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JANTAR À LUZ DE POSTES: MORCEGOS URBANOS FORRAGEIAM EM ÁREAS ILUMINADAS?

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“A nossa tendência diurna permitiu-nos ignorar o óbvio, que o mundo é diferente à noite e que os padrões naturais de escuridão são tão importantes como a luz do dia para o funcionamento dos ecossistemas.” (Longcore e Rich, 2006, p. 1)

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> "A amizade verdadeira e autêntica, pressupõe uma participação sentida, simplesmente objetiva e totalmente desinteressada, nas alegrias e nas dores de uma outra pessoa”
>
> Schopenhauer

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RESUMO

A luz artificial à noite (ALAN) é um estressor antropogênico, responsável por causar alterações no comportamento de morcegos. Ainda assim, grande parte dos estudos sobre os efeitos de ALAN em quirópteros, concentram-se em regiões temperadas, o que limita a compreensão global dos impactos da iluminação artificial noturna sobre esta ordem, ocultando respostas possivelmente distintas entre os hemisférios. Por este motivo, investiguei quais famílias de morcegos insetívoros, que ocorrem em ambiente urbano no Cerrado brasileiro, são atraídas até áreas com ALAN, apresentando maior atividade e forrageamento nestes espaços, em resposta às maiores abundâncias de insetos em postes de luz. Para isso, estabeleci 10 sítios amostrais na metrópole Brasília, cada um contendo um par de pontos amostrais, que correspondem a localização de um poste com lâmpada de vapor de sódio de alta pressão (HPS) e uma área escura. Em cada sítio, registrei a ecolocalização dos morcegos por 12 horas e identifiquei a abundância dos insetos coletados em armadilhas. Os resultados indicaram que apenas morcegos da família Molossidae exibiram maior atividade e forrageamento em postes de luz, com a abundância de insetos sendo positivamente correlacionada com a atividade em ALAN, mas não apresentando correlação para o forrageamento em ALAN. Esta falta de resposta do forrageamento, em relação aos insetos, pode estar ligada a seleção alimentar, sazonalidade e à redução no tempo de busca por presas em ALAN. No contexto deste estudo, os molossídeos parecem ser os únicos quirópteros pré-adaptados a tolerar e aproveitar a luz artificial de forma oportunística. Em contraste, vespertilionídeos e emballonurídeos não forragearam em ALAN, mesmo com a presença de presas consumíveis, apresentando aversão às áreas iluminadas. Esses resultados, destacam como a luz artificial à noite afeta de formas distintas, o comportamento de morcegos insetívoros urbanos no neotrópico.

Palavras-chave: Chiroptera, molossídeos, luz artificial à noite, urbanização, insetos

INTRODUÇÃO GERAL

Mediante a expansão antrópica, a conversão de paisagens naturais em ambientes urbanos tem sido um dos principais fatores que levam ao declínio da biodiversidade (Balvanera et al. 2019). Estimativas recentes apontam para expansão contínua da urbanização até 2050, onde cerca de 0,6 a 1,3 milhões de km^2 de terra serão convertidos em áreas urbanas, um aumento de 78% a 171% em relação às estimativas de 2015 (Huang et al. 2019). Esta expansão, procede o crescimento da população mundial, que poderá aumentar para aproximadamente 9,7 bilhões de pessoas em 2050 (ONU 2022).

Áreas urbanas aumentaram, entre os anos de 1992 e 2015, de 33,2 para 71,3 milhões de hectares (Mha) em escala global, o que resultou em uma perda direta de 3,3 Mha de vegetação nativa e indireta de 17,8 a 32,4 Mha, ao induzir o deslocamento de terras agrícolas para outros locais (van Vliet 2019). Por meio deste processo de conversão da paisagem em espaços urbanos, há alteração dos componentes bióticos e abióticos ao longo do tempo e espaço (Shochat et al. 2006; Alberti et al. 2020; Uchida et al. 2021) o que afeta negativamente a biodiversidade ao reduzir a oferta de sítios, cujas condições e recursos locais estavam previamente disponíveis para a subsistência de espécies silvestres (Johnson e Munshi-South 2017).

Alterações bióticas incluem, por exemplo, a inserção, intencional ou não, de espécies exóticas que se tornam invasoras, extinções locais, diversidade e abundância reduzida de algumas espécies nativas (McKinney 2008; Aronson et al. 2014; Alberti et al. 2017), perda de riqueza filogenética (Sol et al. 2017) e mudanças na composição de espécies das comunidades (Lagucki et al. 2017). Já as mudanças físicas sobre o espaço, envolvem o aumento da cobertura de superfícies impermeáveis (como edifícios e estradas), maiores temperaturas, aumento de ruído, redução da qualidade do ar pela poluição atmosférica (Grimm et al. 2008) e a introdução de fontes de luz artificial (Kernbach et al. 2021).

Mesmo repletas de estressores, cidades podem propiciar para algumas espécies risco reduzido de predação, maior disponibilidade de abrigo e menor variação temporal de alimentos (Lowry et al. 2013; Gallo et al. 2019). A natureza física excepcionalmente uniforme das cidades, combinado com a presença de estressores e elementos benéficos para poucos animais nestes espaços, contribui para a homogeneização biótica (McKinney 2006). Este processo leva à persistência de número diminuto de espécies, reduzindo a biodiversidade e gerando a simplificação de comunidades biológicas, que podem se tornar semelhantes entre áreas urbanas geograficamente distantes (McKinney e Lockwood 1999; McKinney 2006; Fenoglio et al. 2020).

O grau de urbanização (gradiente urbano) e os traços funcionais das espécies, como hábitos generalistas (alimentação e uso de abrigos), plasticidade fenotípica, grandes tamanhos de ninhada, tempo geracional curto e alta capacidade de dispersão, são características associadas às espécies que persistem em cidades (McKinney e Lockwood 1999; Luniak 2004; Lowry et al. 2013; Neto 2018). No entanto, estes traços podem não se aplicar a todos os animais, pois alguns desviam dos aspectos apontados, mas possuem outros tipos de características vantajosas e também encontram-se em áreas urbanas (Santini et al. 2019; Ritzel e Gallo 2020).

Para mamíferos, 190 espécies são classificadas como urbanas, e as que possuíam flexibilidade comportamental (maior massa cerebral), tamanhos de ninhada mais elevados, maiores tamanhos corporais e hábitos alimentares generalistas, foram positivamente relacionados às cidades (Santini et al. 2019). Porém, alguns traços não são importantes para todas as ordens e nem todos os grupos são considerados residentes urbanos, refletindo a diversidade de características e nichos ecológicos das espécies, e as particularidades do processo de adaptação urbana.

Para Chiroptera, ordem de mamíferos que contempla o maior número de espécies encontradas em cidades (Jung e Kalko 2011; Santini et al. 2019), a tolerância de morcegos insetívoros em áreas citadinas, tem sido associada a flexibilidade na escolha de abrigos, maior proporção de aspecto de asas (asas longas e estreitas que permitem voos mais rápidos), ecolocalização em baixas frequências, pulsos com duração relativamente longa, e estratégias de forrageamento para áreas abertas e de borda (Jung e Threlfall 2016, 2018; Wolf et al. 2022). As famílias de morcegos insetívoros, Rhinolophidae e Mormoopidae costumam exibir associação negativa com o desenvolvimento urbano, enquanto as respostas para todas as outras famílias insetívoras, como Vespertilionidae, Emballonuridae e Molossidae, não é globalmente consistente (Jung e Threlfall 2016).

Em regiões temperadas, vespertilionídeos de voo rápido, adaptados para forragear em áreas de borda, como em clareiras e borda de florestas, frequentemente são encontrados em áreas urbanas (Jung e Threlfall 2016, 2018; Wolf et al. 2022). Na região Neotropical, os molossídeos, que são reconhecidos por forragear em ambientes abertos, como acima da copa das árvores (Denzinger e Schnitzler 2013; Denzinger et al. 2018), parecem demonstrar tolerância e, possivelmente, se beneficiar de áreas urbanas (Pacheco et al. 2010; Jung e Kalko 2011; Ávila-Flores et al. 2023). No Brasil, 84 espécies pertencentes a 43 gêneros e seis famílias, sendo estas Emballonuridae, Molossidae, Mormoopidae, Noctilionidae, Phyllostomidae e Vespertilionidae, ocorrem em áreas urbanas do país (Nunes et al. 2017). Contudo, dentre os insetívoros, a família Molossidae é a mais representativa, com 20 espécies ocorrendo em território urbano (Nunes et al. 2017).

O sucesso e a presença comum de Molossidae em cidades, principalmente na América do Sul, é atribuída a alta proporção de aspecto de asa, flexibilidade na escolha de abrigos, plasticidade comportamental e estratégia de forrageamento em áreas abertas, características encontradas na maioria das espécies desta família (Denzinger et al. 2018; Jung e Threlfall 2018; Ávila-Flores et al. 2023). A combinação destas características, permite que molossídeos explorem habitats urbanos com facilidade, utilizando edificações como abrigo (Webb et al.

2021; Ávila-Flores et al. 2023a) aproveitando piscinas de residências para beber água (Nystrom e Bennett 2019) e explorando insetos abaixo da luz dos postes públicos (Bolliger et al. 2020; Pauwels et al. 2021).

Contudo, fatores regionais tais como a presença de áreas verdes, complexidade ambiental, gradiente urbano e tipos de iluminação artificial, também podem influenciar o sucesso e comportamento das famílias de morcegos nas cidades (Straka et al. 2019; Barré et al. 2022; Li e Wilkins 2022; Barré et al. 2023). Sendo assim, generalizações baseadas em estudos realizados em locais distintos podem ser tendenciosas, tornando necessário o emprego de pesquisas em várias áreas geográficas, especialmente no que se relaciona ao efeito específico de alguns estressores urbanos, sobre o comportamento de morcegos. Esse enfoque é vital, quando observa-se que estudos envolvendo a investigação individual de alguns vetores urbanos, estão principalmente concentrados em regiões temperadas, como é o caso dos efeitos da iluminação artificial, sobre o comportamento de quirópteros insetívoros nas cidades (Stone et al. 2015; Voigt et al. 2021).

A luz artificial à noite (ALAN) é a menos compreendida em termos de impactos evolutivos sobre as espécies e ecossistemas (Hopkins et al. 2018; Kernbach et al. 2021) e, dentre a ampla gama de estressores produzidos pela urbanização, tem ganhado destaque em relação aos seus efeitos distintos sobre o comportamento da fauna (Bennie et al. 2018; Falcón et al. 2020). A maioria das perturbações antropogênicas têm análogos naturais: o clima já aqueceu antes, os habitats fragmentaram-se, as espécies invadiram novas áreas de distribuição e novos pesticidas foram desenvolvidos (as plantas já produziam compostos secundários para evitar a herbivoria) (Gaston et al. 2014). No entanto, durante todo o tempo evolutivo, o ciclo diário de luz e escuridão e o ciclo lunar, permaneceram constantes (Kyba e Hölker 2013; Gaston et al. 2014; Bumgarner e Nelson 2021).

A alteração nestes padrões foi sucedida por meio da incorporação luminosa, oriunda de diversas fontes (públicas, doméstica, veículos) e com diferentes assinaturas espectrais, em locais e horários durante a noite, em que previamente não ocorriam (Longcore e Rich 2004; Bradshaw e Holzapfel 2010; Gaston et al. 2015). Uma vez que os sistemas biológicos estão evolutivamente sincronizados com os padrões espaço-temporais de luz/escuridão (Falcón et al. 2020; Häfker e Tessmar-Raible 2020; Jabbur e Johnson 2022), ALAN interfere em hábitos como reprodução, período de atividade e migração (Gaston et al. 2017; Bumgarner e Nelson 2021), ao distorcer os regimes de luz natural, mediante fontes diretas de iluminação, como também indiretamente, por via *skyglow* (Dominoni et al. 2020; Garrett et al. 2020).

Por reduzir o período de escuridão plena, este estressor associado às cidades, modificou intensamente as paisagens noturnas nos últimos 100 anos (Gaston et al. 2015), ameaçando principalmente a fauna notívaga (Sanders et al. 2021), composta por cerca de 30% de todos os vertebrados e 60% de todos os invertebrados (Hölker et al. 2010). Estudos já evidenciaram os efeitos negativos de ALAN em insetos, que exibem navegação desnorteada e atração até a luz (Desouhant et al. 2019; Owens et al. 2020) e em morcegos insetívoros (Mena et al. 2022), que normalmente têm a redução de suas áreas de deslocamento e forrageamento (Haddock et al. 2019; Luo et al. 2021; Barré et al. 2023). Também é sugerido que ALAN afete negativamente a reprodução e o crescimento de juvenis, de morcegos (Boldogh et al. 2007).

No entanto, nem todos os quirópteros apresentam aversão a áreas iluminadas (Frank et al. 2019; Haddock et al. 2019; Seewagen et al. 2023). Uma vez que a luz artificial facilita a predação de insetos (Owens et al. 2020), ALAN pode beneficiar alguns grupos de morcegos insetívoros, em detrimento de outros, aumentado a atividade e forrageamento dos tolerantes à luz (Haddock et al. 2019; Russo et al. 2019; Voigt et al. 2021). Para estes morcegos, a captura de presas é otimizada em ALAN, seja por atrair insetos de forma contínua, restringindo a distribuição espacial a uma área reduzida, atuando como um “aspirador” luminoso (Eisenbeis et al. 2009), ou agindo como um facilitador de caça, ao diminuir a capacidade do inseto em reconhecer a presença do predador, quando transitam por áreas artificialmente iluminadas (Desouhant et al. 2019; Owens et al. 2020).

Isso ocorre porque ALAN, por meio de mecanismos que variam entre os táxons (Owens e Lewis 2018; Desouhant et al. 2019; Owens et al. 2020), interfere na orientação espacial dos insetos, atraindo-os até as lâmpadas dos postes ou reduzindo a sensibilidade visual, cegando-os temporalmente ou em definitivo (Stark et al. 1985; Owens e Lewis 2018). Uma vez dentro do raio luminoso, os insetos ficam atordoados, pousam abaixo das luzes, ou a orbitam indefinidamente, até serem facilmente capturados por morcegos, ou caírem exaustos ao solo, onde morrem e são consumidos por outros predadores (Eisenbeis et al. 2009; Owens et al. 2020).

ALAN também otimiza o forrageamento de alguns morcegos ao reduzir as defesas dos insetos, fazendo com que, por exemplo, mariposas não apresentem respostas evasivas normais aos sinais de ecolocalização, refletindo em maiores médias de captura (Minnaar et al. 2015; Wakefield et al. 2018). A atração destes invertebrados pela luz pode ser tão intensa, que mesmo após um ataque mal sucedido de um morcego, mariposas continuam voando ao redor da luz (Acharya e Fenton 1999). Além disso, a proximidade com os postes também pode favorecer a visão dos quirópteros, auxiliando de forma secundária a ecolocalização na captura de insetos, tornando o forrageamento mais eficiente (Grant 1991; Eklöf e Jones 2003; Ávila-Flores et al. 2023).

De qualquer forma, a acúmulo de insetos no entorno das luzes, acaba por criar um cenário oportunístico único para alguns morcegos insetívoros, pois permite que eles reduzam os custos de energia relacionados à procura de alimento, ao mesmo tempo em que maximizam os retornos de energia pela predação (Acharya e Fenton 1999; Stone et al. 2015; Prat e Yovel 2020). Esta vantagem pode tornar o hábito de forrageamento nestes pontos comum e difundido entre um número considerável de espécies de morcegos, que buscam obter proporções de sua dieta nos postes de luz no ambiente fragmentado das cidades. Jung e Kalko (2010) verificaram que dentre as 25 espécies de morcegos insetívoros presentes em uma cidade com vegetação densa no Panamá, 20 foram documentadas nas cidades, das quais 18 frequentemente forrageavam em torno de postes de luz.

No entanto, determinados tipos de luz podem aprimorar ainda mais a visibilidade do ambiente, algo que pode aumentar o risco de morcegos serem avistados por seus predadores (Stone et al. 2012; Kerbiriou et al. 2020). Junto a isso, cada tipo pode atrair, em menor ou maior grau, riquezas e abundâncias distintas de insetos (Barghini e Souza de Medeiros 2012; Wakefield et al. 2018), que podem afetar os morcegos de forma diferencial (Lewanzik e Voigt 2017; Barré et al. 2023). Para insetos, o impacto na aptidão a uma fonte de luz artificial, vai depender das configurações de ALAN, tais como intensidade, amplitude espectral e percentagem de radiação espectral ultravioleta emitida (Wakefield et al. 2018; van Grunsven et al. 2020; Deichmann et al. 2021), o que interfere nas respostas dos morcegos (Haddock et al. 2019a; Kerbiriou et al. 2020).

A propagação de luz dos postes públicos que usam lâmpadas como vapor de mercúrio e sódio, é mais do que suficiente para perturbar radicalmente o comportamento de insetos (Wakefield et al. 2018; Owens et al. 2020), atraindo vespertilionídeos e molossídeos até ALAN (Stone et al. 2015; Rowse et al. 2016; Haddock et al. 2019). A luz emitida por lâmpadas de vapor de mercúrio, por exemplo, é azul esbranquiçada e emite maiores taxas de ultravioleta, atraindo maiores quantidades de insetos (Elvidge et al. 2010; van Grunsven et al. 2014). Esse tipo de luz é mais frequentada pela maioria dos morcegos (Stone et al. 2015; Rowse et al. 2016; Frank et al. 2019). Já a luz da lâmpada de sódio de alta pressão (HPS) emite principalmente luz laranja, de comprimentos de ondas curto, incluindo ultravioleta, sendo menos atrativa para insetos e para alguns morcegos (Rydell 1992; Barghini e Souza de Medeiros 2012).

Ambos os tipos de lâmpadas são observados em estudos, realizados principalmente em regiões temperadas, como na Europa e América do Norte, que buscam avaliar a interferência da luz no forrageamento de morcegos nas cidades (Stone et al. 2015; Haddock et al. 2019; Voigt et al. 2021; Li e Wilkins et al. 2022; Seewagen et al. 2023). Esses trabalhos demonstram diferentes respostas entre as famílias e espécies, quando em presença de ALAN. A partir de suas discussões, pode-se hipotetizar que os mesmos traços que conferem resistência a urbanização (Jung e Threlfall 2016, 2018; Wolf et al. 2022) possibilitam a tolerância e o uso de ALAN (Ávila-Flores e Fenton 2005; Jung e Kalko 2010; Stone et al. 2015; Voigt et al. 2021).

Morcegos de voo rápido, que possuem adaptações para forragear em espaços abertos (sem obstáculos, como árvores, pedras, folhagem, etc.) e de borda (poucos obstáculos) (Denzinger et al. 2018), são apontados como possivelmente resistentes a iluminação artificial (Stone et al. 2015; Rowse et al. 2016; Voigt et al. 2021). No hemisfério norte, principalmente espécies da família Vespertilionidae, que possuem uma média de voo mais rápida do que o padrão para a família (Findley et al. 1972; Norberg et al. 1987), têm sido registradas utilizando ALAN como áreas de forrageamento. Especificamente, espécies pertencentes aos gêneros *Lasiurus*, *Eptesicus*, *Nyctalus* e *Pipistrellus*, têm sido as mais documentadas capturando os insetos atraídos pela luz artificial (Stone et al. 2015; Rowse et al. 2016; Voigt et al. 2021).

Os poucos estudos realizados em cidades neotropicais (Jung e Kalko 2010; Frank et al. 2019), apontam o uso de ALAN por emballonurídeos, especialmente por espécies dos gêneros *Cormura*, *Diclidurus* e *Saccopteryx*, e também por vespertilionídeos. No entanto, espécies de molossídeos, especificamente dos gêneros *Molossus*, *Eumops*, *Nyctinomops*, *Cynomops* e *Tadarida*, têm sido documentadas como as mais ativas em áreas urbanas com ALAN (Ávila-Flores e Fenton 2005; Jung e Kalko 2010; Frank et al. 2019; Mena et al. 2022; Bernard et al. 2023).

Já espécies de morcegos de voo lento, como as do gênero *Myotis* da família Vespertilionidae, e morcegos da família Rhinolophidae, Furipteridae e Phyllostomidae, que forrageiam em áreas fechadas com muitos obstáculos (Denzinger et al. 2018), são apontados como aversos a ambientes luminosos (Azam et al. 2018; Rowse et al. 2018; Straka et al. 2020; Voigt et al. 2021; Mena et al. 2022). As explicações para este comportamento não são claras, e suposições permeiam a literatura. A principal hipótese é que morcegos lentos, teriam dificuldades para evadir de predadores visuais, como aves noturnas, que poderiam aproveitar estas áreas de maior visibilidade para caça-los, munidos de seus voos de rápida velocidade (Rautenbach et al. 1988; Speakman 1991; Jones e Rydell 1994; Rydell et al. 1996; Stone et al. 2015; Voigt et al. 2021).

Entretanto, é plausível considerar a possibilidade de que morcegos não utilizam ALAN por não consumirem os insetos que são atraídos até a luz, uma vez que a frequência de morcegos na dieta de aves predadoras, ao menos para a coruja *Tyto alba*, não foi associada às características das asas destes quirópteros (Roulin e Christe 2013). Diferenças relacionadas à dieta (Giménez et al. 2021), também podem ser responsáveis pelo uso diferencial de áreas com ALAN, para forrageamento, entre as famílias de morcegos urbanos (Cravens et al. 2018). Isto porque quirópteros insetívoros possuem especializações voltadas para diferentes tipos de insetos, que são utilizados na dieta, incluindo adaptações no crânio (Freeman 1979; Giacomini et al. 2022), na ecolocalização (Fenton et al. 1999; Denzinger et al. 2018), na visão (Davies et al. 2020) e na aerodinâmica do voo (Findley et al. 1972; Norberg et al. 1987; Smith et al. 2023).

Em estudos realizados em regiões temperadas (a maioria não avaliou ALAN), vespertilionídeos foram documentados predando Diptera, Lepidoptera, Neuroptera e Coleoptera (Sample e Whitmore 1993, Feldhamer et al. 1995, Vaughan 1997; Pervushina e Gizullina 2020). Por outro lado, molossídeos já foram registrados predando espécies de Lepidoptera, Coleoptera, Hemiptera e Hymenoptera (Freeman 1979, Lee e McCracken 2002, Aspetsberger et al. 2003, Mata et al. 2016). Todas estas ordens de insetos já foram apontadas como sendo atraídas por postes de iluminação (Barghini e Souza de Medeiros 2012; van

Grunsven et al. 2014; Wakefield et al. 2018).

Ainda assim, espécies de morcegos de voo lento frequentemente são vistos evitando a luz artificial (Haddock et al. 2019; Russo et al. 2019; Voigt et al. 2021). Neste caso, a percentagem das ordens de insetos atraídas por ALAN, consumidos por alguns morcegos, também pode ser baixa mediante as configurações da luz (Barghini e Souza de Medeiros 2012; van Grunsven et al. 2014; Wakefield et al. 2018) e, por isso, algumas famílias não forrageiam em certos tipos de iluminação. Sendo assim, a atividade alimentar no entorno das luzes, pode estar associada a um subconjunto diferente de insetos, que podem ser preferíveis para algumas espécies de morcegos (Ramírez-Chaves et al. 2008; Breviglieri e Esbérard 2018).

Aguiar e colaboradores (2021), por exemplo, investigaram a composição de artrópodes consumidos por cinco espécies de morcegos urbanos no Distrito Federal, das quais quatro são molossídeos. Por meio da técnica metabarcoding de DNA fecal, eles verificaram diferenças significativas na composição e percentagem de consumo de insetos, na qual a dieta mais diversa foi a de *Nyctinomops laticaudatus*. No entanto, estes não consumiram Isoptera, ao contrário do vespertilionídeo *Histiotus diaphanopterus*.

Ainda assim, a hipótese do risco aumentado de predação para morcegos lentos em ALAN, também pode ser válida, uma vez que a pressão de caça é apontada como uma justificativa evolutiva para os hábitos noturnos em morcegos (Rydell e Speakman 1995; Mikula et al. 2016). Mediante esta possibilidade, morcegos urbanos precisariam lidar com um *trade-off* entre os benefícios de forragear no entorno dos postes de luz e a desvantagem relacionada ao aumento do risco de predação, pela exposição à luz (Prat e Yovel 2020; Stidsholt et al. 2023).

Quando o risco de predação for elevado, algo que pode variar entre ambientes urbanos, e talvez seja maior em regiões pouco vegetadas (Mathews et al. 2015; Straka et al. 2019), o morcego pode evitar ALAN para não ser detectado. Dessa forma, o comportamento de aversão pode ocorrer independentemente da taxa de radiação ultravioleta, emitida por lâmpadas distintas, e a abundância de insetos na luz (Frank et al. 2019; Russo et al. 2019).

Neste caso, estas modificações comportamentais podem levar a perdas significativas na aquisição de alimento (Luo et al. 2021), mesmo que a abundância geral de presas aumente em áreas artificialmente iluminadas (Kuijper et al. 2008; Luo et al. 2021). Por exemplo, o tempo de emergência do morcego *Ozimops ridei* em ambientes com ALAN, que é uma espécie de área aberta e voo rápido, foi adiantado, e teve um aumento significativo em seu período de atividade nas áreas com iluminação artificial, quando comparada com áreas escuras (Threlfall et al. 2013; Haddock et al. 2019). Já para *Vespadelus vulturnus*, uma espécie de área fechada e voo lento, foi observado o contrário. O tempo de emergência foi atrasado significativamente pela presença de postes de iluminação na borda da floresta (Haddock et al. 2019).

ALAN também pode afetar indiretamente o forrageamento de morcegos nos ambientes escuros, uma vez que o efeito de "aspirador" causado pelas luzes, atrai grandes quantidades de insetos para pontos específicos da cidade (Eisenbeis et al. 2009; Owens e Lewis 2018). Isto pode resultar em uma menor disponibilidade alimentar, para os morcegos urbanos, que não são capazes de utilizar áreas iluminadas como habitats para forrageio (Stone et al. 2015; Cravens e Boyles 2019). Neste contexto, a luz artificial pode estar contribuindo para o processo de homogeneização biótica (Sanders et al. 2023). No que pode resultar em um empobrecimento ainda maior na diversidade de morcegos em ambientes urbanos, com ALAN selecionando a ocorrência de poucas famílias e espécies, aumentando sua abundância e distribuição, assim modificando as comunidades (Schoeman 2016; Cravens e Boyles 2019; Seewagen and Adams 2021; Seewagen et al. 2023), à medida que ALAN é difundida nas paisagens antrópicas.

Arlettaz e colaboradores (2000), por exemplo, mencionaram que a espécie de morcego *Rhinolophus hipposideros* sofreu um declínio dramático no sudoeste da Suíça, ao mesmo tempo em que as populações de *Pipistrellus pipistrellus*, aumentaram substancialmente. Os pesquisadores observaram que as duas espécies se alimentam das mesmas categorias de presas e que embora estes morcegos utilizem diferentes estratégias de forrageamento, ambas as espécies poderiam visitar os mesmos locais de alimentação, com exceção de áreas iluminadas. Foi sugerido que ALAN pode dar vantagem competitiva para *P. pipistrellus*, permitindo o aumento da área de distribuição desta espécie generalista de voo rápido, e levando à redução da área de ocorrência de *R. hipposidero* e, possivelmente, ao seu declínio populacional (Arlettaz et al. 2000).

Tendo em mente esta problemática, é necessário que estudos com esta temática sejam amplamente desenvolvidos, principalmente em países com elevada biodiversidade e taxa de expansão urbana como o Brasil (Butler 2016; CIA 2022), considerando-se diversos contextos ambientais. Assim, será possível melhorar a compreensão sobre as consequências ecológicas da poluição luminosa em diferentes perspectivas, uma vez que estudos indicam que as respostas das famílias de morcegos insetívoros a ALAN podem ser mais complexas, também variando diante de fatores espaço-temporais, como a época do ano (Lewanzik e Voigt 2017), tipos de habitat (Jones e Rydell 1994; Li e Wilkins 2022), fases da lua (Jung e Kalko 2010), condições meteorológicas (Blake et al. 1994; Straka et al. 2019; Jonker et al. 2022), gradientes de urbanização (Barré et al. 2022) e tempo de permanência da luz no ambiente (Williams et al. 2019).

Em geral, a discussão sobre a poluição luminosa no Brasil é irrelevante e mais restrita ainda a respeito da expansão e interferência no comportamento de morcegos no Cerrado, mesmo diante da alta taxa de urbanização e elevado número de famílias e espécies de morcegos que ocorrem no país e no bioma. De um total de 181 espécies de morcegos, pertencentes a uma das 9 famílias que ocorrem no Brasil (Garbino et al. 2020), 84 podem viver em ambiente urbano (Nunes et al. 2017) e 118 espécies ocorrem no Cerrado (Aguiar et al. 2016). Junto a isso, o Brasil apresenta uma das maiores taxas mundiais de urbanização (CIA 2021), grandes proporções de seu território sendo artificialmente iluminado (Falchi et al. 2016) e seus maiores centros urbanos estão localizados em *hotspots* de biodiversidade, como ocorre no Cerrado (Myers et al. 2000; Strassburg et al. 2017). Muito provavelmente, ALAN pode ameaçar a diversidade nativa de morcegos no bioma, permitindo que poucas famílias ocorram em áreas iluminadas, contribuindo com a homogeneização biótica (Polak et al. 2011; Cravens e Boyles 2019; Russo et al. 2019; Sanders et al. 2023).

Diante desse contexto, e considerando que em 2010, 98,2% da cidade de Brasília, no Distrito Federal, possuía iluminação pública (IBGE 2010), investiguei quais famílias de morcegos insetívoros são atraídos até áreas com ALAN, apresentando maior atividade e forrageamento nestes espaços, em resposta às maiores abundâncias de insetos em postes de luz. Com base nisso, testei as seguintes hipóteses: 1) A abundância e biomassa seca total de insetos será maior em áreas iluminadas, uma vez que os insetos são atraídos por lâmpadas HPS, e se agregam nestes locais. 2) Diante da elevada abundância de insetos, morcegos pertencentes a famílias adaptadas a forragear em áreas abertas e de borda, como molossídeos e vespertilionídeos, respectivamente, serão atraídos até ALAN e vão exibir maior atividade (número de passes) e forrageamento (número de *feeding buzzes*) na luz, variáveis que estarão positivamente correlacionadas com a maior disponibilidade de insetos.

As respostas deste estudo irão, de forma pioneira, fornecer informações a respeito de como ALAN afeta as famílias de morcegos insetívoros que ocorrem em território urbano, no Cerrado brasileiro. Tal conhecimento, é crucial para o desenvolvimento de métodos de gestão que visem manter a disponibilidade de áreas escuras para as famílias de morcegos urbanos, que apresentam aversão ou não são atraídos por ordens de insetos fototáxicos em ALAN, buscando evitar a homogeneização biótica e a redução da biodiversidade de morcegos insetívoros (Arlettaz et al. 2000; Mena et al. 2022; Sanders et al. 2023). A partir disso, os serviços ecossistêmicos prestados por estes grupos nas cidades, como o controle de insetos pragas, que são vetores de doenças para os seres humanos, poderá ser mantido, reduzindo a exposição da população urbana a estas enfermidades (Aguiar et al. 2021; Russo et al. 2023).

Por último, têm ocorrido propostas relacionadas à substituição das lâmpadas com tecnologias convencionais (como HPS), por tecnologias mais avançadas (como LED) (Neoenergia 2021; Izel 2023), em conjunto com a expansão da área iluminada, sem um planejamento adequado para mitigar os impactos causados sobre os morcegos. Esta mudança já tem sido documentada em regiões temperadas e afetam negativamente os morcegos insetívoros, reduzindo a atividade, composição e forrageamento de quirópteros que utilizavam a região quando esta possuía lâmpadas tradicionais (Haddock et al. 2019a; Kerbiriou et al. 2020).

Dessa forma, áreas iluminadas que já eram frequentadas por poucas espécies de morcegos, podem ser completamente abandonadas, quando as tecnologias tradicionais de iluminação pública forem substituídas por LED. Diante disso, este trabalho contém informações que poderão ser importantes para comparações com estudos futuros, visando observar como a mudança de iluminação pode afetar a ocorrência das famílias de morcegos urbanos que utilizam ALAN emitida por lâmpadas HPS, no Distrito Federal.

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DINNER BY STREETLIGHTS: URBAN BATS FORAGE IN ILLUMINATED AREAS?

ABSTRACT

Artificial light at night (ALAN) is an anthropogenic stressor responsible for causing alterations in bat behavior. However, many studies on the effects of ALAN on bats are concentrated in temperate regions, limiting the global understanding of the impacts of nighttime artificial lighting on this order and concealing potentially distinct responses between hemispheres. To address this gap, we investigated which families of insectivorous bats occurring in an urban environment in the Brazilian Cerrado are attracted to areas with ALAN, displaying higher activity and foraging in these spaces in response to increased insect abundances at lighted posts. To accomplish this, we established 10 sampling sites in the metropolis of Brasília, each containing a pair of sampling points, corresponding to the location of a post with a high-pressure sodium (HPS) lamp and a dark area. At each site, we recorded bat echolocation calls for 12 hours and identified the abundance of insects collected in traps. The results indicated that only bats from the Molossidae family exhibited higher activity and foraging at lighted posts, with insect abundance positively correlated with activity in ALAN but not correlated with foraging in ALAN. This lack of foraging response to insects may be linked to food selection, seasonality, and a reduction in prey-searching time in ALAN. In the context of this study, molossid bats appear to be the only ones preadapted to tolerate and opportunistically use ALAN. In contrast, vespertilionid and emballonurid bats did not forage in ALAN, even in the presence of consumable prey, showing aversion to illuminated areas. These results highlight how ALAN affects the behavior of urban insectivorous bats in the Neotropical region in distinct ways.

Keywords: Chiroptera, molossids, artificial light at night, urbanization, insects

ALAN and the City's Nighttime Warriors: Molossidae Bats vs. Streetlight Insects

INTRODUCTION

Urbanization gives rise to novel ecosystems, the effects of which on the evolution of life remain largely unknown (Alberti et al. 2017; Johnson and Munshi-South 2017; Alberti et al. 2020). As urban centers expand in tandem with human population growth (UN 2022), vast natural areas become fragmented and transformed into impermeable spaces for biodiversity (van Vliet 2019). These areas consist of elements primarily designed to meet the relatively narrow needs of the human species (McKinney 2006). Once subjected to these modified environments, the tolerance and adaptability of wild species to the resources and stressors prevalent in urban spaces may determine their persistence within cities (McKinney and Lockwood 1999; Lowry et al. 2013; Ritzel and Gallo 2020).

In tandem with urbanization, although not exclusively, the unprecedented introduction and distribution of artificial light at night (ALAN) have directly affected wildlife interactions, behavior, reproduction, and survival (Gaston et al. 2017; Falcón et al. 2020; Bumgarner and Nelson 2021), particularly for nocturnal species (Hölker et al. 2010; Sanders et al. 2021). This is because biological systems are synchronized with predictable spatial and temporal patterns of natural light (e.g., to define foraging periods) (Häfker and Tessmar-Raible 2020; Jabbur and Johnson 2022), which have become disrupted in urban environments due to direct and indirect effects of artificial lighting (Longcore and Rich 2004; Kyba and Hölker 2013; Garrett et al. 2020). Consequently, ALAN may be selecting for the occurrence of specific families and species, thereby shaping the composition of biological communities in urban settings (Davies et al. 2012; Hopkins et al. 2018; Sanders et al. 2021).

The reduction in family and species richness in illuminated environments (Parkinson et al. 2020; van Grunsven et al. 2020) suggests that ALAN limits the occurrence of certain animal taxa, permitting only those adapted to nighttime illumination (Russo et al. 2019; Mena et al. 2022). This could lead to an overall impoverishment of biodiversity (Hölker et al. 2010; Hopkins et al. 2018; Sander et al. 2023), as cities and ALAN expand, leading to an increase in the distribution area and abundance of a limited number of species, thereby contributing to biotic homogenization (McKinney 2006; Hölker et al. 2010; Sander et al. 2023). Additionally, ALAN spatially impacts ecological interactions among fauna (Sullivan et al. 2019), leading to modifications in the predator-prey relationships, as observed in the interactions between bats and insects (Seymoure et al. 2023).

Since the 1970s, insectivorous bats have been observed feeding around public lighting fixtures (Shields and Bildstein 1979; Stone et al. 2009; Lewanzik and Voigt 2017; Seewagen et al. 2023), taking advantage of accumulations of positively phototactic insects (Eisenbeis et al. 2009; Desouhant et al. 2019) and obtaining a significant portion of their diet from streetlights (Rydell 2006). In these cases, species with relatively high flight speeds that forage in open and edge habitats, such as some molossids and vespertilionids (Denzinger et al. 2018), have been documented using ALAN and are suggested to be the most adapted to exploit insects at streetlights (Stone et al. 2015; Rowse et al. 2016; Haddock 2019; Voigt et al. 2021).

In temperate zones, species within the Vespertilionidae family with flight speeds above the family’s average (Findley et al. 1972; Norberg et al. 1987) have been recorded utilizing ALAN as foraging areas. Specifically, species belonging to the genera *Lasiurus, Eptesicus, Nyctalus,* and *Pipistrellus* have been most frequently documented capturing insects attracted by artificial light (Stone et al. 2015; Voigt et al. 2021). In neotropical cities, the few studies conducted also indicate the use of ALAN by vespertilionids, primarily by the genera *Lasiurus* and *Eptesicus* (Jung and Kalko 2010; Frank et al. 2019).

In addition to Vespertilionidae, the families Noctilionidae (only *Noctilio albiventris*), Mormoopidae (only *Pteronotus gymnonotus*), and Emballonuridae, specifically species belonging to the genera *Cormura*, *Diclidurus*, and *Saccopteryx* (Jung and Kalko 2010; Frank et al. 2019), have also been observed around streetlights. However, species of molossids, particularly from the genera *Molossus*, *Eumops*, *Nyctinomops*, *Cynomops*, and *Tadarida*, have been documented as the most active in urban areas with ALAN (Ávila-Flores and Fenton 2005; Jung and Kalko 2010; Frank et al. 2019; Mena et al. 2022).

Contrary to fast-flying species, it is hypothesized that bats that fly slowly and forage in closed areas remain confined to dark areas (Stone et al. 2009; Rowse et al. 2016; Haddock et al. 2019; Voigt et al. 2021) if they persist in urban spaces. This is suggested to be attributed to the higher risk associated with exposure to predators (Speakman 1991; Jones and Rydell 1994; Ávila-Flores and Fenton 2005; Saldaña-Vázquez and Munguía-Rosas 2013; Stone et al. 2015) and reduced mobility in cities (Jung and Threlfall 2018; Wolf et al. 2022). Neotropical species belonging to the Natalidae, Furipteridae and Phyllostomidae families, adapted for foraging in closed areas with high maneuverability and low flight speed (Findley et al. 1972; Norberg et al. 1987), for instance, are restricted to areas without ALAN, even in cities with more preserved vegetation (Jung and Kalko 2010; Frank et al. 2019; Mena et al. 2022).

However, this hypothesis is challenged by the fact that bats flying more slowly sometimes feed around lamps (Lewanzik and Voigt 2017; Russo et al. 2017), and in some cases, they even frequent them more than fast-flying bats like vespertilionids of the genus *Myotis* (Frank et al. 2019). This raises questions related to the differential diets of these bats, such as their preference for specific orders of insects (Agosta et al. 2003; Emrich et al. 2014; Gordon et al. 2019), which may not be present, for example, in the composition of insects attracted by ALAN. This possibility could make the lack of interest in attracted insects the factor responsible for the absence of some bat families and species in areas with ALAN, something that requires further investigation.

Additionally, the way insectivorous bats react to illumination may depend on complex relationships between foraging strategy (Voigt et al. 2021), flight speed and maneuverability (Ávila-Flores and Fenton 2005; Jung and Threlfall 2018; Haddock et al. 2019), vegetation cover (Straka et al. 2019), moon phases (Jung and Kalko 2010), landscape composition (Barré et al. 2022; Li and Wilkins 2022), and ALAN configurations (Kerbiriou et al. 2020; Barré et al. 2023). This emphasizes the need for studies on this topic, especially considering various environmental contexts, to be extensively conducted. Elucidating the factors characterizing the response of bat families to ALAN enhances our understanding of how anthropogenic lighting filters the composition of bats in cities at local scales (Aronson et al. 2016).

Nevertheless, despite this complexity, studies evaluating the effect of ALAN on the activity and foraging behavior of insectivorous bats are concentrated in the Northern Hemisphere (Stone et al. 2015; Haddock et al. 2019; Voigt et al. 2021; Li and Wilkins 2022; Seewagen et al. 2023) and are scarce in the neotropics (Ávila-Flores and Fenton 2005; Jung and Kalko 2010; Frank et al. 2019; Mena et al. 2022; Bernard et al. 2023). Therefore, findings from temperate regions may not fully apply to the neotropical region, not only due to differences in the origin and geographical distribution of bat families, genera, and species between hemispheres (Stevens 2004; Teeling et al. 2005; López-Aguirre et al. 2019) but also because of differences related to climate variables, biomes, ecosystems (Stevens 2013; Stevens et al. 2019), and urbanization gradients (Jung and Threlfall 2016; de Lima et al. 2023), for instance.

As a result, this knowledge gap regarding the effects of ALAN on neotropical insectivorous bats limits the global understanding of the impacts of artificial light on bats and compromises the conservation of species that may or may not be sensitive to ALAN, depending on local factors. In the neotropics, bats are taxonomically diverse and highly varied in ecological terms (Dos Reis 2007; Taylor 2019). However, urbanization is expanding without planning and with little emphasis on maintaining green areas (Flores et al. 2022; de Lima et al. 2023). Given this fact, greater acquisition of knowledge regarding the effects of ALAN on urban bats in this geographic area is crucial for the development of urban management plans.

Additionally, these plans should reflect regional realities, aiming to preserve the availability of dark areas for bat families averse to ALAN, thereby preventing artificial light from intensifying biotic homogenization induced by urbanization (McKinney 2006; Sanders et al. 2023). Similarly, it is also necessary to take into account, during the development of these plans, the negative effects of ALAN on insect diversity (Owens et al. 2020), so that the ecosystem services provided by these groups (Macgregor et al. 2017; Russo et al. 2023) are maintained, resulting in a better quality of life for the human species.

In general, the discussion regarding light pollution in Brazil is scarce, and even more limited concerning how it expands and interferes with the behavior of bats in the Cerrado biome, despite the high urbanization rate and the substantial number of bat families and species occurring in the country. Out of a total of 181 bat species belonging to one of the 9 families found in Brazil (Garbino et al. 2020), 84 can inhabit urban environments (Nunes et al. 2017), and 118 species occur in the Cerrado (Aguiar et al. 2016). Additionally, Brazil exhibits one of the highest urbanization rates globally (CIA 2022), with significant portions of its territory being artificially illuminated (Falchi et al. 2016), and its largest urban centers are located in biodiversity hotspots, as seen in the Cerrado (Myers et al. 2000; Mata et al. 2006; Nunes et al. 2017; Strassburg et al. 2017).

Therefore, it is highly likely that ALAN may be threatening the native bat diversity in this biome (Mena et al. 2022), allowing only a few families to occur in illuminated areas of Brazilian cities. Within this context, considering that 98.2% of the city of Brasília, located in the Federal District, had public lighting in 2010 (IBGE 2010), we investigated which families of insectivorous bats occurring in this urban environment in the Brazilian Cerrado are attracted to areas with ALAN, displaying higher activity and foraging in response to the greater abundance of insects at streetlights. Based on this, we tested the following hypotheses: 1. The abundance and total dry biomass of insects will be higher in illuminated areas, as insects are attracted to HPS lamps and aggregate in these locations. 2. Given the high abundance of insects, bats belonging to families adapted to forage in open and edge habitats, such as molossids and vespertilionids, respectively, will be attracted to ALAN and will exhibit higher activity (number of passes) and foraging (number of feeding buzzes) in the light, variables that will be positively correlated with the greater availability of insects.

MATERIALS AND METHODS

Study Area

This study was conducted in Brasília, Federal District, between the end of 2022 and the beginning of 2023. Sampling points were distributed in a paired manner across 10 sites located within urban areas (Figure 1), with a distance of 3 km between them. Each site represents the location of two points: one corresponds to a well-lit lamppost containing a high-pressure sodium (HPS) lamp, and the other is a dark control point, positioned at a maximum distance of 500 meters from the lighting. At both points, bat recorders and insect traps were placed (two per site) once a month, specifically in the penultimate week of August and September 2022 (during the dry season) and January 2023 (rainy season).

The definition of the distance between paired points is sufficient to ensure data independence between treatments. Since public lighting negatively impacts light-sensitive bats within a radius of 50 to 75 meters (Azam et al. 2018; Seewagen et al. 2023), this distance is adequate for sampling urban bats that may be averse to ALAN.

Regarding the definition of dark points, these correspond to areas without the presence of any type of direct artificial light source. Specifically, these are more vegetated areas in the city, corresponding to leisure-oriented regions. As these areas are less common, the search for the sampling points began by looking for dark spaces, as lampposts are easily found throughout the city. Therefore, the absence of direct sources of ALAN in these control areas, combined with the established distance from the presence of light, makes the sampling method used suitable for the purpose of the study.

The sites were distributed in the administrative regions of Plano Piloto (15°47'51.07"S 47°53'30.01"W), Núcleo Bandeirante (15°52'13.09"S 47°58'18.32"W), and Park Way, which present an urban landscape consisting of residential blocks, apartment buildings, commercial centers, and green areas with both exotic and native Cerrado species (GDF 2023). Plano Piloto exhibits a more organized landscape and greener areas compared to Núcleo Bandeirante due to its planned city status (Jatobá 2017; GDF 2023a). The sampling sites located in Park Way are within an urban area within the Environmental Protection Area of the Gama and Cabeça-do-Veado Rivers (APA) (15°52'25.1"S 47°52'34.6"W), consisting of individual residences and disorganized condominiums (UNESCO-BR 2003).

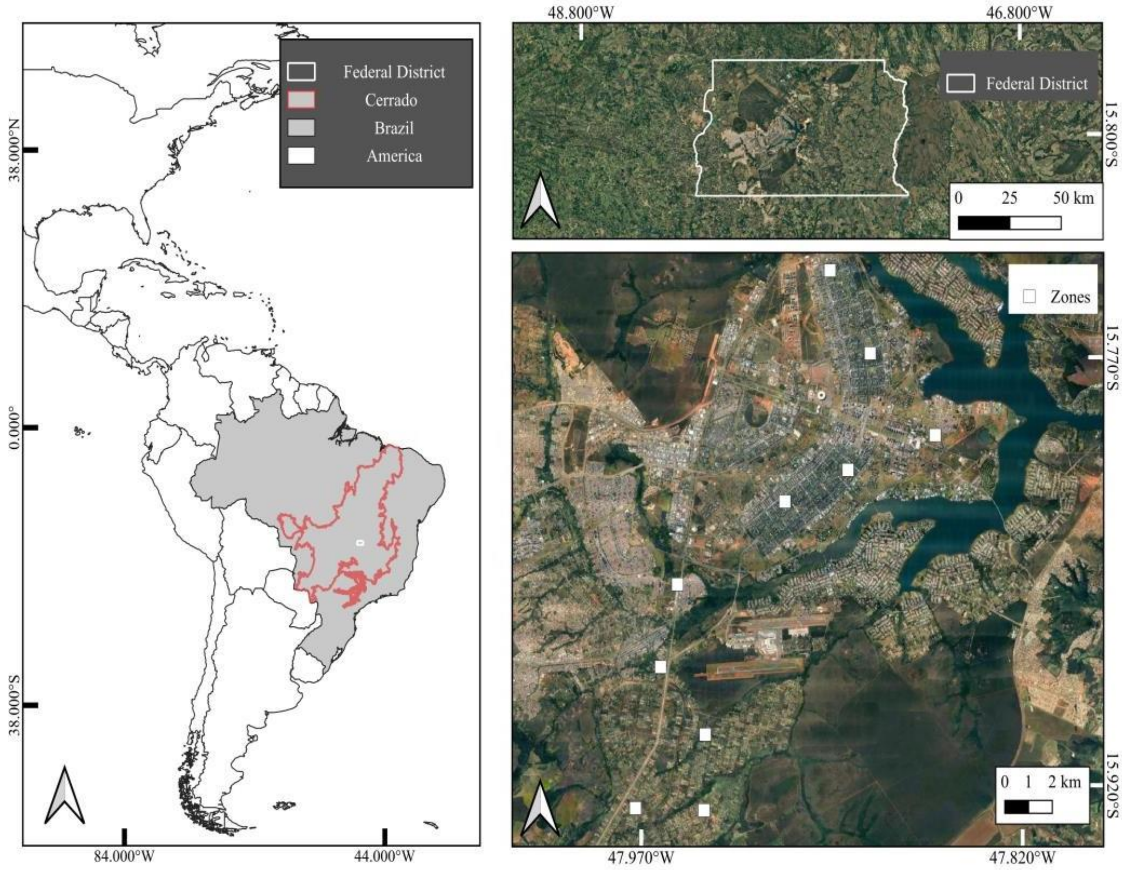

Figure 1. Map of the sampling sites in Brasília, Federal District, located in the Cerrado biome. Each white square corresponds to a site containing paired points: a lamppost with HPS lamps (light point) and, at a maximum distance of 500 meters, a dark area (dark point). In each of the sites (pairs), bat recorders and window-type flight interception traps for insects were simultaneously positioned. Collections were conducted for 12 hours on three nights in the months of August and September 2022 and January 2023 (one night each month). The sites were distributed in urban areas of Plano Piloto, Núcleo Bandeirante, and Park Way.

Collection and identification of Insects

Insects were collected passively between the treatment groups (light vs. dark) using window-type flight interception traps adapted from Murari et al. (2012). These traps were employed for the identification, counting, and weighing of various insect orders. The traps were fashioned from 2-liter PET bottles, cut at the top and on the sides, with a plastic film (made of masking tape) placed in the center, forming the flight interception panel (17 cm x 10 cm) for insect collision and subsequent fall into the bottom of the trap (container). The bottom was filled with water and detergent to preserve the insects until transportation (Figure 2). During the rainy season, two lateral cuts were made in the container, and nylon screens were added to prevent insects from escaping due to water overflow.

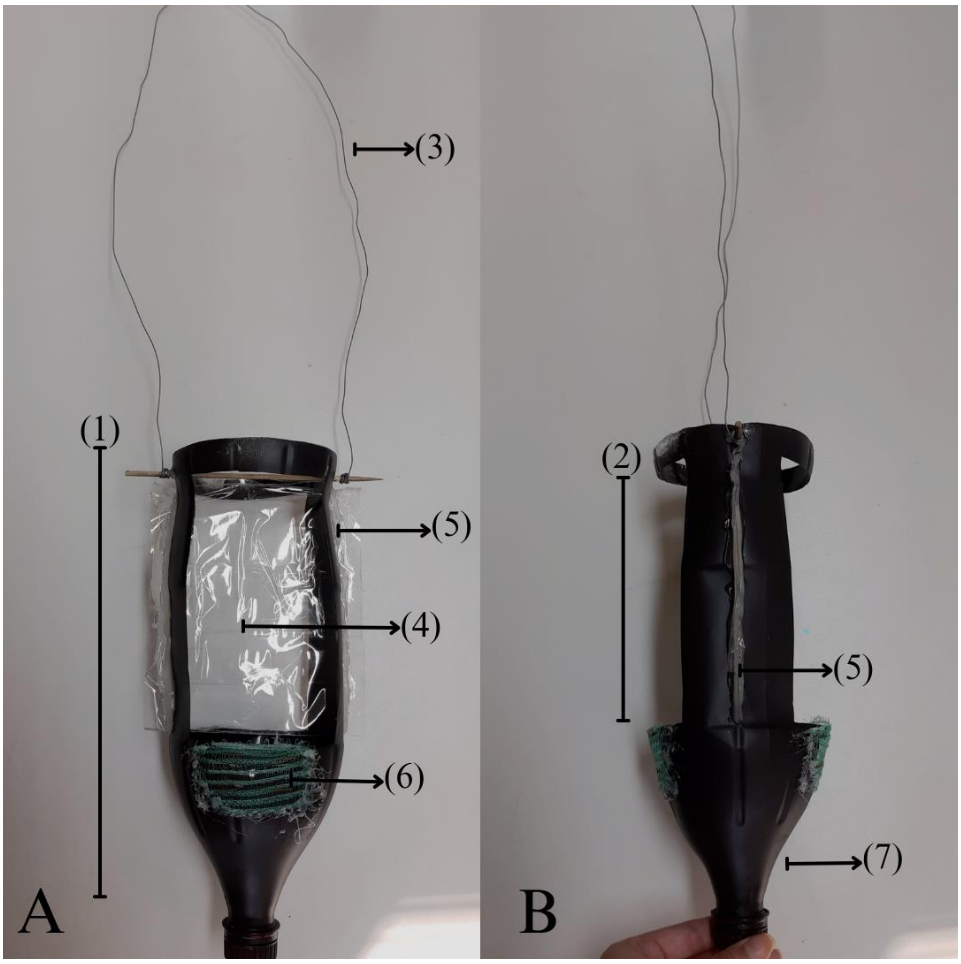

Figure 2. Model of a window-type flight interception trap for insect collection made from a 2L PET bottle (1). Front view (A) and side view (B) of the trap. Flight interception panel (17 cm x 10 cm) (2); wire support rod (3); impact area (4); plastic film (5); nylon screen (6); collection container with water and detergent (7). Trap adapted from Murari et al. (2012).

A total of 20 traps were utilized, with two traps deployed at each site. One trap was positioned beneath the lamppost, at a height of 7.5 meters, by a qualified team provided by the Brasília Power Company (CEB) (Figure 2). Simultaneously, in the dark area, the second trap was installed on a tree using a ladder and a wooden rod, at a height of 5 meters.

The difference in height between the treatments was due to equipment limitations (ladder height limit) and the sampling locations. Since this study was conducted in an urban area, it was not possible to use structures (such as iron stakes) of similar height to the lamppost in the dark areas, as such equipment would attract unwanted attention to the bat recorders, increasing the risk of equipment theft. Therefore, the traps were positioned in trees, within the maximum height limit allowed by the ladder.

Trap placement commenced at 1:00 PM and concluded before 6:00 PM, just before the lampposts were turned on. The traps were removed the following day, from 8:00 AM to 1:00 PM. To increase the randomness of the data, traps were positioned in the direction of Plano Piloto – Park Way in one month and in the reverse direction in the subsequent collection. The lampposts were also revisited one day before the collections to confirm their functionality. The traps did not contain any attractants for insects, except for the lampposts when they were illuminated at night.

The collected insects were stored in containers containing 70% Alcohol until the sorting and drying period. Insects were sorted by Order according to Rafael et al.'s (2012) identification key and subsequently placed in a 40°C oven for 24 hours. Only insects larger than 1 mm were considered for weighing, except for samples that presented at least 10 individuals smaller than the established parameter. This method was adopted due to the high quantity of small insects found after the first rain in September, forming masses with weights to be considered, but during the dry season, they exhibited negligible quantities and weights. After drying, the insects were weighed on an analytical balance with four decimal places (BEL Engineering) to estimate the total dry biomass per sample point and to observe the percentage contribution of different orders in this estimation.

Bat recording and identification

To assess which families of insectivorous bats displayed aversion or attraction for foraging in areas with Artificial Light at Night (ALAN), we recorded echolocation calls using AudioMoth v1.2.0 recorders. These recorders were strategically placed in both the ALAN-exposed areas and dark control areas. The placement of the recorders in lampposts was executed by the CEB team, as illustrated in Figure 3.

In the ALAN-exposed locations, the recorders were positioned directly adjacent to the light sources, typically near the street lamps. Conversely, in the dark control areas, the recorders were mounted on trees at a height of 5 meters, ensuring an unobstructed field of view without branches or leaves that could interfere with the recordings. The AudioMoth recorders were configured to capture echolocation calls for 1 minute followed by a 14-minute pause, resulting in four recording files per hour. These recordings were saved in WAV format with 16-bit resolution and a sampling rate of 384 KHz, in accordance with the approach detailed by Hintze et al.'s (2021).

Recording sessions commenced at 6:00 PM and concluded at 06:00 AM, spanning a total duration of 12 hours. This recording schedule was consistent across all sampling points. Over the course of three months, the recordings and insect collections were conducted once per month at each sampling point. As a result of this meticulous recording setup, a total of 48 audio files were generated per point per night, leading to a grand total of 2,880 files (equivalent to 2,880 minutes of recording) over the three-month period. This comprehensive dataset enabled the subsequent analysis of bat echolocation calls and their association with ALAN exposure.

Figure 3. Bat recorders and window-type interception traps were simultaneously positioned by a team provided by the Brasília Power Company (CEB). They were placed on street lamps (lighted areas) equipped with high-pressure sodium vapor (HPS) lamps. Paired with each of these lighted areas was a dark control area located 500 meters away, creating a sampling site. Collections were conducted for 12 hours on a single night each month, in August and September 2022, and January 2023 (totaling three nights). The sampling sites were distributed across urban areas in Plano Piloto, Núcleo Bandeirante, and Park Way.

Bat calls were manually identified at the family level using the identification guide by Arias-Aguilar et al.'s (2018). The bat calls were visually examined using Raven Pro software, version 1.6.3 (Yang 2023), with three windows displayed simultaneously: one displaying an oscillogram and two displaying spectrograms. The spectrogram windows had the same parameters (Hann window with DFT size: 512 samples and 50% overlap), except for the color and contrast in the second window, which were set to "plasma" and 75%, respectively (the first window used "Jet" color and 50% contrast). Using one of the two windows with these color and contrast parameters facilitated the visualization of the pulses, especially during rainy periods and when the bats were possibly farther away from the recorders. Pulses whose shapes were only clearly visible with higher contrast were compared to the standard window, and their sounds were played back to confirm that they belonged to bats and were not background noise.

The parameters used for family identification based on echolocation calls included maximum and minimum frequency (kHz), peak frequency (kHz), pulse duration (ms), and pulse interval (ms). To estimate bat activity, the number of passes (Fenton 1970) was counted, defined as a minimum of 5 sequential pulses in the search phase followed by a period of ≥1 second of silence (Gilmour et al. 2020; Ramalho et al. 2021). Foraging behavior was determined by counting feeding buzzes, characterized by a sharp increase in pulse repetition rate as bats approached their prey (Griffin et al. 1960).

Data Analyze

To analyze the data, four Generalized Linear Mixed Models (GLMMs) were generated, one for insects and three for bats, along with one Linear Mixed Model (LMM) for insects, using the 'lme4' package (Bates et al. 2015) to test the hypotheses. Due to the repeated collections at the same sampling sites, the sites were included in all models as a random variable.

First, we examined whether the treatment affected the abundance and dry biomass of insects. For this, a null model was constructed containing only the interaction between the random variable and each of the response variables, which were total dry biomass or total insect abundance. Then, the candidate model including the fixed predictor variable treatment (light vs. dark) was inserted and subsequently compared to the null model. GLMM was applied for abundance, with a Poisson distribution (discrete variable), and for total biomass (continuous variable), LMM was adopted. In all these models, fixed and random factors were adjusted by maximum likelihood (Pinheiro and Bates 2000).

Once the interaction between insects and treatment was confirmed, we proceeded to the models with bats to determine which families showed higher or lower activity (number of passes) and foraging (number of feeding buzzes) in areas with ALAN. We also observed whether the increase in these variables was related to higher insect abundance and dry biomass in the light. Thus, higher activity and foraging around the light poles would indicate a behavior of attraction to areas with ALAN, with the intention of using them as feeding habitats.

We decided to use only the abundance variable in the models due to the positive correlation between insect abundance and biomass (Pearson r = 0.75), which were predictor variables in the bat models, and for reasons of redundancy, as both showed the same trends in the treatment. Therefore, the relationship between insect variables and the context of this study allows bat responses to abundance to be interpreted similarly for biomass. We did not include the predictor variables (treatment and insect abundance) together in the bat models because, when they were inserted in this way, the models produced conflicting results due to problems related to unstable estimates generated by multicollinearity between the predictor variables, abundance, and treatment.

Due to the low number of records in the ALAN points for emballonurids (only 1 pass), we did not include this family in the models. For the same reason, only the activity of vespertilionids was modeled, given the absence of foraging by these bats around streetlights. For the models with bats, the treatment as well as the total insect abundance (log-transformed) were considered predictor variables. Foraging and activity were considered response variables (only passes for vespertilionids). To observe whether the treatment and total insect abundance affected bat behavior, leading to attraction or aversion to illuminated areas, the GLMM was structured using the Poisson distribution for activity and foraging.

For each response variable we constructed a null model containing only the random variables. Then, two candidate models were structured, including the treatment or total insect abundance to avoid problems related to multicollinearity. Due to the separate integration of predictor variables into the models, we used the 'AICcmodavg' package (Mazerolle 2019) for the pre-selection of models based on Akaike Information Criterion, corrected for small sample sizes (AICc). The AICc values of the null models for each response variable were compared to the values of their respective candidate models (Burnham and Anderson 2004), with the latter being considered supported only when AICc ≥ 2 compared to the AICc of the null model. Finally, the models supported by AICc had their fixed and random factors adjusted by maximum likelihood (Pinheiro and Bates 2000). All analyses were performed in the R software (R Core Team 2023).

RESULTS

General Data

Of the 2,880 audio files generated, 965 contained echolocation calls. We recorded 2,533 bat passes and 763 feeding buzzes distributed among three families. Out of this total, 1,282 passes and 320 feeding buzzes were observed in the dark treatment, and 1,251 passes and 443 feeding buzzes in ALAN. The Molossidae family was the most recorded (n = 2,275; 89.81%), followed by Vespertilionidae (n = 125; 4.93%) and Emballonuridae (n = 117; 4.61%). Three audio files contained individual passes of the same call type, for which the family was not identified (8 passes). Phyllostomidae was also present in three files (8 passes).

Species from the Molossidae family were the most frequent in the ALAN-treated areas compared to dark areas. There were 1,224 passes and 443 feeding buzzes at the lighted posts, with 1,051 passes and 235 feeding buzzes in the dark areas. Species from the Vespertilionidae and Emballonuridae families exhibited higher activity and foraging in the dark areas, avoiding illuminated areas. Vespertilionidae had 20 passes at the lighted posts compared to 105 passes and 2 feeding buzzes in the dark areas. Emballonuridae also followed this pattern, with 116 passes and 83 feeding buzzes in the dark areas, and a single pass at the lighted posts. No feeding buzzes were recorded in the recordings for these two families at the lighted posts (Table 1; for passes/min and fb/min, refer to Table 2).

Regarding insects, a total of 5,071 individuals were weighed and identified at the order level. In the traps installed at the lighted posts, 4,898 individuals were collected, corresponding to a biomass of 9.7165 grams. In the dark areas, on the tree-positioned traps, 174 individuals were collected, corresponding to 0.2403 grams of the total insect biomass (Table 3). The most captured orders were Hymenoptera, Hemiptera, and Coleoptera. The first accounted for 66.32% of the total biomass with 1,987 individuals; Hemiptera composed 20.33% of the biomass but was the most abundant order, with 2,201 individuals; Coleoptera represented 10.55% of the total biomass, with 315 individuals. Like Coleoptera, the Diptera order was also captured in the hundreds, with 257 individuals; however, its percentage of the total biomass was small (0.27%). The orders Lepidoptera, Blattodea (Isoptera), Psocoptera, Trichoptera, Dermaptera, Neuroptera, Strepsiptera, and Thysanoptera were also sampled (Table 4).

Effects of Artificial Light At Night on Urban Insects and Insectivorous Bats

The abundance of insects significantly differed between locations with and without Artificial Light At Night (ALAN) ($\chi 2=5327.1$, df=1, $p < 0.001$). In public lighting poles, the number of individuals was approximately 28 times higher than in dark locations (Figure 4). The same applies to the dry biomass of insects ($\chi 2=6.7098$, df=1, $p < 0.01$), with a weight 20 times higher in the lighted areas than in the absence of lighting poles. Models with both predictor variables were better fitted than the null model (Table 5), revealing significant differences (Table 6) in the activity (number of passes) of molossids among treatments (χ2=13.168, df=1, p<0.001), which was positively related to locations with ALAN (Figure 5), mainly corresponding (Table 5) to the higher abundance of insects (χ2=84.963, df=1, p<0.001) (Figure 6).

The foraging behavior (number of feeding buzzes) of molossids also differed among treatments (χ2=64,852, df=1, p<0.001), with locations with ALAN displaying the highest foraging values (Figure 7). However, there was no relationship between the total abundance of insects and foraging, as the null model was better fitted than the model including insect abundance (Table 5).

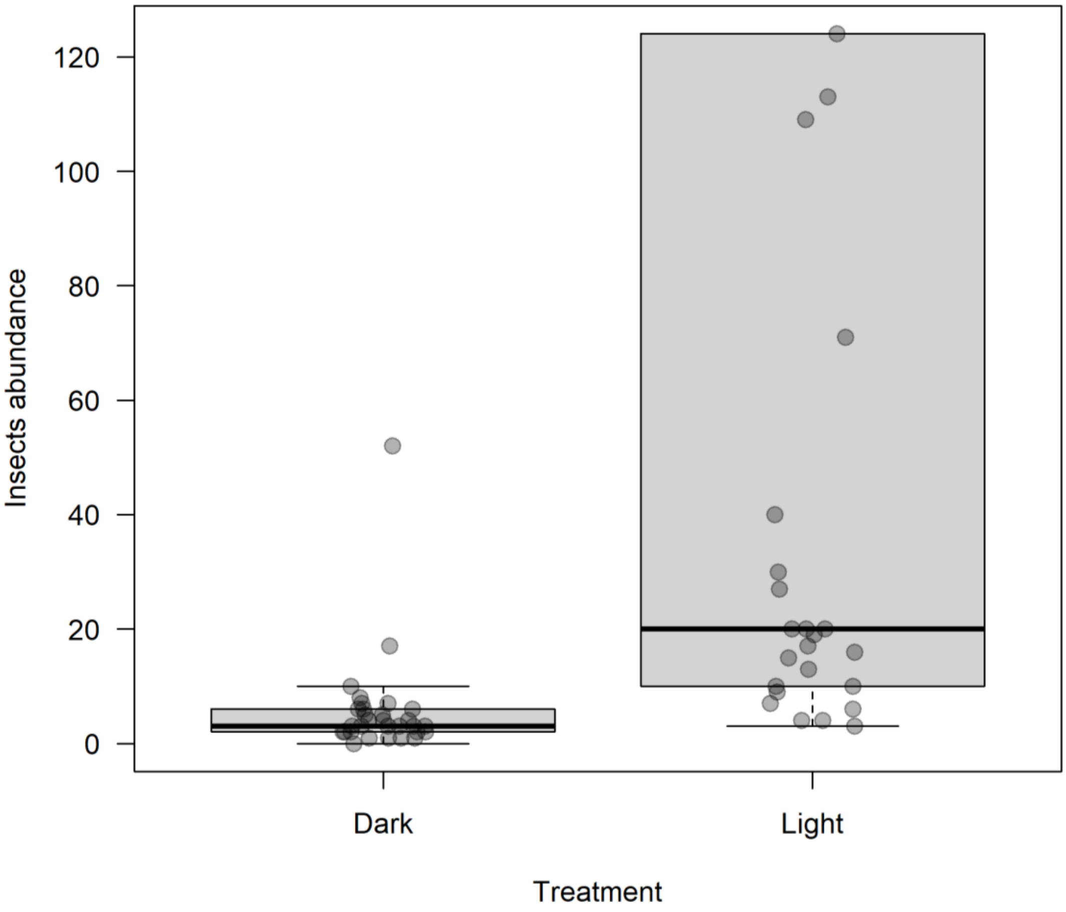

Figure 4. Abundance of insects collected in window-type traps for each treatment (χ2=5327.1, df=1, p <0.001),

which are public lighting poles (light) containing high-pressure sodium vapor lamps (HPS) and dark spots in the city of Brasília, Federal District, located in the Cerrado biome. Transparent circles represent individual collection points for each treatment, and the bars depict maximum and minimum values. Collections were conducted for 12 hours on three nights in the months of August and September 2022 and January 2023 (once in each month).

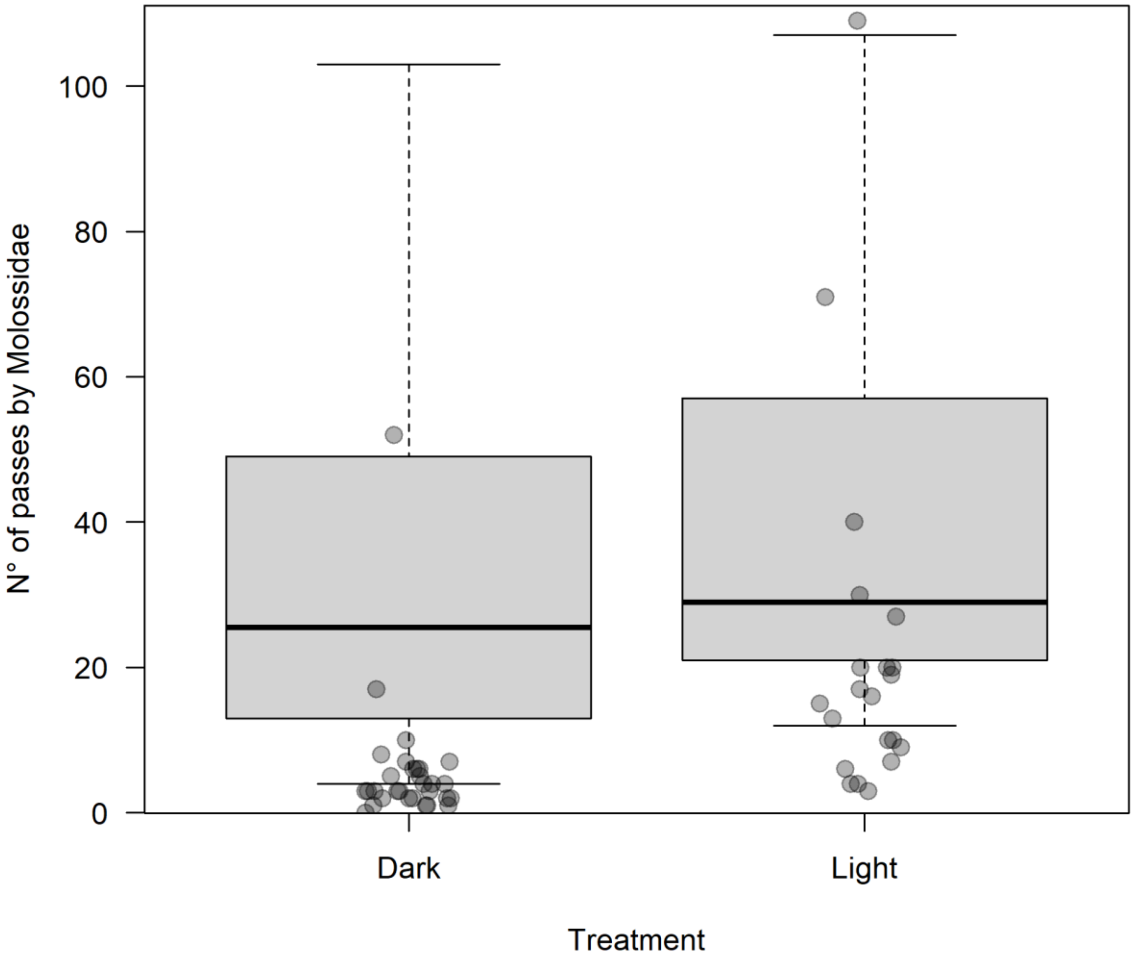

Figure 5. Activity (number of passes) of molossid bats among treatments (χ2=13.168, df=1, p<0.001), corresponding to the recording of bats on public lighting poles (light) with high-pressure sodium vapor lamps (HPS) and in dark areas. Sampling was conducted in the city of Brasília, Federal District, a metropolis located in the Cerrado biome. Transparent circles represent individual collection points for each treatment, and the bars depict maximum and minimum values. Sampling was carried out over three nights in the months of August and September 2022 and January 2023 (once in each month), for a duration of 12 hours each night.

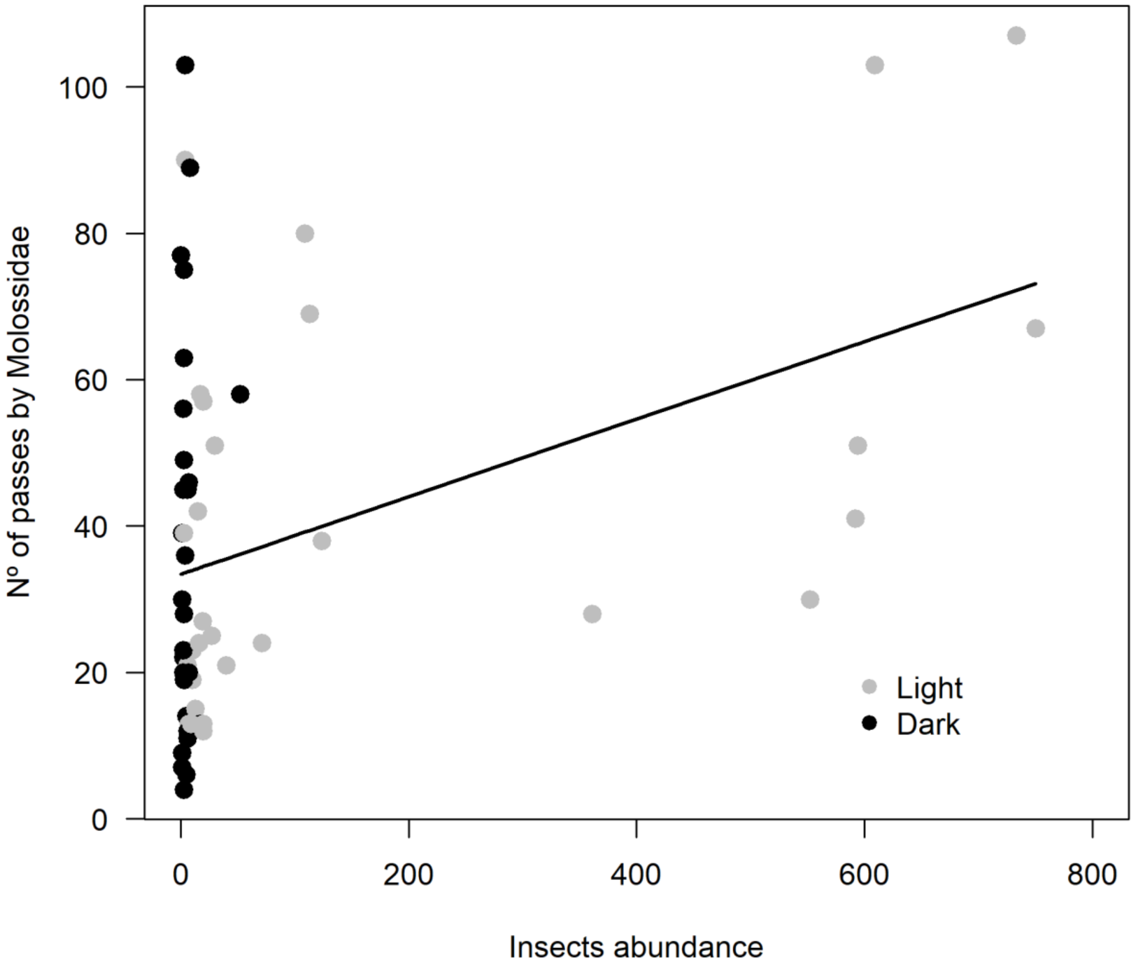

Figure 6. Correlation between the activity (number of passes) of molossid bats and total insect abundance ($\chi2=84.963$, df=1, $p<0.001$), among treatments ($\chi2=13.168$, df=1, $p<0.001$). Circles represent individual collection points for each treatment; gray circles represent collections conducted on public lighting poles (light) with high-pressure sodium vapor lamps (HPS), and black circles correspond to collection points in dark areas, with the solid line representing the trendline. Bat recordings and insect collection were conducted for 12 hours on three nights in the months of August and September 2022 and January 2023 (once in each month) in the city of Brasília, Federal District, located in the Cerrado biome.

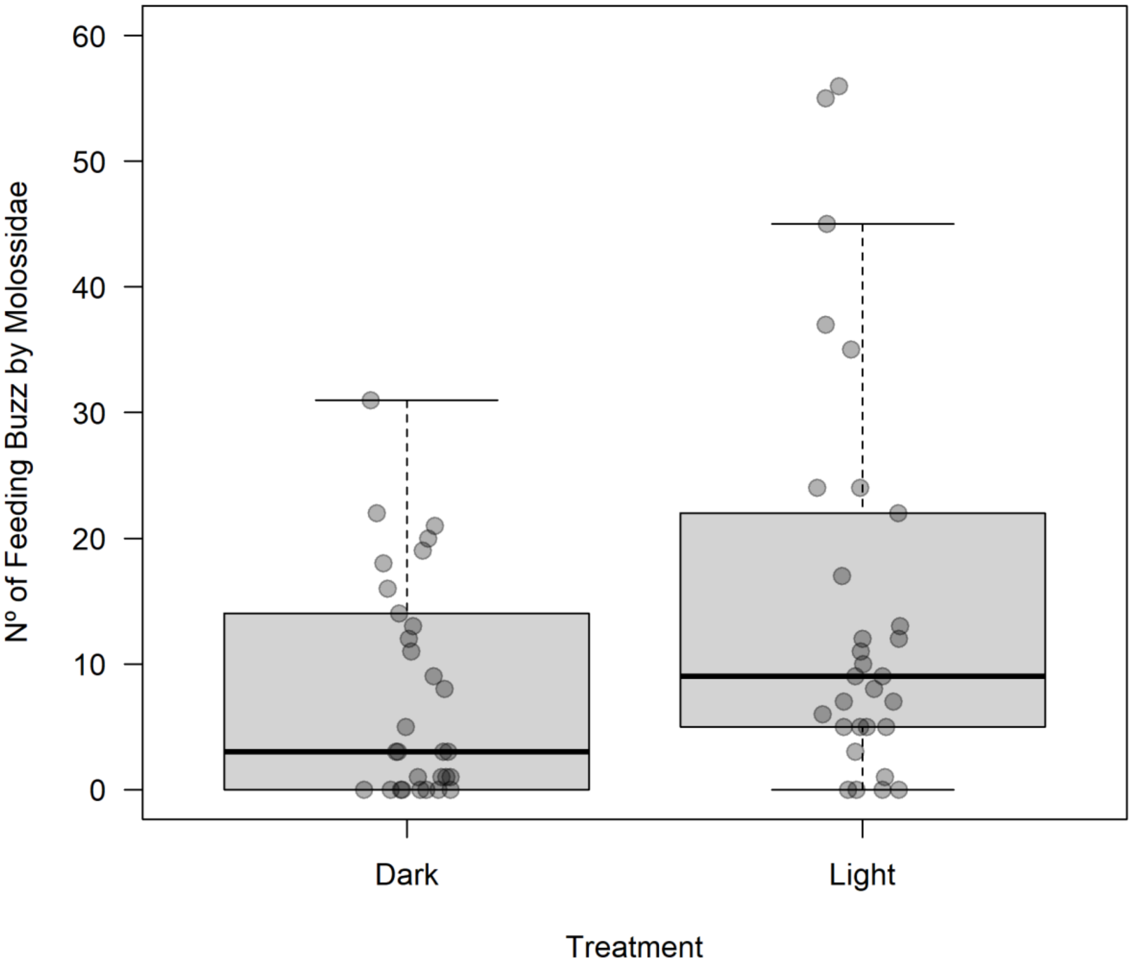

Figure 7. Foraging (number of feeding buzzes) of molossid bats in each of the treatments (χ2=64,852, df=1, p<0.001), corresponding to the recording of bats on public lighting poles (light) with high-pressure sodium vapor lamps (HPS) and in dark areas in the city of Brasília, Federal District, located in the Cerrado biome. Transparent circles represent individual collection points for each treatment, and the bars depict maximum and minimum values. Sampling was conducted over three nights in the months of August and September 2022 and January 2023 (once in each month), for a duration of 12 hours each night.

Finally, models with both predictor variables (treatment or insect abundance) were better fitted than the null model for vespertilionid bats (Table 5). The treatment was found to be significant for activity (χ2=63.369, df=1, p<0.001), indicating an aversion behavior in urban vespertilionid bats towards ALAN (Figure 8). Due to this negative relationship with ALAN, which had higher insect abundances, vespertilionid bat activity, consequently, showed significance ($\chi2=23.907$, df=1, $p<0.001$) and a negative association with insect abundance. Emballonurids also exhibited aversion to ALAN, as only a single pass was recorded by the recorders positioned on light poles (Table 1).

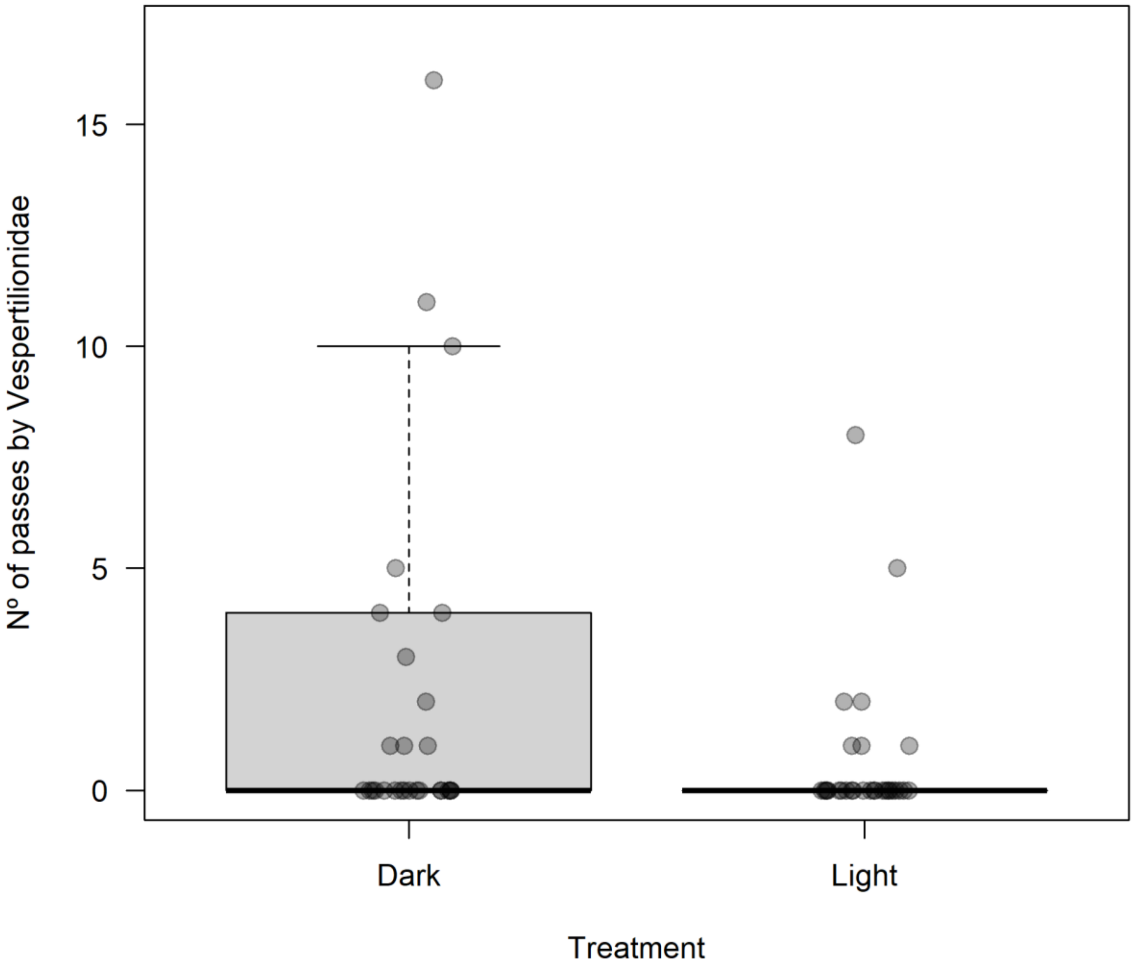

Figure 8. Activity (number of passes) of vespertilionid bats in each of the treatments ($\chi2=63.369$, df=1, $p<0.001$), corresponding to the recording of bats on public lighting poles (light) with high-pressure sodium vapor lamps (HPS) and in dark areas in the city of Brasília, Federal District, located in the Cerrado biome. Transparent circles represent individual collection points for each treatment, and the bars depict maximum and minimum values. Sampling was conducted over three nights in the months of August and September 2022 and January 2023 (once in each month), for a duration of 12 hours each night.

DISCUSSION

Beyond Diet: Attraction and Aversion of Urban Bats to Artificial Light At Night (ALAN)

This is one of the first studies in a Cerrado-urban interface to employ acoustic monitoring for the identification of insectivorous bat families in a neotropical metropolis, either showing aversion to Artificial Light at Night (ALAN) or being tolerant and attracted to it for foraging purposes. As expected, ALAN demonstrated a significant influence on the behavior of insectivorous bats and their prey through the use or avoidance of illuminated areas. However, as indicated in the second hypothesis, it was expected to find bats foraging in edge areas, especially vespertilionids, even if in lower frequencies, using illuminated areas for feeding, a phenomenon observed in other studies in temperate regions (Stone et al. 2015; Voigt et al. 2021) and in the neotropics (Jung and Kalko 2010; Frank et al. 2019).

The Brazilian Cerrado shares the occurrence of bat families and species already documented in areas with ALAN (Jung and Kalko 2010; Aguiar et al. 2016; Nunes et al. 2017; Frank et al. 2019), and probably dietary restrictions, morphology, and reduced dependence on green areas in the Molossidae family confer preadaptation to the use of ALAN in broader contexts than vespertilionids and emballonurids. Even considering the limited distribution of some urban bat taxa that may use ALAN (Stone et al. 2015; Voigt et al. 2021) in different geographical regions (Stevens 2004; Teeling et al. 2005; López-Aguirre et al. 2019), in places where these coexist, molossids have been observed to dominate over vespertilionids in urban centers (Ávila-Flores and Fenton 2005; Li and Wilkins 2014; Krauel and LeBuhn 2016; Rodríguez-Aguilar et al. 2017) and in the use of ALAN (Ávila-Flores and Fenton 2005; Jung and Kalko 2010; Haddock et al. 2019).

The difference in the composition of urban bat families in dark and light areas in our results highlights that not all bats in urban areas tolerate all stressors associated with this environment. Considering that the distance between the sampling points (500 meters) would be easily covered by bats and that the composition of insect orders attracted by ALAN from HPS lamps (Table 3), discussed below, could be consumed by vespertilionids and emballonurids, the evidence suggests aversion behavior in these two families towards ALAN.

The most abundant insect orders in the samples in this study, namely Hemiptera, Hymenoptera, Coleoptera, and Diptera, are consumed and may even make up the majority of the diet of vespertilionid bats in tropical areas (Aguiar et al. 2021), as observed in the genera *Eptesicus*, *Myotis*, and *Lasiurus* (Gnocchi et al. 2019; Giménez et al. 2021). Vespertilionid bats in the Federal District also exhibit this tendency (Aguiar and Antonini 2008).

Few studies have shown the dietary composition of tropical emballonurid species or genera that can occur in urban areas of the Cerrado. Nevertheless, the orders of insects found in this study align with those documented for species belonging to the genera *Saccopteryx* and *Peropteryx* (García et al. 2011; Batista 2018; Cruz-Parrado et al. 2018; Vivas-Toro and Mendivil-Nieto 2022), demonstrating that Hymenoptera, Coleoptera, Hemiptera, and Isoptera make up the majority of the diet of these species, which are part of the sampled families.

Additionally, none of the three collection months (dry in August and rainy in late September and January) vespertilionids and emballonurids were observed foraging in ALAN (Table 1). This indicates that neither the availability nor the abundance of consumable insect orders (Table 3), which are more abundant in the rainy season in the Cerrado (Pinheiro et al. 2002; de Oliveira and Frizza 2008; Silva et al. 2011), led these bats to forage on light poles.

Nevertheless, it is possible that the vespertilionid and emballonurid species sampled have dietary preferences for orders that were not attracted by HPS lamp light, such as Orthoptera, Odonata, and Mantodea (Kalcounis-Rueppell et al. 2007; Aguiar and Antonini 2008; Aguiar et al. 2021). Or that were attracted, but in smaller proportions, such as Lepidoptera, Trichoptera and Neuroptera (Table 3) (Aguiar and Antonini 2008; Aguiar et al.

2021; Alurralde and Dias 2021; Giménez et al. 2021).

Most insects, such as lepidopterans, are more attracted to mercury vapor lamps than HPS lamps (Barghini and Souza de Medeiros 2012), where higher activities of neotropical vespertilionids and emballonurids have been observed (Frank et al. 2019). However, genera of vespertilionids in temperate regions that also occur in the neotropics have been observed using the type of lamps sampled in this study for foraging (Rydell 1992). Furthermore, molossids in the Federal District can also constitute a major part of their diet with lepidopterans (Aguiar et al. 2021), but still foraged on light poles in this study.

Moreover, the type of insect trap used, originally designed for collecting Coleoptera (Murari et al. 2012), may have reduced the capture of larger insects and certain orders, such as lepidopterans. Therefore, there is a possibility that HPS ALAN attracted higher abundances of some orders (especially lepidopterans) than recorded in our traps. However, even if these traps collected an underestimated number of insects compared to what HPS ALAN is capable of attracting, the argument that vespertilionids and emballonurids avoided light for other reasons is still supported.

If HPS ALAN attracts even higher values of consumed orders than documented, the assumption that both bat families lack interest in consuming insects found on light poles is not corroborated. Therefore, given that the insect orders found, which were most abundant on light poles, are important elements of the diet of vespertilionids and emballonurids, the hypothesis of increased predation risk in ALAN, rather than a lack of interest in the attracted insects, seems to be a more viable explanation. This behavior of aversion is evident in our results.

Nevertheless, dietary comparisons between species with broad geographical distributions can be biased, as dietary preferences can vary based on the distribution of specific insect groups in different environments and seasons (Willig et al. 1993; Aguiar and Antonini 2008; Aguiar et al. 2021; Alurralde and Diaz 2021). It is possible that dietary differences are better understood by comparing species that occur together in the same habitat, as has been done for some bat genera and families in different parts of the world (e.g., Gordon et al. 2019; Aguiar et al. 2021; Alurralde and Diaz 2021)

Unlike vespertilionids and emballonurids, molossid bats are attracted to lighting poles containing HPS lamps for foraging. In illuminated areas, insect abundance was higher, and the intense molossid activity around public lighting poles reflects this abundance, motivating bats to frequent these areas more often in cities, seeking larger quantities of food. Amidst the variety of orders and the abundance of insects attracted by ALAN (Table 3), public lighting poles offer a unique scenario: the opportunity to consume various types of prey concentrated in a small area, reducing the energy costs associated with foraging in a fragmented space, such as in cities.

However, the relationship between increased foraging in areas with ALAN and higher insect abundance around light poles may be more complex, as there was no correlation between these two variables in the light, something seen in a similar way in other studies (e.g., Lee and McCracken 2002; Ávila-Flores and Fenton 2005). ALAN emitted by HPS lamps attracts orders of insects that are part of molossids diet (Willig et al. 1993; Gnocchi et al. 2019; Aguiar et al. 2021), but insectivorous bats may have specific preferences for subsets of prey (Ramírez-Chaves et al. 2008; Breviglieri and Esbérard 2018), which are identifiable only at the family and species levels (Aguiar et al. 2021) and may vary with seasonality (Willig et al. 1993; Agosta et al. 2003; Akasaka et al. 2009; Andreas et al. 2012; Mata et al. 2016).

Therefore, the preferred prey types for molossids may have been attracted in smaller numbers to public lighting (Barghini and Souza de Medeiros 2012), may have exhibited seasonal periods of dispersion, common for insects in the Cerrado (Pinheiro et al. 2002; de Oliveira and Fizza 2008; Silva et al. 2011), becoming available around the lamps during specific periods, and/or may have varied vertically (Chapman et al. 2004; Krauel et al. 2018). Consequently, the number of less interesting prey for molossids may have contributed to a more significant increase in total abundance, and thus, foraging did not respond to overall insect abundance.

Hence, the attraction that molossids exhibited for foraging in areas with ALAN may have been influenced by a combination of factors, such as reduced search time for prey and the opportunity to selectively capture groups of insects (Minnaar et al. 2015; Cravens et al. 2018; Manfrin et al. 2018), even if they are in smaller quantities compared to other orders in the light. Consequently, the relationship between predator activity and prey abundance in such contexts can be intricate, and insect abundance alone does not fully explain the foraging behavior of molossids in ALAN. Additional research on the dietary preferences of bat species belonging to the three sampled families, especially at the local scale, is necessary to better understand this dynamic.

Are molossids preadapted to use ALAN in an urban setting within the Cerrado?

Among the three families of insectivorous bats sampled, only the molossids foraged and exhibited greater activity around light poles, while vespertilionids and emballonurids restricted themselves to dark areas. Molossid bats have specialized adaptations for foraging and capturing insects that fly high in open areas, equipped with high speed (Vaughan 1966; Norberg et al. 1987; Gardiner et al. 2011; Jung et al. 2014; Denzinger et al. 2018), as well as high acoustic (Mora et al. 2004; Jung et al. 2014; Oliveira et al. 2018) and behavioral plasticity (Santini et al. 2019; Ávila-Flores et al. 2023). These characteristics make this family the most successful group of mammals among urban exploiters, comprising more than two-thirds of the species found in cities worldwide (Santini et al. 2019).

The traits related to the adaptation of this family to their natural environments may have conferred preadaptation to urban areas, as well as the opportunistic use of artificial night light for foraging (Ávila-Flores and Fenton 2005; Jung and Kalko 2010; Jung and Threlfall 2016, 2018; Ávila-Flores et al. 2023). Therefore, the use of ALAN by urban molossids in the Cerrado, unlike vespertilionids and emballonurids, is likely due to the presence of the mentioned traits, in addition to their natural tolerance for foraging in brighter conditions (Holland et al. 2011; Saldaña-Vázquez and Munguía-Rosas 2012; Vásquez et al. 2020; Mena et al. 2022; Ávila-Flores et al. 2023a), found in this bat family (Ávila-Flores et al. 2023).

However, it is worth noting that the responses of molossids may depend on other factors, such as moon phases and microhabitats (Jung and Kalko 2010), types of lighting (Frank et al. 2019; Barré et al. 2023), and landscape composition (Li and Wilkins 2022; Barré et al. 2022). Therefore, we should not disregard the negative effects that ALAN can have on species of this family (Mena et al. 2022), or how light in different contexts and configurations may harm bats that have been identified as using ALAN (Kerbiriou et al. 2020).

In contrast to molossids, in this study, vespertilionids and emballonurids exhibited aversion to ALAN, showing negative effects in the presence of HPS lamps, contrary to what was expected in the second hypothesis. As mentioned, the insect orders collected can be consumed by vespertilionids and emballonurids. Therefore, as suggested by the hypothesis of predation risk in ALAN (Ávila-Flores and Fenton 2005; Jung and Kalko 2010; Stone et al. 2015; Haddock et al. 2019), the groups sampled in both families in our study may have a more general wing morphology for the group, with greater maneuverability but limited speed (Findley et al. 1972; Norberg et al. 1987), which could make foraging in lighted areas dangerous.

The higher lunar aversion observed in tropical vespertilionids and emballonurids (Saldaña-Vázquez and Munguía-Rosas 2013), and the high diversity of predatory birds in these regions (Lima and O'Keefe 2013; De Piacentini et al. 2015), also suggests greater risks in using illuminated areas for these two groups. Additionally, the occurrence of these families is reduced in human-disturbed environments (García-Morales et al. 2013; Gonçalves et al. 2017; Rodríguez-Aguilar et al. 2017), and the use of ALAN by these bats is usually associated with small towns surrounded by forested environments (Jung and Kalko 2010; Frank et al. 2019), which can mitigate the "light spill" and reduce its negative effects on more sensitive species (Mathews et al. 2015; Straka et al. 2019).

Despite the existence of native and exotic trees (GDF 2019), Brasília is a metropolis with 2,817,068 people (IBGE 2022), characterized by low, spaced buildings, similar to the open areas of the Cerrado (Eiten 1972), the biome in which the city is situated. This type of landscape may make the urban environment in Brasília more suitable for molossids but more exposed for vespertilionids and emballonurids. The many roads, open areas with little vegetation where humans and cars traverse, are also locations where streetlights are typically associated, which possibly do not create a safe enough scenario for these families to forage in the light.

Flying in such circumstances can be dangerous for bats with slow and low-altitude flight, as they risk being hit by vehicles, disturbed by people, or preyed upon by urban nocturnal birds. However, there is also the possibility that vespertilionids and emballonurids restrict themselves to dark areas because they cannot compete with molossids for the use of illuminated areas in Brasília (Arlettaz et al. 2000; Polak et al. 2011; Salinas-Ramos et al. 2021). Additionally, there was a low emission of feeding buzzes by Vespertilionidae in dark zones (Table 1), indicating that these bats possibly do not use urban areas as habitats primarily for foraging.

Even though bats of this family can shelter in buildings and urban trees (Kervyn and Libois 2008; Almeida et al. 2011), vespertilionids have been observed crossing urbanized areas towards forested and agricultural sites for foraging, preferring these environments over urban ones (Duchamp et al. 2004). These habitats have been recorded as having higher insect abundances and diversity than cities (Lee and McCracken 2002; Ávila-Flores and Fenton 2005;

Lagucki et al. 2017).

Moreover, dark-edge-urban areas, marking the intersection between illuminated urban zones and vegetated areas, may have lower insect abundance compared to the interior of preserved areas and illuminated spaces in urban centers (Jung and Kalko 2010), potentially reducing the attractiveness of these regions as feeding areas for vespertilionids. The low emission of feeding buzzes by these bats may be linked to the reduced availability of food in these dark-edge-urban areas, as the street lamps that line these locations can create a 'vacuum effect' (Eisenbeis et al. 2009; Stone et al. 2015; Owens and Lewis 2018), attracting insects from surrounding dark areas to ALAN and consequently depleting the food resources for these bats in these spaces.

This leads to the inference that, in urban areas, the locations with sufficient food resources for these bats are likely very dispersed and primarily limited to urban parks (Ávila-Flores and Fenton 2005). The sites sampled in this study were close to urban parks, such as Parque Olhos D'água in Asa Norte (in Plano Piloto), Parque Ezechias Heringer in Núcleo Bandeirante, and Fazenda Água Limpa in Park Way. This makes it plausible that Vespertilionidae use the dark areas of the city as corridors to move between patches of parks, as they have a preference for preserved habitats (García-Morales et al. 2013; Gonçalves et al. 2017; Rodríguez-Aguilar et al. 2017) and likely prefer cavities in large trees as roosts (Kunz 1992).

Therefore, it is concluded that the success of urban molossids, particularly in a metropolis rich in ALAN in the Cerrado, unlike vespertilionids and emballonurids, arises from less dependence on preserved areas, in conjunction with preadaptive characteristics that enable them to navigate and opportunistically use illuminated urban landscapes. This may serve as a warning regarding the reduction in bat diversity caused by ALAN, especially related to biotic homogenization (McKinney 2006; Sander et al. 2023), as the occurrence of more specialized bat species, which are normally the most sensitive (McKinney and Lockwood 1999; Luniak 2004; Jung and Threlfall 2018; Wolf et al. 2022), may be further reduced in urban spaces when illuminated (Schoeman et al. 2016; Russo et al. 2019; Seewagen and Adams 2021).

The benefit of urban molossids from ALAN, in comparison to other families, may thus be leading to an increase in the occurrence and distribution of molossids in the Cerrado, while reducing that of vespertilionids and emballonurids (Arlettaz et al. 2000; Polak et al. 2011; Cravens and Boyles 2019; Seewagen et al. 2023). Therefore, our results provide insights into the responses of bats to urbanization and artificial lighting and how this may be simplifying the composition of insectivorous bats in illuminated urban environments, through the competitive advantage offered by ALAN to molossids.

Implications for the Management and Conservation of Urban Bats

The bat families analyzed here exhibit significant differences in the use of illuminated areas during movement and foraging in cities. Notably, molossids appear to be preadapted to survive in urban environments and actively forage around light poles equipped with HPS lamps. However, this adaptability does not extend to vespertilionids and emballonurids, which, although present in urban areas, avoid moving and foraging in locations with ALAN. It can be concluded that some species within these families are tolerant of urbanization but intolerant of light pollution, something that can affect the performance of ecosystem services in cities.

Insectivorous bats can play a crucial role in suppressing pest insects in urban environments (Russo et al. 2023), and the reduction in the diversity of these bats in cities can affect the dynamics of disease transmission, where synanthropic insects act as vectors, thereby increasing the exposure of the urban population to diseases (Moore et al. 2010; Russo et al. 2023). With fewer natural predators to control pests in cities, there may be an increase in the use of insecticides, leading to a reduction in the quality of life and health of the human population due to the toxicity of these compounds (Rani et al. 2021). For example, Aguiar et al.' s (2021) observed that four out of five species of urban bats in the Federal District consume synanthropic insects, especially species of bats that have been documented on public streetlights by Jung and Kalko (2010). This suggests that these bats may play a crucial role in mitigating urban pests.

Therefore, human populations residing in regions with lower socioeconomic levels, with less access to pest control services provided by insectivorous bats, may suffer from increased exposure to potential disease vectors (LaDeau et al. 2013). This can occur due to the local increase in conditions favorable for the propagation of vector insects, as well as the limited access of some bats to these areas (Li and Wilkins 2014; Li et al. 2019), as regions with low socioeconomic levels often have low vegetation levels (Avelar et al. 2009; EEA 2022; Viinikka et al. 2023), reducing the chances of vespertilionids and emballonurids occurring (Li et al. 2019).

Considering that this study was conducted in some of the most vegetated regions of the city, it is possible that emballonurids and vespertilionids do not occur in many of the administrative regions of the Federal District. These families have preferences for preserved habitats (Silva de Araújo and Bernard 2016; Nunes et al. 2017), which offer more shelter and feeding locations (Kunz 1992), especially if they are more selective regarding roosting and foraging sites (Jung and Threlfall 2018).

Additionally, the global replacement of traditional streetlight bulbs with more energy-efficient technologies that increase brightness and color perception for the human eye (Knight 2010; Gaston et al. 2012) is also a concerning issue. This may alter the current balance of species interactions (Grubisic and van Grunsven 2021), harming molossids by reducing attraction and/or changing the composition of insects around the streetlights, reducing their foraging areas in cities (Lewanzik and Voigt 2017; Haddock et al. 2019a; Kerbiriou et al. 2020). Therefore, the results of this study are also essential for future behavioral comparisons when a significant portion, if not all, of the Federal District is illuminated by LED lamps.

In light of the discussed observations, we suggest that the integrated use of green and dark areas in cities (Straka et al. 2019), along with light regimes (Azam et al. 2015; Pauwels et al. 2021) and strategic use of different types of lamps (Barré et al. 2023), should be considered in urban management plans to conserve insectivorous bats. As mentioned earlier, these bats are essential for ecosystem functioning (Kalka et al. 2008; Brasileiro et al. 2022), and the decline in their populations can compromise the services they provide (Williams-Guillén et al. 2008; Boyles et al. 2013; Aguiar et al. 2021; Russo et al. 2023), which would also harm humans.

It is equally important to conduct research that seeks to assess the impact of ALAN on populations and communities of Brazilian insects, as in just three nights of collection on 10 streetlights, we sampled 4,898 individuals (including a rare order like Strepsiptera). This value leads to reflection on the impact that constant nighttime lighting, especially when considering the extent of ALAN in cities, may be having on insects.

In conclusion, HPS ALAN in the Cerrado alters the behavior of chiropterans, reducing the occurrence of insectivorous bat families in illuminated areas of the city. For vespertilionids and emballonurids, the absence of foraging in ALAN is due to an aversion response to illuminated areas, probably driven by high predation risks, in addition to a metropolis (a more disturbed environment than villages) with a structure resembling open Cerrado areas. Therefore, these bats do not avoid ALAN due to a lack of interest in food items attracted to streetlights, as the collected orders make up the diet of bats from these families. Thus, we have demonstrated for the first time that urban molossids in the Brazilian Cerrado are the only bats foraging in ALAN, and they do so for reasons that are not limited to the total abundance of insects in the light.

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TABLES

Table 1. Activity (number of passes) and foraging behavior (number of feeding buzzes) of bat families recorded by AudioMoth recorders in each treatment at sampling sites (paired points). The sites were distributed throughout Brasília, Federal District, a metropolis located in the Cerrado biome. Two recorders were placed at each site: one was positioned near high-pressure sodium vapor lamps (HPS) on public lighting poles (light treatment), and the other on trees located in dark areas. Collections were conducted for 12 hours on three nights in August and September 2022 and January 2023 (once each month). The sites were established in three administrative regions of Brasília, namely Plano Piloto (1 to 5), Núcleo Bandeirante (6 and 7), and Park Way (8 to 10).

ORDER	**MOLOSSIDAE**				**VESPERTILIONIDAE**				**EMBALLONURIDAE**					
	N° passes		N° Feeding buzzes		N° passes		N° Feeding buzzes		N° passes		N° Feeding buzzes		TOTAL	
Treatmet **Sites**	Light	Dark	Light	Dark	Light	Dark	Light	Dark	Light	Dark	Light	Dark	*N° passes	N° Feeding buzzes
1	155	65	51	22	0	0	0	0	0	94	0	75	314	148
2	155	159	34	41	6	0	0	0	0	0	0	0	320	75
3	63	72	63	11	0	26	0	0	0	0	0	0	161	74
4	207	133	60	48	2	13	0	0	0	12	0	7	367	115
5	79	104	60	23	0	1	0	0	0	0	0	0	184	83
6	68	163	30	23	0	15	0	0	0	10	0	1	256	54

7	170	127	31	33	3	42	0	2	1	0	0	0	343	66
8	64	38	17	1	0	0	0	0	0	0	0	0	102	18
9	114	94	22	10	1	6	0	0	0	0	0	0	215	32
10	149	96	75	23	8	2	0	0	0	0	0	0	255	98

*Family passes that are not of interest in this study were not included. Specifically, there were 8 passes from filostomid bats, with 2 passes recorded at site 5 and 6 passes at site 10. Additionally, there were 8 passes from a bat whose pulse parameters did not match those provided in the identification key by Arias-Aguilar et al. 2018. These instances occurred with 3 passes recorded at site 1 and 5 passes at site 2. These excluded passes do not pertain to the families of primary focus in this analysis.

Table 2. Relative activity and foraging behavior (Passages/min and Feeding Buzzes (FB)/min, over 3 nights) of urban insectivorous bat families recorded in each treatment. The treatment corresponds to the comparison between bat records at public lighting poles (light) containing high-pressure sodium vapor lamps (HPS) in relation to dark areas. Records were conducted for 12 hours on three nights in August and September 2022 and January 2023 (one night in each month) in the city of Brasília, Federal District, located in the Cerrado biome. Emballonurids and vespertilionids did not forage in areas with light poles (light) in the city (NA).

Family	**Pass/min Light**	**Pass/min Dark**	**FB/min Light**	**FB/min Dark**
Molossidae	0.56	0.48	0.20	0.10
Emballonuridae	0.0004	0.05	NA	0.03
Vespertilionidae	0.009	0.04	NA	0.0009
TOTAL	0.57	0.59	0.20	0.13

Table 3. Abundance and total dry biomass, by order, of insects collected in window-type flight interception traps in each of the treatments in the city of Brasília, Federal District, a metropolis located in the Cerrado biome. The window-type traps were placed near high-pressure sodium vapor lamps (HPS) on public lighting poles (light) and on trees located in dark areas. Collections were carried out for 12 hours on three nights in August and September 2022 and January 2023 (once in each month)

Order	**Light Abundance**	**Dark Abundance**	**Light Biomass (g)**	**Dark Biomass (g)**
Hymenoptera	1946	41	6.5215	0.082
Hemiptera	2191	10	1.0296	0.0014
Coleoptera	300	15	1.0103	0.0406
Blattodea (Isoptera)	78	49	0.88	0.076
Lepidoptera	68	11	0.2495	0.0289
Diptera	218	39	0.0171	0.0105
Trichoptera	14	0	0.0037	0
Psocoptera	5	7	0.001	0.0009
Neuroptera	1	0	0.0015	0
Dermaptera	1	0	0.002	0
Strepsiptera	2	0	0.0003	0
Thysanoptera*	74	1	-	-
TOTAL	4.898	173	9.7165	0.2403

* Thysanoptera, even in quantities equal to or greater than 10 individuals per sampling point, did not register a measurable weight on the precision balance to four decimal places.

Table 4. Total abundance of insects collected, by order and treatment, at each of the sampling sites (paired points), using window-type flight interception traps. The sites were distributed throughout the city of Brasília, Federal District, a metropolis located in the Cerrado biome. The traps were positioned adjacent to high-pressure sodium vapor lamps (HPS) on public lighting poles (lighted - L) and on trees located in dark areas (D). Collections were conducted for 12 hours on three nights in the months of August and September 2022 and January 2023 (once each month). The sites were established in three administrative areas of Brasília, namely, Plano Piloto (sites 1 to 5), Núcleo Bandeirante (6 and 7), and Park Way (8 to 10). The following orders were collected: Hymenoptera (HY); Hemiptera (HE); Coleoptera (CO); Lepidoptera (LE); Diptera (DI); Blattodea/Isoptera (BL); Trichoptera (TR); Neuroptera (NE); Thysanoptera (TH); Dermaptera (DE); Strepsiptera (ST); Psocoptera (PS).

ORDER	**HY**		**HE**		**CO**		**LE**		**DI**		**BL**		**TR**		**NE**		**TH**		**DE**		**ST**		**PS**		**TOTAL**	
Treatment Sites	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D
1	251	4	326	0	7	0	1	2	8	1	1	0	0	0	0	0	17	0	0	0	0	0	1	0	612	7
2	335	3	211	2	38	3	13	0	14	2	19	49	0	0	0	0	25	0	0	0	0	0	0	1	655	60
3	41	6	58	1	12	2	4	5	34	4	1	0	0	0	0	0	0	0	0	0	0	0	1	0	151	18
4	444	3	280	1	19	2	7	0	14	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	765	7
5	174	1	390	1	6	0	2	0	9	2	1	0	0	0	1	0	31	0	0	0	0	0	2	1	616	5
6	82	0	210	1	70	2	7	1	34	6	1	0	6	0	0	0	0	1	0	0	0	0	1	2	411	13
7	44	6	61	2	10	4	2	0	22	2	2	0	1	0	0	0	0	0	0	0	0	0	0	1	142	15
8	106	4	422	0	17	1	10	0	20	1	0	0	1	0	0	0	1	0	0	0	1	0	0	2	578	8
9	417	8	187	1	107	0	20	2	43	9	50	0	6	0	0	0	0	0	0	0	1	0	0	0	831	20
10	52	6	46	1	14	1	2	1	20	11	3	0	0	0	0	0	0	0	0	0	0	0	0	0	137	20

Table 5. Results of model selection for modeling the activity (passes) and foraging behavior (feeding buzzes) of insectivorous bats, indicating the predictive variables utilized in the models. K = number of estimated parameters; AICc = Akaike Information Criterion for small sample sizes; ΔAICc = difference between the AICc of the specific model and the lowest AICc (Burnham & Anderson 2002). AICcWt = Akaike weight, representing the relative probabilities of each model being the best model to describe the data; Cum.Wt = cumulative weights assigned to the models during selection using AICc; LL: Log-Likelihood, logarithmic likelihood function indicating the degree of fit of a model. The selected models (AICc ≥ 2) are denoted with an asterisk (*). Insect and bat data were collected in the months of August and September 2022 and January 2023 in Brasília, Federal District, a metropolis located in the Cerrado biome. The treatment corresponds to the comparison of data collected in dark areas relative to areas with Artificial Light at Night (ALAN - lighted).

Modelos com GLMM	**K**	**AICc**	**ΔAICoc**	**AICcWt**	**Cum. Wt**	**LL**
Total Insect Abundance~ (1|Sample Sites)[a]	2	14081.75	5518.86	0	1	-7038.77
Total Insect Abundance~ Treatment+(1|Sample Sites)*	3	8562.88	0.00	1	1	-4278.23
Molossids Passes~ (1|Sample Sites)[a]	2	1168.63	82.74	0	1	-582.21
Molossids Passes ~Treatment+(1|Sample Sites) *	3	1157.68	71.79	0	1	-575.63
Molossids Passes~ log(Total Insect Abundance +1) + (1|Sample Sites)*	3	1085.89	0.00	1	1	-539.73
Molossids Feeding Buzzes~(1|Sample Sites) [a]	2	933.72	62.63	0	1	-464.75
Molossids Feeding Buzzes ~Treatment+(1|Sample Sites)*	3	871.08	62.07	1	1	-432.33

Molossids Feeding Buzzes~log (Total Insect Abundance+1) + (1|Sample Sites)	3	933.15	0.00	0	1	-463.36
Vespertilionids Passes~(1|Sample Sites)[a]	2	372.91	61.15	0	1	-184.35
Vespertilionids Passes~Treatment +(1|Sample Sites)*	3	311.76	0.00	1	1	-152.76
Vespertilionids Passes~ log(Total Insect Abundance +1) +(1|Sample Sites)*	3	351.22	39.46	0	1	-172.40

Modelos (LMM)	**K**	**AICc**	**ΔAICc**	**AICcWt**	**Cum. Wt**	**LL**
Total Insect Biomass ~1+(1|Sample Sites)[a]	2	90.31	4.41	0.1	1.0	-41.94
Total Insect Biomass ~Treatment+(1|Sample Sites)*	3	85.90	0.00	0.9	0.9	-38.58

[a] In the null models, the response variables are modeled solely based on the random effect, which is the same for all models (1|Sample Sites).

Table 6. Models supported by AICc (≥ 2), adjusted by maximum likelihood (fixed and random factors), and associated precision measures, including chi-square, degrees of freedom (df), and p-value. The treatment (light vs. dark) had a significant effect on the total abundance and dry biomass of insects in urban areas of Brasília, Federal District, located in the Cerrado biome. Total insect abundance and treatment were relevant to the total activity (passes) of molossids and vespertilionids in the cities. However, only the treatment was significant for the foraging behavior (feeding buzzes) of molossids. Bat and insect data were collected over three nights, for 12 hours each night, in August and September 2022 and January 2023 (once per month).

Models	**χ2**	**df**	**p-value**
Total Insect Abundance~ Treatment+(1|Sample Sites)	5327.1	1	<0.001
Total Insect Biomass~ Treatment+(1|Sample Sites)	6.7098	1	<0.01
Molossids Passes~Treatment +(1| Sample Sites)	13.168	1	<0.001
Molossids Passes~ log(Total insect abundance+1)+(1| Sample Sites)	84.963	1	<0.001
Molossids Feeding Buzzes~ Treatment+(1| Sample Sites)	64.852	1	<0.001
Vespertilionids Passes~ Treatment +(1| Sample Sites)	63.369	1	<0.001
Vespertilionids Passes~ log(Total Insect Abundance+1)+(1| Sample Sites)	23.907	1	<0.001