Published by Associazione Teriologica Italiana
Hystrix, the Italian Journal of Mammalogy
Volume 36 (1): 36–40, 2025
OPEN ACCESS
Available online at:
http://www.italian-journal-of-mammalogy.it
doi:10.4404/hystrix-00787-2024

Research Article

Stormwater ponds along major roads enhance bat species richness and activity

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Keywords:
biodiversity conservation
road ecology
habitat use
artificial water bodies
motorway ecology

Article history:
Received: 9 March 2025
Accepted: 25 June 2025

Acknowledgements
We thank the two anonymous referees for their numerous critical and useful comments on previous drafts of this paper. This research was supported by the University of Siedlce, Poland.

Abstract

Road infrastructure significantly impacts ecosystems, with road-associated environmental changes posing challenges to biodiversity conservation. However, certain elements of road infrastructure may offer unintended ecological benefits. In this study, we assessed the role of stormwater ponds located along motorways and expressways in eastern Poland as habitats for bats. We compared bat species richness and echolocation activity between sites with (38) and without (33) these artificial water bodies. Bats were detected at 83.1 % of the surveyed sites, with six species recorded, the most common being Cnephaeus serotinus and Nyctalus noctula. Species richness and echolocation activity were both positively associated with pond surface area, while other habitat variables had no significant effect. The results suggest that stormwater ponds may enhance bat presence by providing drinking water, increased insect abundance, and open foraging space. Nevertheless, such ponds may also pose risks due to their proximity to roads, potentially creating ecological traps and increasing the likelihood of bat–vehicle collisions. Future research should evaluate mortality rates, seasonal dynamics, insect availability, and water quality to better understand the dual role of stormwater ponds as both resources and potential hazards. Our study highlights the importance of integrating artificial water bodies into conservation planning to enhance biodiversity within road-dominated landscapes.

Introduction

Road infrastructure plays a crucial role in driving socio-economic growth and development (Palei, 2015). A lack of well-developed infrastructure can significantly hinder economic progress. Furthermore, an even distribution of infrastructure contributes to balanced regional development and reduces socio-economic disparities between states and regions (Zhang et al., 2017). Current global estimates suggest that there are approximately 21.6 million kilometers of roads globally, with projections indicating a further 14–23 % increase in road length by 2050. Most of this expansion is expected in Africa, South and East Asia, and South America (Meijer et al., 2018). Alarmingly, much of the projected growth is expected in biodiversity hotspots such as the Amazon Basin, where road construction frequently coincides with logging and land conversion, leading to forest fragmentation and ecological degradation (Laurance et al., 2014). In Brazil alone, the Amazon road network expanded by nearly 17.000 kilometers per year between 2004 and 2007 (Fraser, 2014). Among various types of road infrastructure, highways and expressways are particularly significant due to their role in facilitating rapid transportation and connectivity (Lewis, 1997; Alcock et al., 2012).

However, road construction and use entail considerable environmental costs, posing significant ecological threats. Increased emissions of greenhouse gases, air pollutants such as carbon dioxide and nitrogen oxides, along with fine particulate matter, contribute to climate change and human health problems (Banister et al., 2011; Stanley et al., 2011). Beyond their impact on humans, roads also profoundly affect wildlife populations, making them one of the most pressing contemporary conservation concerns (Trombulak and Frissell, 2000; Benítez-López et al., 2010). Roads lead to habitat loss and fragmentation, as well as pollution through light, noise, and chemicals contaminants, altering animal movement patterns and population dynamics (Coffin, 2007; Goosem, 2007; Barbosa et al., 2020). Perhaps the most conspicuous and direct consequence for wildlife is vehicle collisions (Orłowski, 2008; Pagany, 2020). For example, in North America, badgers (*Taxidea taxus*) have been observed using road corridors to traverse fragmented landscapes, while simultaneously avoiding roads with high traffic volumes (Sunga et al., 2017). Similarly, road networks frequently disrupt migration routes for large ungulates worldwide (Benítez-López et al., 2010; D'Amico et al., 2016).

Interestingly, certain elements of road infrastructure can provide unintended benefits for wildlife (Underhill and Angold, 1999). One such feature are stormwater ponds, which are constructed alongside highways and expressways to manage runoff and trap pollutants, including heavy metals, hydrocarbons, nutrients, salts, and pesticides. These ponds facilitate the accumulation of sediments and contaminants before water infiltrates into the ground or is discharged into natural water bodies (Barrett et al., 1998; Davis et al., 2001). These ponds have been shown to promote biodiversity (Brittain et al., 2017; Sun et al., 2018; Meland et al., 2020). They serve as important breeding grounds for amphibians, particularly in the context of the rapid drainage of agricultural landscapes and the global loss of wetland habitats (Scher et al., 2004; Le Viol et al., 2012). Additionally, they provide key habitats for aquatic insects, such as Odonata (Ołdak, 2022; Šigutová et al., 2022), and support a variety of other taxa (review in Dixon et al. 2022). Despite their ecological value, stormwater ponds may also act as ecological traps - like many other human-made structures - by attracting wildlife with misleading environmental cues that mask suboptimal or hazardous conditions due to pollutant accumulation (Clevenot et al., 2018; Holzinger et al., 2023). The build-up of heavy metals and organic pollutants in pond sediments can have long-term negative effects on aquatic organisms, and both metals and polycyclic aromatic hydrocarbons (PAHs) are known to bioaccumulate readily (Grung et al., 2016). In a study on lesser treefrogs (*Dendropsophus minutus*) inhabiting roadside storm-

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water ponds, individuals exhibited increased DNA damage, a higher lymphocyte-to-neutrophil ratio, reduced hepatic melanin, smaller locular areas in the gonads, and decreased diameters of secondary spermatocytes and spermatogonia. Overall, frogs from highway-adjacent sites exhibited a greater prevalence of physiological abnormalities than those from protected natural habitats, likely reflecting increased environmental stress from traffic-derived pollutants (Benvindo-Souza et al., 2025). Similarly, dragonfly larvae inhabiting such ponds displayed DNA damage that was strongly correlated with PAH and zinc concentrations in the sediment (Meland et al., 2019).

Water bodies are known to influence bat species richness and activity. They provide drinking water for bats and support higher insect abundances, thereby creating attractive foraging habitats (Russo and Jones, 2003; Russo-Petrick and Root, 2023). Furthermore, calm water surfaces offer a less cluttered acoustic signal return from echolocation pulses, facilitating more efficient prey detection (Siemers et al., 2001). In Europe, several bat species rely on aquatic habitats: *Myotis* spp. are specialists of these environments, while others, such as *Pipistrellus* spp. and *Nyctalus* spp., frequently forage and drink in riparian habitats (Korine et al., 2016). Bats have been observed utilising various types of ponds (Lisón and Calvo, 2014; Ancillotto et al., 2019). Given this, stormwater ponds adjacent to motorways and expressways may also provide suitable foraging and drinking habitats for bats. However, despite extensive research on the broader impacts of roads on bats - predominantly negative due to vehicle collisions and traffic noise that hinders hunting (Lesiński et al., 2011; Abbott et al., 2012; Devaux et al., 2024) - there is a striking lack of studies investigating the importance of these artificial reservoirs for bats.

The aim of our study was to evaluate the significance of stormwater ponds located along motorway and expressways in eastern Poland as foraging habitats for bats. Specifically, we compared bat species richness and activity at sites with stormwater ponds to sites without such ponds. We hypothesised that stormwater ponds positively influence both bat species richness and activity. Additionally, we accounted for the role of nearby habitats, such as woodlots and settlements, which are known to affect bat activity (Ancillotto et al., 2019). Understanding the habitat characteristics that drive bat presence and activity near these ponds could inform future conservation and management efforts. Since stormwater ponds were initially designed for technical purposes but have been naturally colonised by wildlife, it is important to maintain them in conditions that maximise their ecological value. However, because their primary role is to retain and remediate polluted runoff, studies - as noted above - have highlighted their potential to act as ecological risks for amphibians, invertebrates, and potentially foraging vertebrates due to pollutant accumulation. Therefore, a comprehensive assessment of both their ecological benefits and risks is crucial when considering their role in biodiversity conservation.

Materials and Methods

Study Area

The study was conducted in east-central Poland along a major transport corridor connecting Warsaw, Siedlce, Ostrów Mazowiecka, and Lublin. This route comprises one highway (A2) and two expressways (S8 and S17), spanning a total length of approximately 200 km. These roads traverse diverse landscapes predominantly composed of arable fields and meadows, with forested sections accounting for no more than 10 % of the total study area (Fig. 1). The regional climate is characterised by an average annual temperature of 10 °C and annual precipitation of approximately 550 mm. During the sampling period (June - July 2023), the average mean temperature across both months was 18.4 °C, and the total precipitation reached 53 mm (climatic data from Siedlce town, https://en.tutiempo.net/).

Study Design

The research was conducted in June and July 2023, coinciding with the breeding and offspring-rearing period for bats in Poland (Sachanowicz and Ciechanowski, 2005). Each recording day, we surveyed specific

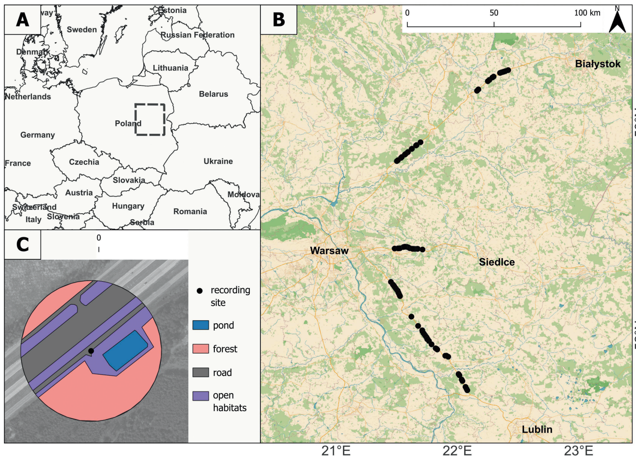

Figure 1 – (A) The map of study area, (B) distribution of survey sites along major roads in central-eastern Poland, and (C) an example site with marked habitat features used in the analysis.

road sections to select suitable recording locations. Sampling focused exclusively on stormwater ponds intentionally constructed for drainage along the highway and expressway network. In Poland, the construction of such retention reservoirs is regulated by national water legislation and road engineering guidelines. These reservoirs are designed to ensure sufficient retention capacity, taking into account rainfall intensity, catchment characteristics, and environmental protection requirements. Typically, their surface areas range from several hundred to several thousand square meters, with spacing along roads varying from a few hundred meters to several kilometers (Marszelewski et al., 2024). Only ponds visibly holding water at the time of survey were included in the study. Additionally, control sites were selected along the same road sections, ensuring the absence of any visible water bodies or drainage features within a 100 m radius. All sites were at least 500 m apart, and travel between them was conducted by car to minimise the time and risk of recording the same individuals at multiple locations. In total, 71 sites were inspected, comprising 38 locations with ponds and 33 non-pond (control) sites.

Bat activity was measured by placing the detectors on a tripod at a height of 1.5 m. Acoustic monitoring was performed for a single 15-minute session at each site, commencing at sunset and continuing until 02:00 h. Sampling was conducted only once per site. To control for temporal variability, pond and control sites were sampled alternately within each night to ensure comparable environmental conditions. Bat recordings were not conducted during periods of precipitation, wind speeds $\geq$10 km/h, or temperatures <10 °C, as these conditions have been shown to significantly affect bat activity levels (Johnson et al., 2008).

Bat Activity Measurement

Acoustic monitoring is widely recognised as a reliable method for assessing bat activity (Frick, 2013; Fraser et al., 2020). Bat activity was recorded using two types of detectors operating simultaneously to enhance data reliability. Primary recordings were obtained using a Batcorder 3.1 (ecoObs GmbH), configured with the following settings: quality = 20, threshold = 27 dB, post-trigger = 400 ms, and critical call frequency = 16 kHz. The software bcDiscriminator (bcAnalyze 4.0, ecoObs GmbH, Nürnberg, Germany) was used for automatic bat species identification based on echolocation calls, ensuring the exclusion of non-bat calls. Bat activity was quantified as the number of echolocation calls recorded per 15-minute session at each site. Species identifications performed by bcIdent with a probability $\geq$90 % were considered statistically valid. We did not analyse call sequences for feeding buzzes; therefore, activity values should be interpreted as indicative of general activity rather than confirmed foraging.

Table 1 – Characteristics of variables describing habitat parameters.

Variable	Description	Mean ± SD	Range
Road	Total area of roads in 100 m radius (ha)	0.75±0.20	0.19-1.16
Pond	Total area of ponds in 100 m radius (ha)	0.11±0.15	0-0.66
Open	Total area of open field in 100 m radius (ha)	1.96±0.55	0.42-2.95
Forest	Total area of forests in 100 m radius (ha)	0.32±0.49	0-1.70
Treeline	Length of tree line (km) in 100 m radius	0.12±0.15	0-0.52
Distforest	Distance to the nearest forest (km)	0.22±0.23	0.01-1.01
Distbuild	Distance to the nearest built-up (km)	0.32±0.18	0.08-0.78
Ntree	Number of single trees (n) in 100 m radius	1.1±1.90	0-8

Simultaneously, bat echolocation calls were also recorded using a ultrasound detector model D230 (Pettersson Elektronic AB, Upsala, Sweden) in broadband frequency division mode (10–120 kHz), connected to a Marantz PDM620 digital recorder (Marantz America, Mahwah, USA). The recordings from the D230 detector served as supplementary data, addressing the limitations of the Batcorder 3.1, which did not always allow for unambiguous species identification. Additionally, the D230 detector was capable of detecting bat calls from greater distances, beyond the range of the Batcorder 3.1 (only data that did not duplicate recordings from Batcorder 3.1 were included in the analysis). For the Pettersson D230, bat activity was quantified as the number of bat passes per 15-minute session. We defined bat passes as either $\geq$ two call pulses per at least 2 ms of duration or a single call pulse per at least 5 ms (see Weller and Baldwin 2012. The recorded echolocation calls were subsequently analysed using BacScan 9 software, which facilitated the generation of spectrograms to aid in species identification.

Data Processing and Statistical Analyses

Sampling site coordinates were uploaded into QGIS (ver. 3.22) as a point layer. A 100 m radius buffer was created around each site to characterise the surrounding land cover (see Table 1). Within each buffer, the surface areas of roads, open fields, forests, and built-up areas (including villages, farmsteads, and building clusters) were calculated. The number of isolated trees and length of treelines were also recorded. Additionally, using recent satellite imagery (Landsat 8 images viewed via Google Earth), we measured the distance from each site to the nearest forest (min. 1 ha) and the nearest built-up area. These habitat types were included as potential bat roosting sites whose proximity could influence bat activity. Due to the fragmented nature and small patch sizes of local forests, we did not distinguish between forest types. The area of each stormwater pond was also measured, and all ponds were small enough to fit entirely within the 100 m buffer. While this radius was selected to capture immediate habitat features influencing bat activity, we acknowledge that species with extensive home ranges (e.g., *Nyctalus noctula*) may forage over much larger areas (Sachanowicz and Ciechanowski, 2005).

Statistical analyses were conducted using R 4.3.3 (R Core Team, 2023) to evaluate the influence of environmental factors (see Table 1) on bat species richness and activity, with a particular focus on the role of pond surface area. Two separate models were employed for this purpose, each addressing a distinct response variable: the number of bat species observed (spec) and the number of bat calls recorded (echolocation calls). For the analysis of first response variable (spec), the global model was defined as follows: Spec ~ Pond + Road + Open + Treeline + Forest + Ntree + Distforest + Distbuild, with a Poisson distribution specified for the response variable. Multicollinearity among predictors was assessed using variance inflation factors (VIFs) calculated with the car package (Fox and Weisberg, 2018). Based on these calculations, two predictors (open and treeline) with excessively high VIF coefficients were excluded from the global model. After this operation, the remaining predictors had VIF values below the threshold of 2, indicating an acceptable level of multicollinearity. Predictors for the final model were selected using the Akaike Information Criterion (AIC) values (Burnham and Anderson, 2002) via the dredge function in the MuMIn package (Bartoń, 2023). This step involved comparing all possible subsets of predictors from the global model. Model fit was evaluated using diagnostic tools from the DHARMa package (Hartig, 2024). Residual diagnostics included tests for zero inflation and dispersion, both of which indicated that the model adequately captured the data structure without evidence of overdispersion or excess zeros. For the analysis of second response variable (echolocation calls), a generalised linear mixed model (GLMM) (Brooks et al., 2017) was constructed using the glmmTMB package with the global formula: Echolocation calls ~ Pond + Road + Forest + Ntree + Distforest + Distbuild, specifying a Poisson (negative binomial) distribution for the response variable. This model was chosen based on diagnostic indicators from the initial GLM, which revealed overdispersion and residual patterns inconsistent with model assumptions. Subsequently, an AIC-based model selection procedure (dredge function from the MuMIn package) was applied to identify the best fitted set of predictors. Residual diagnostics confirmed that the final GLMM adequately addressed issues of zero inflation and overdispersion.

Results

Bats were detected at 59 sites, representing 83.1 % of all surveyed locations ($n = 71$). Species richness per site ranged from 1 to 4 (mean = 1.8, SD = 0.87), with a total of six species identified, including unidentified *Myotis* spp. The most frequently recorded species were *Cnephaeus serotinus*, followed by *Nyctalus noctula* and *Pipistrellus nathusii*. The remaining three species were each detected at only 1–2 sites (Table 2). Echolocation call frequency per 15-minute session ranged from 1 to 67 (mean = 12.3, SD = 14.25), with a total of 724 calls recorded. The number of echolocation signals per species reflected their frequency of occurrence at the recording sites (Table 2).

Table 2 – Characteristics of bat activity at 71 bat monitoring sites.

Species	Frequency of occurrence	Number of calls
Cnephaeus serotinus	48	408
Nyctalus noctula	30	265
Pipistrellus nathusii	6	14
Pipistrellus pipistrellus	1	1
Pipistrellus pygmaeus	1	1
Myotis spp.	2	2
Unidentified	16	33

Models containing six predictors were created based on Akaike's Information Criteria. The modelling of environmental factors determining the species richness showed that five models achieved an AICc value <2 (Table 3). For the analysis of second response variable (echolocation calls), the same criterion was fulfilled by four models. The best models for both analyses: species richness and echolocation call frequency contained only one predictor: pond area (Table 3). Other habitat parameters: road area, forest area, number of trees, length of tree line, distance to the nearest built-up area and distance to the nearest forest area, were omitted from further analyses. The best models indicated that pond area positively affected both species richness (R-square = 0.042) and echolocation call frequency (R-square = 0.045; Table 4).

Table 3 – Results of the models describing the influence of habitat parameters on species richness and number of echolocation calls. Degrees of freedom (df), model log-likelihood (LL), corrected AIC (AIC), difference between the model and the best model in the data set (Δ AIC), and weight for the model (AICwt) are shown.

Fixed effects	df	logLik	AICc	Δ AIC	AICwt
Species richness					
Intercept+Pond	2	-100.474	205.1	0.00	0.114
Intercept+Pond+Distbuild	3	-100.032	206.4	1.30	0.060
Intercept+Pond+Distforest	3	-100.034	206.4	1.30	0.059
Intercept	1	-102.340	206.7	1.61	0.051
Intercept+Pond+Forest	3	-100.202	206.8	1.64	0.050
Echolocation calls					
Intercept+Pond	3	-230.502	467.4	0.00	0.159
Intercept+Pond+Road	4	-230.021	468.6	1.29	0.084
Intercept+Pond+Distforest	4	-230.125	468.9	1.49	0.075
Intercept+Pond+Distbuild	4	-230.359	469.3	1.96	0.060

Table 4 – Estimates of general linear model coefficients for the best models affecting the species richness and number of echolocation calls.

Variable	Estimate	SD	z	p-value
Species richess				
Intercept	0.242	0.127	1.89	0.058
Pond	1.184	0.584	2.02	0.043
Echolocation calls				
Intercept	2.064	0.181	11.43	<0.001
Pond	1.903	0.599	3.17	0.002

Discussion

Our study demonstrated that stormwater ponds adjacent to major roads serve as important habitats for bats. The presence of these artificial water bodies was the sole significant habitat factor influencing both bat species richness and activity at the study sites. This finding highlights the ecological potential of stormwater ponds, which likely provide both drinking water and enhanced foraging opportunities for bats utilising road corridors.

The positive impact of stormwater ponds on bat activity aligns with previous studies demonstrating the role of water bodies in sustaining bat populations (Russo and Jones, 2003; Ancillotto et al., 2019; Russo-Petrick and Root, 2023). Bats depend heavily on water, especially in regions where it can be a limiting resource (Blakey et al., 2018). These ponds not only offer a stable source of hydration (Nystrom and Bennett, 2019) but also support a high abundance of aquatic insects, a crucial food source for many bat species (Nummi et al., 2011; Stahlschmidt et al., 2012). In particular, stormwater ponds support large populations of *Chironomidae* (*Diptera*) and caddisflies (*Trichoptera*), two of the most significant prey groups for bats species recorded on our study area (Ciechanowski and Zapart, 2012; Metcalfe et al., 2023). Furthermore, smooth water surfaces may enhance echolocation efficiency, facilitating prey detection (Siemers et al., 2001). The presence of water bodies has also been associated with increased bat commuting activity, as they with the roadway corridor serve as navigational landmarks in fragmented landscapes (Limpens and Kapteyn, 1991). Compared to cluttered terrestrial habitats, water surfaces provide more open airspace for navigation and foraging (Ober and Hayes, 2008).

Other habitat variables had no significant effect on bat species richness or echolocation intensity. Several factors may explain this result. Firstly, individual bat species exhibit specific habitat preferences and foraging ranges (Zukal and Rehak, 2006; Ciechanowski, 2015), and the 100 m radius around each recording site may have been too small to capture broader habitat relationships. Additionally, the strong influence of pond presence on bat activity may have masked the effects of other habitat features, a pattern observed in Germany (Heim et al., 2017). Moreover, some recording sites were located near illuminated road exits, which may have attracted foraging bats due to insect aggregation around artificial lights (Stone et al., 2015; Azam et al., 2018), further obscuring habitat-specific preferences. Nevertheless, habitats along roads can strongly influence bat activity, as demonstrated in numerous studies (Ancillotto et al., 2019; Medinas et al., 2019; Russo-Petrick and Root, 2023). This issue requires further research, particularly in relation to the presence of water bodies.

Despite their benefits as foraging and drinking sites, stormwater ponds near roads may also pose risks to bat populations. Noise generated by vehicles on major roads has been shown to reduce bat activity and foraging efficiency in some species (Schaub et al., 2008; Shannon et al., 2016). While this might limit bat activity and road mortality (Berthinussen and Altringham, 2012), the attractiveness of stormwater ponds to bats could counteract this effect. The ecological trap hypothesis suggests that while stormwater ponds provide valuable resources, their close proximity to roads may increase collision risks. This risk is especially high when ponds are located directly opposite each other on either side of a road, leading bats to cross at low altitudes and making them vulnerable to vehicle strikes (Lesiński, 2007; Russell et al., 2009). While collision risk is highest for low-flying species (Fensome and Mathews, 2016), even species typically flying at higher altitudes, such as *Nyctalus noctula* and *Pipistrellus nathusii*, may be frequently impacted by vehicle collisions (Lesiński et al., 2011).

Future research should explore bat utilisation of stormwater ponds on a broader spatial and temporal scale, incorporating all seasons rather than focusing solely on the breeding period. In particular, assessing insect abundance, pond productivity, and water quality could clarify the mechanisms driving bat use of these habitats. Additionally, assessing roadkill rates in relation to stormwater pond placement is crucial, because ecological trap for bats should be considered. Such studies present logistical challenges due to high traffic volumes and the removal of bat carcasses by scavengers (Medinas et al., 2021). However, emerging methodologies, such as thermal imaging, could improve data collection in high-risk areas. Furthermore, landscape-scale assessments would provide valuable insights into how road networks and artificial water bodies collectively influence bat populations over larger spatial scales (Roemer et al., 2017).

In conclusion, stormwater ponds along major roads provide valuable ecological resources for bats, yet their ecological benefits must be weighed against the increased risk of road mortality, particularly under conditions conducive to ecological traps. Our study highlights the necessity of integrated conservation planning to maximise the ecological benefits of artificial ponds while mitigating associated risks. Future studies should investigate bat movement patterns along road sections with stormwater ponds and evaluate the efficacy of mitigation measures in reducing road mortality. Addressing these knowledge gaps will contribute to the development of transportation networks that are more compatible with biodiversity conservation.

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Associate Editor: John Koprowski