major pest of rice around the world, was studied in the Ebre Delta, Northeastern Iberia. Evidence was found on the ability of this particular bat species to control borer infestations: (a) the moth was consumed during at least the last two peaks of the moth activity, when most crop damage is done; (b) the activity of bats significantly increased with moth abundance in the rice paddies; (c) the pest levels have declined in the study area (Buda Island, Eastern Ebre Delta) after the deployment of bat boxes and their subsequent occupation by soprano pipistrelles. The value of the ecosystem service provided by bats was estimated at a minimum of 21€ per hectare, equivalent to the avoided pesticide expenditure alone. We suggest that this natural service can be enhanced by providing bat populations with artificial roosts in rice paddies were some key ecosystem features are present.

Bats initiate vital agroecological interactions in corn. (*Maine, J. & Boyles, J. 2015*) In agroecosystems worldwide, bats are voracious predators of crop pests and may provide services to farmers worth billions of U.S. dollars. However, such valuations make untested assumptions about the ecological effect of bats in agroecosystems. Specifically, estimates of the value of pest suppression services assume bats consume sufficient numbers of crop pests to affect impact pest reproduction and subsequent damage to crops. Corn is an essential crop for farmers, and is grown on more than 150 million hectares worldwide. Using large exclosures in corn fields, we show that bats exert sufficient pressure on crop pests to suppress larval densities and damage in this cosmopolitan crop. In addition, we show that bats suppress pest-associated fungal growth and mycotoxin in corn. We estimate the suppression of herbivory by insectivorous bats is worth more than 1 billion USD globally on this crop alone, and bats may further benefit farmers by indirectly suppressing pest-associated fungal growth and toxic compounds on corn. Bats face a variety of threats globally, but their relevance as predators of insects in ubiquitous corn-dominated landscapes underlines the economic and ecological importance of conserving biodiversity.

Economic Importance of Bats in Agriculture. (*Boyles, J. et al. 2011*) White-nose syndrome (WNS) and the increased development of wind-power facilities are threatening populations of insectivorous bats

in North America. Bats are voracious predators of nocturnal insects, including many crop and forest pests. We present here analyses suggesting that loss of bats in North America could lead to agricultural losses estimated at more than $3.7 billion/year. Urgent efforts are needed to educate the public and policy-makers about the ecological and economic importance of insectivorous bats and to provide practical conservation solutions.

Economic value of the pest control service provided by Brazilian free-tailed bats in south-central Texas. (*Cleveland, C. et al. 2006*) Brazilian free-tailed bats (Tadarida brasiliensis) form enormous summer breeding colonies, mostly in caves and under bridges, in south-central Texas and northern Mexico. Their prey includes several species of adult insects whose larvae are known to be important agricultural pests, including the corn earworm or cotton bollworm (Helicoverpa zea). We estimate the bats' value as pest control for cotton production in an eight-county region in south-central Texas. Our calculations show an annual value of $741 000 per year, with a range of $121 000–$1 725 000, compared to a $4.6–$6.4 million per year annual cotton harvest.

Bat activity and species richness on organic and conventional farms: impact of agricultural intensification. (*Wickramasinghe, L. et al. 2003*) Agricultural intensification is perceived to be a major cause of the decline in many European bat populations. Because organic farming prohibits the use of agrochemicals, we compared organic vs. conventional farm types to test the hypothesis that agricultural intensification based on high levels of agrochemical use has been a factor in bat population declines. Bat activity and species richness were compared on matched pairs of organic and conventional farms. Bat activity was quantified using acoustic surveys within specific habitats on farms in southern England and Wales. Eighty-nine per cent of bat passes were identified to species level using artificial neural networks (ANN). A further 9% were identified to genus. Total bat activity was significantly higher on organic farms than on conventional farms. Significantly more bat passes were recorded over water on organic farms than on conventional farms. Foraging activity (quantified in two ways: total feedings buzzes and feeding buzzes per pass) was significantly higher on organic farms than on conventional farms. The dominant species on both farm types were Pipistrellus pipistrellus and Pipistrellus pygmaeus. Significantly more passes of Myotis species were recorded on organic farms than on conventional farms. This difference was also significant when water habitats were considered alone. The activity of both Myotis daubentonii and Myotis brandtii was significantly higher on organic farms than on conventional farms. The activity of Myotis bechsteinii and Myotis brandtii was significantly higher over organic water habitats than over conventional water habitats. Rhinolophus hipposideros and Rhinolophus ferrumequinum were only recorded on organic farms in wooded, arable and pasture habitats. Synthesis and applications. This study highlights the position of bats as bioindicators and victims of agricultural change. The differences in bat activity between farm types may reflect features such as taller hedgerows and better water quality on organic farms. Higher foraging activity also suggests that habitat quality in terms of prey availability is greater on organic farms. Less intensive farming benefits bats, and as the number of organic enterprises increases it may help to reverse declines in bat populations.