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Hunting at the highway: traffic noise reduces foraging efficiency in acoustic predators

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Noise pollution from human traffic networks and industrial activity impacts vast areas of our planet. While anthropogenic noise effects on animal communication are well documented, we have very limited understanding of noise impact on more complex ecosystem processes, such as predator–prey interactions, albeit urgently needed to devise mitigation measures. Here, we show that traffic noise decreases the foraging efficiency of an acoustic predator, the greater mouse-eared bat (*Myotis myotis*). These bats feed on large, ground-running arthropods that they find by listening to their faint rustling sounds. We measured the bats' foraging performance on a continuous scale of acoustically simulated highway distances in a behavioural experiment, designed to rule out confounding factors such as general noise avoidance. Successful foraging bouts decreased and search time drastically increased with proximity to the highway. At 7.5 m to the road, search time was increased by a factor of five. From this increase, we predict a 25-fold decrease in surveyed ground area and thus in foraging efficiency for a wild bat. As most of the bats' prey are predators themselves, the noise impact on the bats' foraging performance will have complex effects on the food web and ultimately on the ecosystem stability. Similar scenarios apply to other ecologically important and highly protected acoustic predators, e.g. owls. Our study provides the empirical basis for quantitative predictions of anthropogenic noise impacts on ecosystem processes. It highlights that an understanding of the effects of noise emissions and other forms of 'sensory pollution' are crucially important for the assessment of environmental impact of human activities.

Keywords: anthropogenic noise; sensory ecology; foraging; bats; masking; attention

1. INTRODUCTION

Noise pollution from human traffic networks and industrial activity occurs in vast areas of our planet [1] and potentially affects wildlife over both terrestrial and aquatic environments [2,3]. A considerable body of research documents how anthropogenic noise impacts animal communication [4–6]. Some birds adjust pitch [7,8], amplitude [9] or timing [10] of their song to counteract masking, right whales change the tune of their communication calls in response to shipping noise [11] and male frogs lose acoustic space for attracting females to traffic noise [12].

A more comprehensive understanding of how anthropogenic noise influences ecosystem processes, albeit urgently needed to devise mitigation measures [2,6], is only starting to emerge, however. Here, a crucially important question is how noise pollution affects predator–prey interactions, as these stand at the heart of ecosystem stability and dynamics. Recent evidence suggests that songbirds experience decreased predation rate in noisy environments [13], and hermit crabs are distracted by boat motor noise and hence less vigilant against approaching predators [14]. No study has as yet directly assessed how anthropogenic noise interacts with the foraging efficiency of a predator. We hypothesize that acoustic predators, such as owls [15], some carnivores and nocturnal primates [16], and many species of bat [17–19], that detect and localize animal prey by eavesdropping on their communication or locomotion sounds, are likely to experience reduced foraging success in noise, because it masks the prey cues. In the present study, we assessed for the first time, to our knowledge, anthropogenic noise impact on prey detection performance of an acoustic predator. We chose the greater mouse-eared bat (*Myotis myotis*) as a model species. These bats feed on large, ground-running arthropods such as carabid beetles, hunting spiders and centipedes [20] that they detect and track down by listening to the faint rustling sounds that the arthropods produce when walking [21,22]. Most of these arthropods are predators themselves and thus noise impact on the bats' foraging performance might have complex effects on the food web (B. M. Siemers, S. Greif, I. Borissov, S. L. Voigt-Heucke & C. C. Voigt 2010, unpublished data). Greater mouse-eared bats occur in most of Central and Southern Europe and can cover nightly foraging distances of more than 25 km [23]. Most of Europe's existing and planned highways thus cross potential mouse-eared bat foraging habitat. As the species is protected under the highest conservation category of the European Habitats Directive, the potential impact of traffic noise on the bats' foraging efficiency is of

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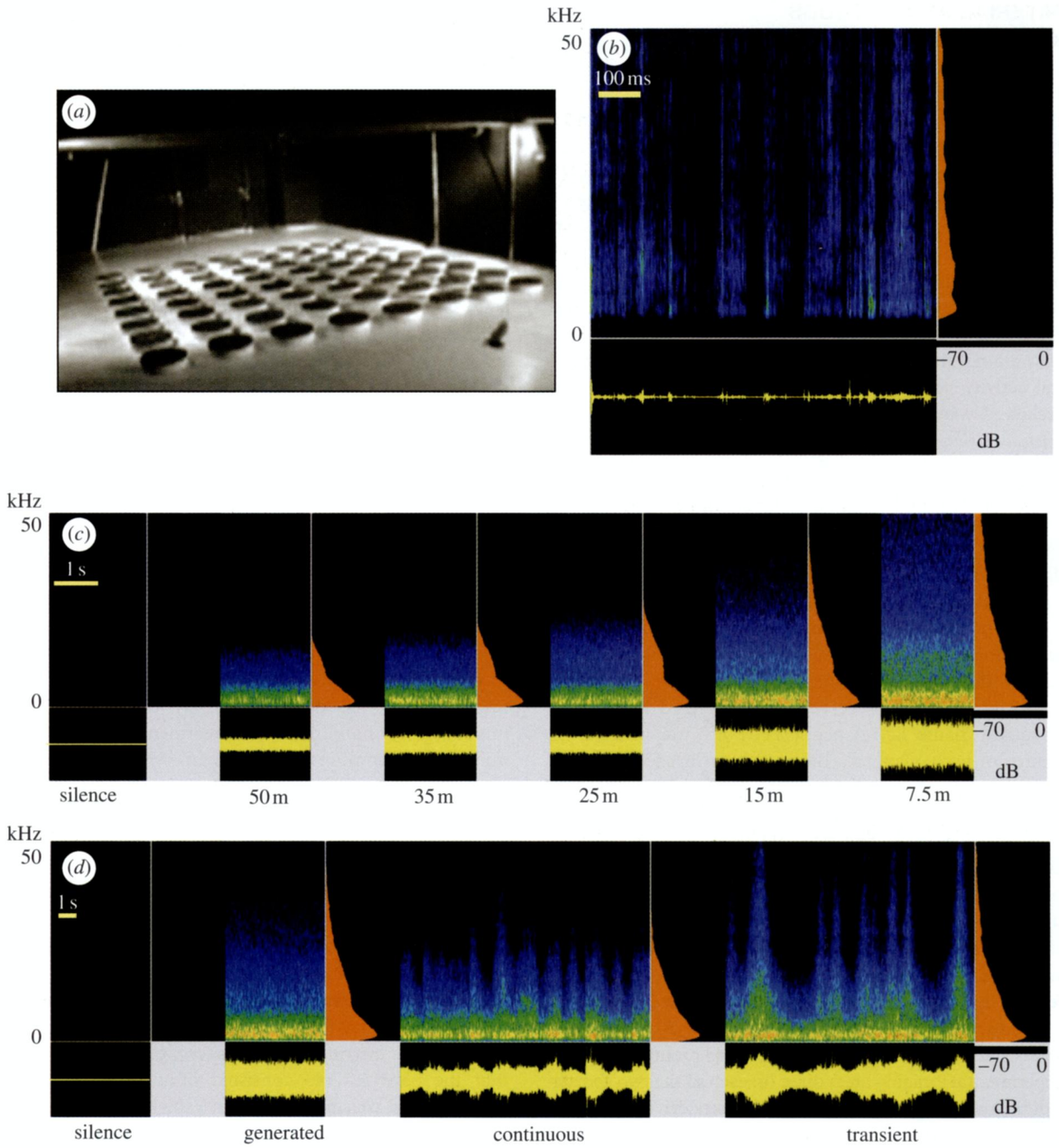

Figure 1. Experimental set-up and sound stimuli. (*a*) Video screenshot of the experimental foraging area. (*b*) Example of a carabid beetle walking sound that we used to signal prey to the bats. (*c*) Noise treatments in experiment 1; 'silence' as a control and digitally generated, standardized traffic noise corresponding to different distances to a highway (from the right, i.e. outer, lane. (*d*) Examples of the noise treatments in experiment 2; the digitally generated 15 m stimulus from experiment 1, recorded traffic noise as 15 m from a highway, but with silent intervals between passing cars cut out, unchanged recorded traffic noise as 15 m from a highway, and again 'silence'. All sound examples in spectrogram representation with oscillogram below and averaged power spectrum on the right. Amplitude is colour coded (relative dB scale).

strong practical relevance. In laboratory experiments, these bats avoid loud, broadband noise, including playback of traffic noise corresponding to 10–15 m from a highway [24], but the reason for noise avoidance has not been studied. Here, we tested the hypothesis that traffic noise affects foraging efficiency in these bats, as a model for acoustic predators. In a large flight room, we set up an experimental foraging area with 64 platforms (figure 1*a*) in each of which we hid a loudspeaker that could play rustling sound of the bats' main prey—carabid beetles [20,22]—at naturalistic amplitudes [25] (figure 1*b*). The set-up mimicked the natural foraging scenario of these bats. As soon as they heard the prey walking sounds they landed briefly on the respective platform and picked up a food reward from above the speaker (see electronic supplementary material, video S1). We then applied different noise treatments through an array of broadband loudspeakers mounted on two sides of the experimental foraging area and conducted a total of 5069 1 min foraging trials with eight bats. It was not possible for the bats to avoid the noise, as the entire foraging area was ensonified. Thus, we could measure the bats' prey detection and localization performance under the noise profiles of a series of highway distances.

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2. MATERIAL AND METHODS

(a) *Animals and housing*

Eight adult male greater mouse-eared bats (*Myotis myotis*) were used for experimentation. The animals were captured for these experiments under licence from Regierungspräsidium Freiburg (licence no. 55-8852.44/1095) and held and tested in specially designed facilities at the University of Tübingen (approved by Regierungspräsidium Tübingen). They were housed in a flight cage of $2 \times 1.5 \times 2$ m ($l \times w \times h$) with an inverted light regime (8 h D: 16 h L) and tested during their activity phase. The bats had been on an inverted photoperiod for more than six months before the experiments started and thus were fully accustomed to it. All training and testing was conducted during the bats' natural activity period; i.e. during the (artificial) night. The bats received water ad libitum and food (mealworms, larvae of *Tenebrio molitor*) during the experiments, which were run 5 days a week. Their diet was also supplemented with crickets (*Schistocerca gregaria*) at the weekends, and with vitamins and minerals once every four weeks.

(b) *Experimental set-up*

Bats were tested in a large flight room with dimensions of $13 \times 6 \times 2$ m; walls and ceiling were covered with sound absorbing foam to reduce echoes and reverberations. In the middle of the room, 64 cylindrical platforms (diameter: 40 cm, height: 10 cm) were regularly arranged in a 4.6×4.6 m square (figure 1*a*). A plastic Petri dish was inserted on the centre of each platform. Below a hole in each dish, we hid a small, broadband speaker (Sennheiser HD 555/595) connected to a laptop via an external soundboard (RME Fireface 800 Interface, sampling rate 192 kHz). In each trial, we played a prey rustling sound from one of the 64 platforms. If the bat landed on the correct platform within 1 min from the onset of playback, it was allowed to take a mealworm from the dish. Mealworms were freshly killed by cooling and thus did not crawl or produce noise.

For the noise treatments, six broadband tweeter loudspeakers (Swans, RT2H_A, operational from 1–70 kHz; noise high-pass filtered at 1 kHz, see below) were mounted around the experimental foraging area; three on each of the two shorter sides of the rectangular flight room. They were driven using the RME Fireface 800 (sampling rate 192 kHz) and broadband amplifiers (WPA-600 Pro, Conrad Electronics). Files were played continuously throughout a trial.

Each bat was tested in each test condition 64 times, with the prey stimulus played from each of the platforms exactly once. This approach was chosen to factor out any interaction of the exact noise sound field and the prey location. We also avoided repeating any noise stimulus type more than three times in a row. Within these constraints, the sequence of stimuli and prey positions was randomized for each bat. With the exception of one bat that flew in only 13 of 64 trials for the 7.5 m treatment, all eight bats performed in all 64 trials of the six test conditions of experiment 1 and the four conditions of experiment 2, so that our results are based on a total of 5069 trials. We first performed experiment 1 and then experiment 2. Each bat was tested as long as it showed clear foraging motivation (resting bouts between trials less than 2 min).

Experiments were run in the dark with one bat at a time and filmed (Sanyo BW CCD camera VCB-3572 IRP, Computar lens M0518, Sony recorder GVD1000E) under infrared (IR) illumination (custom-made IR-strobes) for online display and video-taped for later off-line analysis.

(c) *Acoustic stimuli*

All playback files were arranged or generated in Adobe Audition 1.5 (adobe) and had a sampling rate of 192 kHz, i.e. contained frequencies up to 96 kHz. All files were high-pass-filtered at 1 kHz (digital fast Fourier transform filter, 2048 points, Blackman window) to remove sound probably not audible to the bats and to avoid damage to the speakers.

For experiment 1, an empty wav-file (amplitude values of all samples at zero) was generated for the 'silence' treatment. For the traffic noise treatments, we digitally generated noise that would correspond to the average loudest 0.5 s of a passing vehicle as experienced at 7.5, 15, 25, 35 and 50 m from the right (outer) lane of a highway. This approach was taken to have a standardized and representative traffic noise background. The average power spectral density of a passing vehicle was computed based on broadband recordings of 50 passing cars and 50 passing trucks at speeds of approximately 80 km h^{-1} at the Autobahn A8 close to Stuttgart, Germany, at 7.5 m distance (see [24] for details). For the four treatments that corresponded to larger distances, we calculated the decay of frequency and amplitude over distance and verified our calculations with empirical recordings [24]. High frequencies, which were already faint, decayed quickly with distance (comp. figure 1*c*). The playback files were filtered to compensate for the speaker characteristics and amplified so that the sound field at the experimental foraging area corresponded to the desired highway distances [24]. It is important to note that our treatments in experiment 1 mimicked a continuous stream of vehicles, as we played sound levels corresponding to the loudest 0.5 s of a passing vehicle for the entire 1 min trial.

For experiment 2, a representative 1 min recording of traffic noise at a highway was used (Autobahn A8; 29 passing vehicles per minute); for details see [24]. It was filtered to compensate for the speaker characteristics and amplified so that intensities at the experimental foraging area corresponded to 15 m next to the highway [24]. For the 'transient' treatment, it was left unchanged otherwise, i.e. the noise rose and fell as cars and trucks passed by. For the 'continuous' treatment, more silent parts were cut out so that the playback file consisted of a series of 1.5 s peak levels around the moment when vehicles passed the microphone. Silence treatment and 15 m treatment as in experiment 1.

As prey sound at the feeding platforms, we played back rustling sounds at naturalistic amplitudes [25] of typical mouse-eared bat prey. For this purpose, we had recorded four different individual ground beetles (*Carabus monilis*; 23–26 mm body lengths and 0.5–0.7 g) walking on moist leaf litter, a typical substrate in mouse-eared bat foraging areas, with a broadband, especially sensitive microphone (Type 40HH, G.R.A.S., Holte, Denmark); for details, see [25].

(d) *Data analysis*

From the videos, we extracted whether a trial was successful, i.e. the bat landed on the correct platform, and if so, how long it took from onset of playback to landing ('search time'). For each animal and test condition, we broke down all trials (generally 64) into a single value for each of the two behavioural variables to avoid pseudo-replication as follows.

— The proportion of successful trials, as displayed in the graphs. For statistical analysis, we transformed this

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proportion as follows in order to approximate a normal distribution [26],

$$p' = \frac{1}{2}\left[\arcsin\sqrt{\frac{X}{n+1}} + \arcsin\sqrt{\frac{X+1}{n+1}}\right].$$

See [26, eqn. (13.8)], where X is the number of successful trials and n the total number of trials.

— Average search times over all trials per test condition.

Statistical tests were computed in SPSS 15.0.

3. RESULTS

(a) *Experiment 1: effect of highway distance*

In experiment 1, we used computer-generated noise spectra that represented average traffic noise at different distances to a highway (figure 1*c*). The main energy of traffic noise is clearly within the human hearing range, largely below 5 kHz [12]. Yet, traffic noise does have an ultrasonic component that decays rapidly over distance [24]. Close to a highway, it strongly overlaps the frequency spectrum of prey rustling sounds (main energy 3–30 kHz [25]; (compare panels *b* and *c* in figure 1) and hence there is a strong potential for acoustic masking. Indeed, the bats showed a markedly decreased foraging performance under noise conditions as found close to a highway. First, the noise treatment had a significant effect on the proportion of successful foraging trials (figure 2*a*; repeated measures ANOVA, $F_{5,35} = 85.71$, $p < 0.0001$). While success rate was close to 100 per cent under the control condition ('silence'), it was reduced to 54.6 per cent for 7.5 m from the highway (for post hoc tests see figure 2). This performance is still high above the 1.6 per cent chance level that results from our 64 potential prey locations. The noise treatment effect on our second behavioural parameter, search time, was even more profound (figure 2*b*; $F_{5,35} = 157.47$, $p < 0.0001$). Average search time in the control condition was 5.2 s, while it rose to 24.6 s for 7.5 m from the highway. Even at 50 m, search time was still significantly higher and at 150 per cent of search time under the control condition (figure 2*b*). Extrapolation of our results suggests traffic noise effects on the bats' prey detection ability up to about 60 m from the highway.

(b) *Experiment 2: a control for noise type and continuity*

We used the same 64 platform experimental foraging area and type of prey sound, but this time employed a different set of noise treatments (figure 1*d*). The aim was to compare the effect of the digitally generated noise stimuli from experiment 1—tailored to represent average highway noise [24]—with the effect of samples of real, recorded traffic noise. We thus repeated the 15 m treatment from experiment 1 and also played back two versions of traffic noise as recorded 15 m from a highway. One version was left unchanged (transient traffic noise), while in the other we cut out the silent intervals between passing cars (continuous traffic noise). The bats' performance in the 15 m treatment and in the silence treatment, which we also repeated, did not differ between experiments 1 and 2 (paired *t*-tests; 15 m, proportion of successful trials, $t_7 = 0.08$, $p = 0.9406$; search time, $t_7 = 0.89$, $p = 0.4044$; silence, proportion of successful trials, $t_7 = 2$, $p = 0.0856$; search time, $t_7 = 1.02$, $p = 0.3430$), which

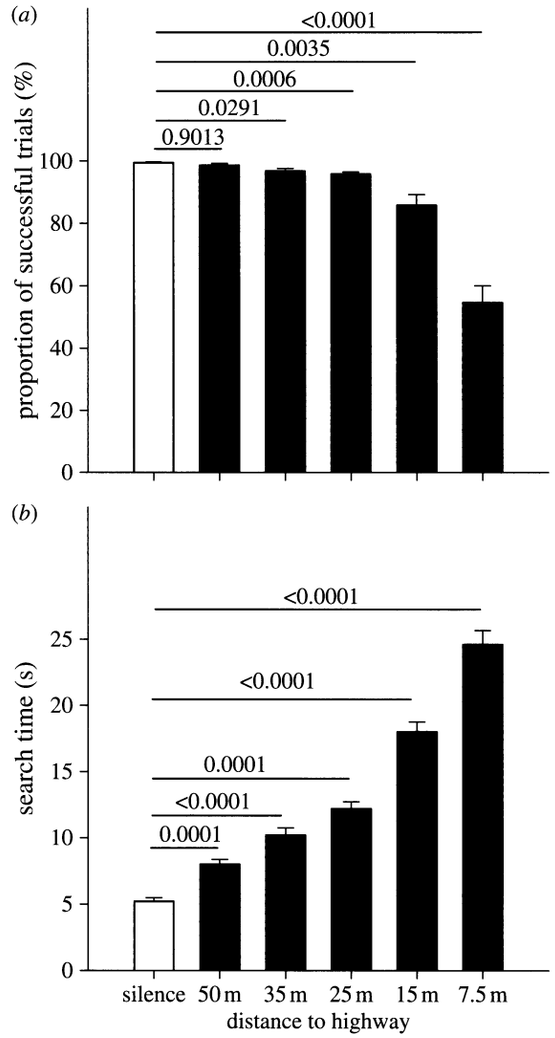

Figure 2. Foraging performance of the bats under noise conditions of different highway distances (experiment 1). (*a*) Proportion of successful foraging trials (prey found within a 1 min time window). (*b*) Search time; i.e. time from onset of prey rustling playback to the moment when the bat landed on the platform (only successful trials included). Means plus one standard error. *p*-values from paired *t*-test performed post hoc to a repeated measures ANOVA (see text) are indicated above the bars. We compared each highway distance to the silence treatment (control; white bar); *p*-values were Bonferroni corrected to account for the five pairwise comparisons. For noise stimuli, see figure 1*c*.

we take as evidence for the robustness and repeatability of our behavioural assay. Within experiment 2, the type of noise treatment had a significant effect on the proportion of successful foraging trials (repeated measures ANOVA, $F_{3,21} = 17.45$, $p < 0.0001$; figure 3*a*) and, again stronger, on the bats' search time ($F_{3,21} = 82.53$, $p < 0.0001$; figure 3*b*). Post hoc tests revealed that the bats' performance did not differ between the digitally generated 15 m stimulus and the 'continuous' version of the recorded traffic noise (figure 3). This confirms that the digitally generated noise stimuli we had used in experiment 1 realistically mimicked traffic noise. By contrast, the search time of the bats was more strongly increased under the digitally generated 15 m noise than under the 'transient' version of the recorded traffic noise (figure 3*b*). This indicates that the bats were at least to

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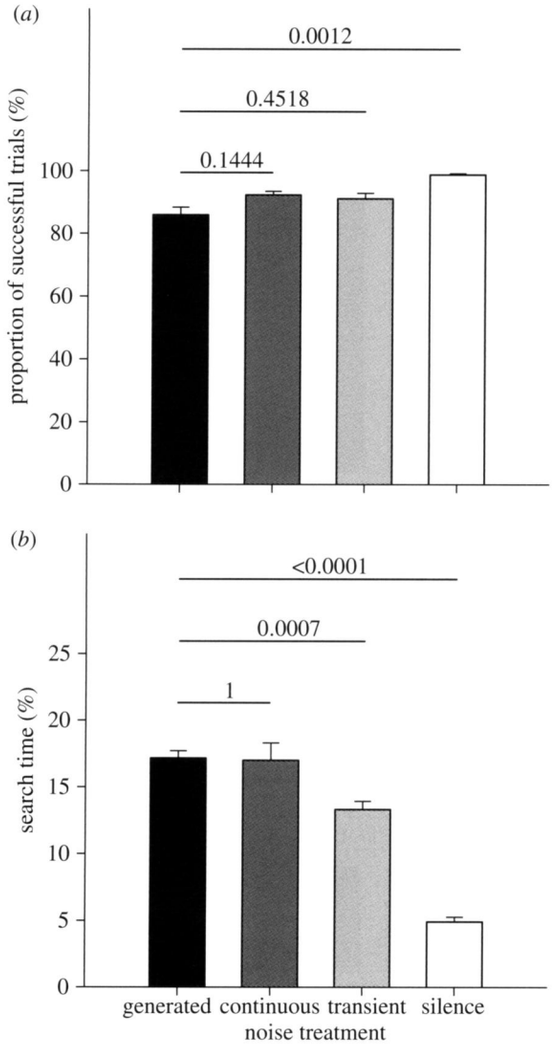

Figure 3. Foraging performance of the bats under digitally generated and recorded highway noise (experiment 2). (*a*) Proportion of successful foraging trials. (*b*) Search time. Means plus one standard error. *p*-values from paired *t*-tests performed post hoc to a repeated measures ANOVA (see text) are indicated above the bars. We compared each digitally generated playback stimulus with the 15 m treatment ('generated', black bar) as used in experiment 1; *p*-values were Bonferroni corrected to account for the three pairwise comparisons. For noise stimuli, see figure 1*d*.

some degree released from acoustic masking between passing vehicles, where the noise intensity and especially the high-frequency content dropped (figure 1*d*).

4. DISCUSSION

We assume that search time, as measured in our experiments, is directly related to foraging efficiency in the wild. A long search time indicated that the bats had to fly close to the respective platform to still detect and localize the faint prey rustling sound in noise, i.e. they experienced a reduced detection distance under traffic noise. Our measurements are likely to be conservative estimates, i.e. they probably overestimate the true detection distance. This is because the bats circled above the experimental foraging area in the laboratory and thus passed close to every platform repeatedly, while in the field, mouse-eared bats typically forage in linear flight about 1 m above ground and pass every potential prey only once. If the fivefold increase in search time between control condition and just next to the highway (7.5 m) thus is assumed to indicate a fivefold reduction in detection distance, we would predict a roughly 25-fold decrease in the surveyed ground area for a wild bat. This effect levels off with distance from the highway. Extrapolation of our results suggests traffic noise effects on the bats' prey detection ability up to about 60 m from the highway, which is not a very large distance. However, considering the hundreds of thousands of kilometres of motorways on our planet [1,2], a strip of 50 to 60 m left and right of the tarmac adds up to considerable areas that will be degraded in their suitability as foraging habitats for acoustic predators such as bats and owls. It is important to note that our treatment in experiment 1 mimicked the acoustic situation when a vehicle is passing a foraging bat. The extrapolation of our results to estimating degradation of foraging habitat quality alongside highways owing to noise pollution thus requires taking traffic density into account.

We hypothesize that the mechanistic reason for the deterioration of the bats' foraging performance in noise was acoustic masking [4]; i.e. the loud traffic noise interfering with the perception of the faint prey rustling sound as a separate stimulus. An alternative, but mutually non-exclusive explanation is that the bats' attention was distracted from the prey sounds by the noise background. An animal's attention, i.e. the neuronal representations activated at any given time, is limited, and this can result in important fitness consequences with respect to foraging or vigilance against predators [27]. As an example, Chan *et al.* [14] showed that boat motor noise may distract the finite attention of hermit crabs from approaching predator dummies. Also bats appear to experience some difficulty in processing more than one stream of information at a time [28]. However, in our experiments, we did not observe any sign for a shift of the bats' attention from search for prey cues to the noise; at least not on a behavioural level. During noise treatments, they did not approach or inspect the speakers that were located at the sides of the foraging arena. Rather, they showed the same type of search flight above the feeding platforms as during the silence treatment. The better performance of the bats under transient as compared with continuous traffic noise also indicates that masking and not distraction might have been the main factor. This is because it is unlikely that attention would have fully refocused on foraging in the short intervals between car passes, whereas release from masking can happen within milliseconds [29]. While we therefore consider masking to be the predominant mechanistic cause, we cannot exclude that distraction may play some role for explaining our results as well. Regardless, none of these mechanistic explanations would in any way affect our main empirical result and its ecological implications: bat prey detection performance deteriorates under traffic noise, which might alter predator–prey dynamics and affect ecosystem processes.

As mouse-eared bat echolocation calls are dominated by frequencies between 25–120 kHz [30], there is little overlap with traffic noise and hence hardly any potential for acoustic masking of echoes. Indeed, we had no

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indication that the bats' orientation by echolocation was impaired. They navigated the flight room and showed well-controlled approach flights to the landing platforms under all noise treatments. Yet, it is known that bats can adapt time–frequency structure and amplitude of their echolocation pulses to interfering noise if it overlaps frequencies crucial for echo imaging [31–33].

Despite the clear noise effect on foraging efficiency, it is astonishing to note that the bats performed way above chance level even at 7.5 m from the highway; they still detected and localized the rustling sound under intense traffic noise in about 50 per cent of the trials. Bats and other acoustic predators are to some degree evolutionarily adapted to foraging under natural noise such as wind or running water. Traffic noise does thus not constitute a completely new situation [34], but it confronts animals with unusually high noise levels over large areas of land [2]. As one strategy to reduce noise interference, bats probably make use of the directional characteristics of their ears [35] to achieve some spatial separation between the prey sound from the ground and the traffic noise from the side or ahead. Furthermore, bats may benefit from a disparity in the temporal structure of noise and prey rustling sounds [29]. Prey rustling is transient and click-like and the highest frequency components of these clicks exceed the traffic noise band [24,25], which again explains why the bats had to pass very close to the prey in strong noise to still hear these quickly attenuating high frequency components. In exceptional cases, natural noise can be more similar to prey rustling in time and frequency structure and thus even have stronger masking effects than traffic noise. One example is the click-like noise produced by wind-moved reeds (B. M. Siemers & A. Schaub 2008, unpublished data; see [24]).

Our study provides direct experimental evidence that anthropogenic noise can affect the foraging efficiency of acoustic predators such as bats and probably also owls, some nocturnal primates, carnivores and others. Many of those are endangered and protected under national and international law. Through interference with the predators sensory performance or attention, traffic noise can reduce predation pressure [13] and thus alter predator–prey dynamics, which in turn affect other ecological processes and ultimately ecosystem stability. We thus argue that noise emissions and other forms of 'sensory pollution' [36] need to be considered for the assessment of environmental impact of human activities.

All animals were captured under licence from Regierungspräsidium Freiburg (no. 55-8852.44/1095) and experiments were approved by Regierungspräsidum Tübingen.

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The Legacy of Mercury Pollution in California's Bay Area

Sigi Ocker | March 21, 2014 2:00 pm | Comments

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Sigi Ocker is a senior at The Urban School of San Francisco and is attending Whittier College in the Fall. Sigi finds interest in Evolutionary Biology and Environmental Science and will likely pursue a degree in one of these areas.

California Bay Area fishermen are losing business due to increased awareness of mercury contamination in their fish. Members on the lower end of the socio economic class spectrum are complaining about clean fish availability and soaring prices of fish. The Bay Area is experiencing the full effect of mercury accumulation in the Bay's aquatic sediment and marsh-land zones.

Mercury, upon reaching aquatic systems, is converted by marine bacteria to methyl-mercury. Methyl-mercury is a neurotoxin that biomagnifies, or increases in dosage, as it works its way up the aquatic food chain. So, as bigger fish eat mercury saturated smaller fish, the bigger fish's tissue then becomes stained or sown with the methyl-mercury. By the time these higher trophic level fish are consumed by humans, the neurotoxin has then biomagnified to an extent that makes it volatile and harmful to any organism's nervous system. The adverse effects of methyl-mercury include: Fetus development issues in pregnant mothers, possibility of impaired neurological development or impaired brain development. Effects also include problems with cognitive thinking, memory retention, attention span, and motor and visual spatial skills.

So what's causing mercury to accumulate in the Bay Area?

Mercury and Industry

Mercury is a rare, dense, Earth metal that naturally occurs in the Earth's crust. While it is a liquid at room temperature it quickly evaporates once exposed to the atmosphere. Because of these evaporative qualities its usage in industry has contributed to its wide spread presence throughout the atmosphere. When referencing industrial use of mercury, it's easy to point the finger at the environmentally damaging use of coal and its combustion.

Coal only has small trace amounts of mercury in it however, but the U.S.'s large reliance on coal as an energy source means that large volumes of coal are combusted for usable energy. The U.S. in 1995 alone, through the combustion of coal for energy, released a whopping 50 tons of mercury into the Earth's atmosphere. And according to the California Water and Science Center, North America emitted almost 70 tons of mercury to the atmosphere through oil and coal combustion in 2005. In the global arena China was responsible for 295 tons worth of a mercury emissions in 2010, only a portion of the global total 890 tons.

Globally, oil refining and coal combustion contribute to an atmosphere polluted with mercury however, in the Bay Area most of the mercury deposits in marine sediment come from California's coastal mountains ranges. The affect is less atmospheric and more aquatic as most of the mercury washing down from the watershed has been converted to methyl mercury by bacteria in the Bay Area's wet-lands and marshes. In the coastal ranges mercury is found naturally in hydrothermal systems. These naturally occurring hydrothermal springs where once used in commercial mining.

Mercury and Mining

The industrial age of mining in the 1800's is responsible for most of the mercury accumulation in the Bay. The miners that participated contributed on grand scale to mercury accumulation in sediment and marine life in the Bay Area. The first mine in New Almaden, CA, was discovered in the 1820's and was known for its abundance of Cinnabar. Cinnabar is the name for the naturally occurring Earth ore containing mercury. This mine was about 10 miles south of San Jose, in the Santa Cruz Mountains. Along with this mine, and other mountainous mines, became some of the most productive mercury harvesting and gold mining sites in the world. Starting in the 1840s numerous mines extended up and down California's mountain ranges as industries took to westward expansion for profit, essentially exploiting these natural mercury deposits.

Contrary to popular belief, the majority of gold-rush miners did not wade around in rivers and streams panning for gold, at least not corporate mining. It's important to remember that locomotion and travel was a much harder thing to achieve in the 1800's and not everybody had the money to simply change shop and move to the west to mine for gold. Therefore, gold mining was a corporate ordeal where private organizations paid miners to operate their industrial tools of manufacture.

These companies sought gold by eroding entire hillsides with high-pressure water cannons, effectively blasting the hill's sediment to pieces. The blasted and detached sediment from the hills was then run through what was known as "sluice boxes," where mercury, because of its natural attraction to gold, was added to bind to gold, separating it from random sediment. The problem was that this process of hydro-blasting the hills and funneling the sediment into industrial size strainers was a messy process with little to no containment efforts in place. Large amounts of the mercury contaminated sediment made its way out of the strainers and down stream into the California Watershed. Excessive water usage in the hydro-blasting caused more and more sediment to flood into California's Central Valley, polluting rivers and streams with mercury rich sediment. The federal government finally shut down much of the gold mining activity in 1884.

Below is a diagram showing the California watershed with all the rivers and streams that connect and funnel through the California Central Valley and into the Bay Area. If you can imagine the commercial mines in the Sierra Nevada mountain range then you can fathom the amount of mercury rich run off sediment that found its way through the watershed into the Bay Area.

Image credit: U.S. Environmental Protection Agency

Mercury Pollution and California

Although the excessive mining took place during the 1800s and 1900s there are still a number of oil refineries in California, and although they aren't hydro-blasting hills with water and mercury, the coal that the refineries combust still releases evaporative mercury into the atmosphere. That evaporated mercury, because of its hot temperature then rises into the atmosphere's clouds and once it rains, that mercury finds it's way back down onto California coastal mountain ranges. In the mountains the acid rain is subject to movement via the watershed into California's Central Valley and later into the Bay Area. There are a number of current coal, oil and tar sand refineries in Northern and Central California who's locations are stationed in watershed areas that funnel into the Bay Area.

Northern California Refineries producing Gasoline:

- Chevron(Richmond)
- Shell (Martinez)
- ConocoPhilipps (Rodeo)
- Tesoro (Avon-Martinez)
- Valero (Benecia)

All of the refineries above either combust coal, or refine oil in the form of tar sands. Tar sands are a combination of clay, sand, water and the mineral bitumen, what the usable oil is actually extracted from. Bitumen is a heavy, viscous, oil and it takes some processing in order to separate the bitumen from the sand, water and clay. The oil extracted from the bitumen in the tar sands is similar to oil extracted from conventional oil wells to create crude oil. This whole process of mining tar sands and extracting their oils has lead to a heavy increase in Bay Area pollution as industrial and green house gasses are released into the atmosphere.

Refineries in the Central Valley contributing to the California Watershed are listed below:

- Big West of California (Bakersfield)
- Kern Oil and Refining Company (Bakersfield)

These refineries as well are responsible for tar sand pollution and oil refining.

Government Intervention and Possible Solutions

The completion of the Keystone XL pipeline would essentially increase the flow of tar sands to be refined by California coal and oil refineries, furthering our reliance on fossil fuels. Understanding that coal combustion and oil refining are some of the key contributors to atmospheric and aquatic mercury pollution allows for government interference to stop further pollution but it requires the help of the American people in passing new laws and regulations.

There are ways that the government can intervene between these coal and oil companies to limit the amount of mercury evaporation. BayKeeper, a San Francisco based organization focused on reducing mercury pollution around the bay, has stated a number of ways to monitor and regulate mercury pollution. Below are their solutions.

A couple ways the government can help out:

- Require municipal and industrial waste water dischargers to monitor methyl mercury levels in discharges to the bay.
- Strengthen requirements to protect communities that rely on fish out of the bay as a food source.
- Require dischargers to undertake and fund efforts to protect our communities from mercury contamination.
- Improve strategies to deal with dredged spoils that are high in mercury levels.

The solutions above are virtually calling for oil refineries and coal combustion facilitators to internalize their externalities, in this case, evaporation of mercury into the Earth's atmosphere. These solutions call for the basic ownership and responsibility for one's pollution, a byproduct of their main production. If the government requires coal combustors and oil refineries to take control of their external pollution by setting a federal standard or law demanding awareness of and accountability for emission of green house gases then all companies have to take measures to regulate their pollution.

Pollution permits are another solution that don't necessarily solve the problem of industrial pollution but rather present the polluter with a fiscally weighted choice. The prices of these permits to pollute would most likely be on the higher end of the spectrum of prices making internalization of external pollution and green house gas emission a cheaper method to facilitate rather than buying a permit. So, by raising the price of pollution the government can hope to move refineries and combustors in the direction of technological innovation, regulating and controlling their own pollution simply because it cheaper than paying to pollute.

The innovation method towards regulation of pollution also opens up jobs in the renewable energy sector as companies seek cleaner ways of producing energy. Companies wishing to innovate for cleaner methods of production could also potentially receive government subsidies for their research on renewable energy.

Another form of regulation that the government can use is taxation. The first carbon tax has already been designed and brought forward to Congress to consider in order to regulate and potentially curve industrial emissions. The permit system stated earlier is just another form of taxation in disguise, although it works. All these methods of regulation via taxing and permitting, forcing companies to internalize their externalities, are all effective in reducing

industries carbon footprint and mercury pollution.

Of course the desirable end is to eliminate the mercury present in the Bay Area completely however, that takes time, about 70 years to be specific. The bay filters naturally as it regularly exchanges fresh water with salt water from the Pacific Ocean but the government can still step in to halt further mercury accumulation in the Bay Area.

The biggest factor in mercury contribution in the past was the Gold Rush, now most of the deposits come from coal and oil refineries. Sure innovating to regulate industrial pollution and emissions cost money, but if less people are experiencing asthma due to dirty air and nerve damage due to mercury exposure, aren't we all a little more productive because we're healthier? Controlling coal combustion and mercury evaporation not only benefits the American people allowing for better health but also potentially stimulates the economy as it moves the energy market towards cleaner, renewable energy.

Visit EcoWatch's ENERGY page for more related news on this topic.

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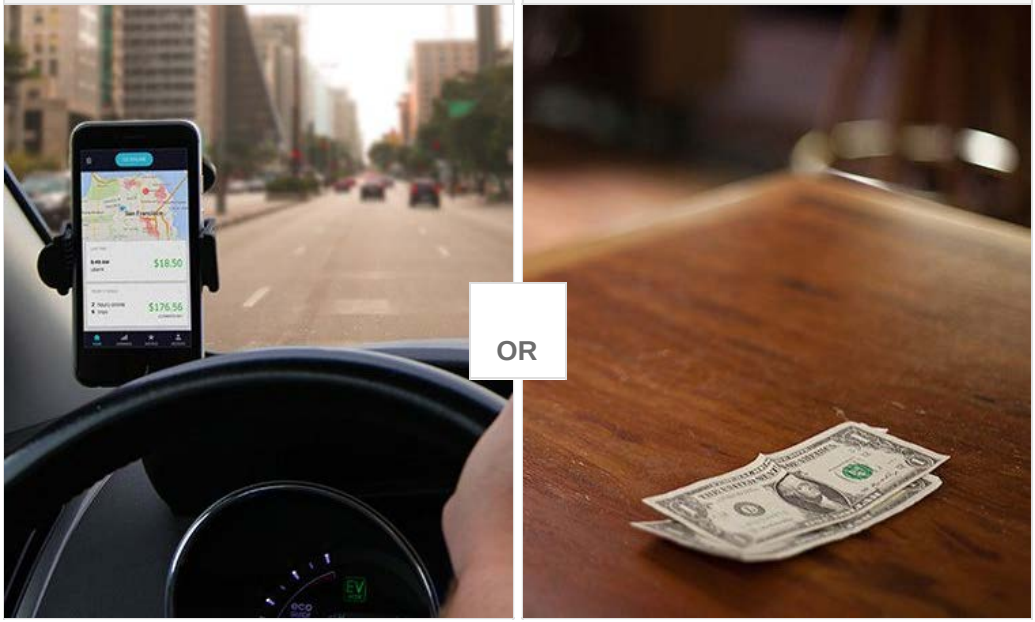

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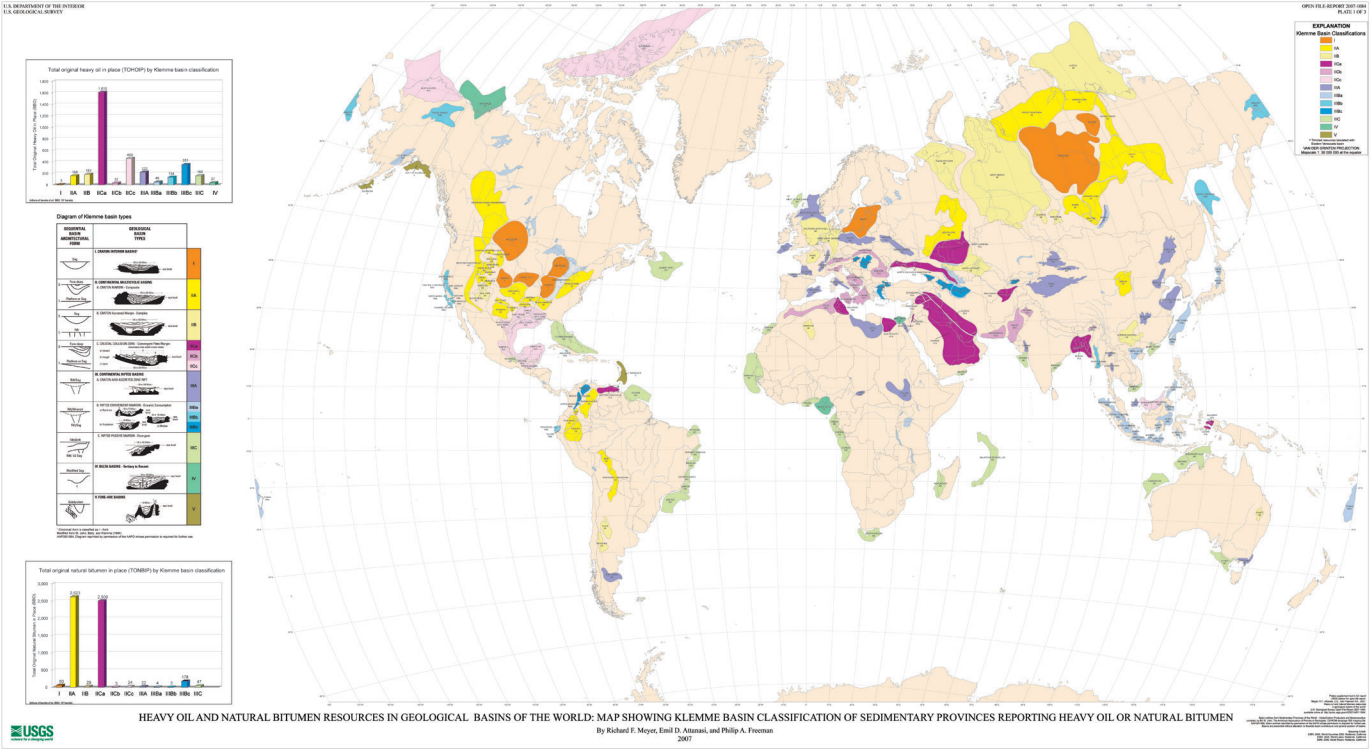
Heavy Oil and Natural Bitumen Resources in Geological Basins of the World



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Heavy Oil and Natural Bitumen Resources in Geological Basins of the World

By Richard F. Meyer, Emil D. Attanasi, and Philip A. Freeman

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Heavy Oil and Natural Bitumen Resources in Geological Basins of the World

By Richard F. Meyer, Emil D. Attanasi, and Philip A. Freeman

Abstract

Heavy oil and natural bitumen are oils set apart by their high viscosity (resistance to flow) and high density (low API gravity). These attributes reflect the invariable presence of up to 50 weight percent asphaltenes, very high molecular weight hydrocarbon molecules incorporating many heteroatoms in their lattices. Almost all heavy oil and natural bitumen are alteration products of conventional oil. Total resources of heavy oil in known accumulations are 3,396 billion barrels of original oil in place, of which 30 billion barrels are included as prospective additional oil. The total natural bitumen resource in known accumulations amounts to 5,505 billion barrels of oil originally in place, which includes 993 billion barrels as prospective additional oil. This resource is distributed in 192 basins containing heavy oil and 89 basins with natural bitumen. Of the nine basic Klemme basin types, some with subdivisions, the most prolific by far for known heavy oil and natural bitumen volumes are continental multicyclic basins, either basins on the craton margin or closed basins along convergent plate margins. The former includes 47 percent of the natural bitumen, the latter 47 percent of the heavy oil and 46 percent of the natural bitumen. Little if any heavy oil occurs in fore-arc basins, and natural bitumen does not occur in either fore-arc or delta basins.

Introduction

Until recent years conventional, light crude oil has been abundantly available and has easily met world demand for this form of energy. By year 2007, however, demand for crude oil worldwide has substantially increased, straining the supply of conventional oil. This has led to consideration of alternative or insufficiently utilized energy sources, among which heavy crude oil and natural bitumen are perhaps the most readily available to supplement short- and long-term needs. Heavy oil has long been exploited as a source of refinery feedstock, but has commanded lower prices because of its lower quality relative to conventional oil. Natural bitumen is a very viscous crude oil that may be immobile in the reservoir. It typically requires upgrading to refinery feedstock grade (quality). When natural bitumen is mobile in the reservoir, it is generally known as extra-heavy oil. As natural asphalt, bitumen has been exploited since antiquity as a source of road paving, caulk, and mortar and is still used for these purposes in some parts of the world. The direct use of mined asphalt for road paving is now almost entirely local, having been replaced by manufactured asphalt, which can be tailored to specific requirements.

This study shows the geological distribution of known heavy oil and natural bitumen volumes by basin type. These data are presented to advance a clearer understanding of the relationship between the occurrence of heavy oil and natural bitumen and the type of geological environment in which these commodities are found. The resource data presented were compiled from a variety of sources. The data should not be considered a survey of timely resource information such as data published annually by government agencies and public reporting services. With the exception of Canada, no such data source on heavy oil and natural bitumen accumulations is available. The amounts of heavy oil yet unexploited in known deposits represent a portion of future supply. To these amounts may be added the heavy oil in presently poorly known and entirely unexploited deposits. Available information indicates cumulative production accounts for less than 3 percent of the discovered heavy oil originally in place and less than 0.4 percent of the natural bitumen originally in place.

Terms Defined for this Report

- Conventional (light) Oil: Oil with API gravity greater than 25°.
- Medium Oil: Oil with API gravity greater than 20°API but less than or equal to 25°API.
- Heavy Oil: Oil with API gravity between 10°API and 20°API inclusive and a viscosity greater than 100 cP.
- Natural Bitumen: Oil whose API gravity is less than 10° and whose viscosity is commonly greater than 10,000 cP. It is not possible to define natural bitumen on the basis of viscosity alone because much of it, defined on the basis of gravity, is less viscous than 10,000 cP. In addition, viscosity is highly temperature-

dependent (fig. 1), so that it must be known whether it is measured in the reservoir or in the stock tank. In dealing with Russian resources the term natural bitumen is taken to include both maltha and asphalt but excludes asphaltite.

- Total Original Oil in Place (TOOIP): Both discovered and prospective additional oil originally in place.
- Original Oil in Place-Discovered (OOIP-Disc.): Discovered original oil in place.
- Reserves (R): Those amounts of oil commonly reported as reserves or probable reserves, generally with no further distinction, and quantities of petroleum that are anticipated to be technically but not necessarily commercially recoverable from known accumulations. Only in Canada are reserves reported separately as recoverable by primary or enhanced methods. Russian reserve classes A, B, and C1 are included here (See Grace, Caldwell, and Hether,1993, for an explanation of Russian definitions.)
- Prospective Additional Oil in Place: The amount of resource in an unmeasured section or portion of a known deposit believed to be present as a result of inference from geological and often geophysical study.
- Original Reserves (OR): Reserves plus cumulative production. This category includes oil that is frequently reported as estimated ultimately recoverable, particularly in the case of new discoveries.

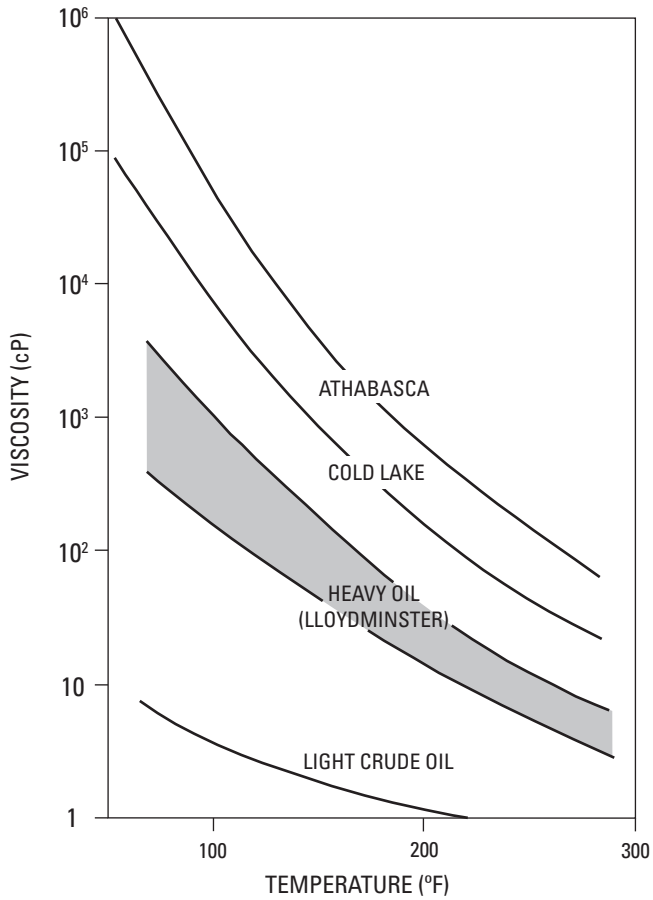

Figure 1. Response of viscosity to change in temperature for some Alberta oils (cP, centipoise), (Raicar and Proctor, 1984).

Chemical and Physical Properties

Fundamental differences exist between natural bitumen, heavy oil, medium oil, and conventional (light) oil, according to the volatilities of the constituent hydrocarbon fractions: paraffinic, naphthenic, and aromatic. When the light fractions are lost through natural processes after evolution from organic source materials, the oil becomes heavy, with a high proportion of asphaltic molecules, and with substitution in the carbon network of heteroatoms such as nitrogen, sulfur, and oxygen. Therefore, heavy oil, regardless of source, always contains the heavy fractions, the asphaltics, which consist of resins, asphaltenes, and preasphaltenes (the carbene-carboids) (Yen, 1984). No known heavy oil fails to incorporate asphaltenes. The large asphaltic molecules define the increase or decrease in the density and viscosity of the oil. Removal or reduction of asphaltene or preasphaltene drastically affects the rheological properties of a given oil and its aromaticity (Yen, 1984). Asphaltenes are defined formally as the crude oil fraction that precipitates upon addition of an n-alkane, usually n-pentane or n-heptane, but remains soluble in toluene or benzene. In the crude oil classification scheme of Tissot and Welte (1978), the aromatic-asphaltics and aromatic-naphthenics characterize the heavy oil and natural bitumen deposits of Canada and Venezuela and are the most important of all crude oil classes with respect to quantity of resources. The aromatic-intermediate class characterizes the deposits of the Middle East (Yen, 1984).

Some of the average chemical and physical properties of conventional, medium, and heavy crude oils and natural bitumen are given in table 1, in order to show their distinguishing characteristics. The data are derived from multiple sources, some old and others adhering to standards employed in different countries. The conversion factors outlined in table 2 were used to convert published data to a uniform standard. Some of the properties in table 1 are important with respect to heavy oil and natural recovery from the ground and other properties in table 1 serve as the basis for decisions for upgrading and refinery technologies. Moving across table 1 from conventional oil to natural bitumen, increases may be seen in density (shown as reductions in API gravity), coke, asphalt, asphaltenes, asphaltenes + resins, residuum yield (percent volume), pour point, dynamic viscosity, and the content of copper, iron, nickel, vanadium among the metals and in nitrogen and sulfur among the non-metals. Values diminish for reservoir depth, gasoline and gas-oil yields, and volatile organic compounds (VOC and BTEX –Benzene, Toluene, Ethylbenzene, and

Xylenes). The significance of these differences is often reflected in the capital and operating expenses required for the recovery, transportation, product processing, and environmental mitigation of the four oil types. The principal sources of analytical data for table 1 are Environmental Technology Centre (2003), Hyden (1961), Oil & Gas Journal Guide to Export Crudes (2006), U.S. Department of Energy, National Energy Technology Laboratory (1995), and various analyses published in technical reports.

The resins and asphaltenes play an important role in the accumulation, recovery, processing, and utilization of petroleum. The resins and asphaltenes are the final form of naphtheno-aromatic molecules. The carbon skeleton appears to comprise three to five polyaromatic sheets, with some heterocyclic (N-S-O) compounds. These crystallites may combine to form high molecular weight aggregates, with the high viscosity of heavy oils related to the size and abundance of the aggregates. Most asphaltenes are generated from kerogen evolution in response to depth and temperature increases in sedimentary basins. Different types of asphaltenes may be derived from the main kerogen types. Asphaltenes are not preferentially mobilized, as are light hydrocarbons during migration from source rocks to reservoir beds, where they are less abundant if the crude oil is not degraded (Tissot, 1981).

Some heavy oil and natural bitumen originates with chemical and physical attributes shown in table 1 as immature oil which has undergone little if any secondary migration. The greatest amount of heavy oil and natural bitumen results from the bacterial degradation under aerobic conditions of originally light crude oils at depths of about 5,000 feet or less and temperatures below 176°F. The consequence of biodegradation is the loss of most of the low molecular weight volatile paraffins and naphthenes, resulting in a crude oil that is very dense, highly viscous, black or dark brown, and asphaltic. An active water supply is required to carry the bacteria, inorganic nutrients, and oxygen to the oil reservoir, and to remove toxic by-products, such as hydrogen sulfide, with low molecular weight hydrocarbons providing the food (Barker, 1979). The low molecular weight components also may be lost through water washing in the reservoir, thermal fractionation, and evaporation when the reservoir is breached at the earth's surface (Barker, 1979). The importance of this process to the exploitation of heavy oil and natural bitumen lies in the increase of NSO (nitrogen-sulfur-oxygen) compounds in bacterially-altered crude oil and the increase in asphaltenes (Kallio, 1984).

Bacterial degradation of crude oil may also take place under anaerobic conditions, thus obviating the need for a fresh water supply at shallow depths (Head, Jones, and Larter, 2003; Larter and others, 2006). This proposal envisions degradation even of light oils at great depths so long as the maximum limiting temperature for bacterial survival is not exceeded. This theory does not account in any obvious way for the high percentage in heavy oil and natural bitumen of polar asphaltics, that is, the resins and asphaltenes.

Oil mass loss entailed in the formation of heavy oil and natural bitumen deposits has been the subject of numerous research studies. Beskrovnyi and others (1975) concluded that three to four times more petroleum was required than the reserves of a natural bitumen for a given deposit. Based upon material balance calculations in the Dead Sea basin, Tannenbaum, Starinsky, and Aizenshtat (1987) found indications that 75% of the original oil constituents in the C15+ range had been removed as a result of alteration processes. By accounting for the lower carbon numbers as well, they estimated that the surface asphalts represented residues of only 10-20% of the original oils. Head, Jones, and Larter (2003) diagram mass loss increasing from essentially zero for conventional oil to something more than 50% for heavy oils, which of themselves are subject to no more than 20% loss. Accompanying the mass loss is a decrease in API gravity from 36° to 5-20°; decrease in gas/oil ratio from 0.17 kg gas/kg oil; decrease in gas liquids from 20% to 2%; increase in sulfur from 0.3wt% to 1.5+wt%; and decrease in C15+ saturates from 75% to 35%. This calculation of mass loss shows: (1) the enormous amount of oil initially generated in heavy oil and natural bitumen basins, especially Western Canada Sedimentary and Eastern Venezuela basins; and (2) the huge economic burden imposed by this mass loss on the production-transportation-processing train of the remaining heavy oil and natural bitumen.

Origins of Heavy Oil and Natural Bitumen

It is possible to form heavy oil and natural bitumen by several processes. First, the oil may be expelled from its source rock as immature oil. There is general agreement that immature oils account for a small percentage of the heavy oil (Larter and others, 2006). Most heavy oil and natural bitumen is thought to be expelled from source rocks as light or medium oil and subsequently migrated to a trap. If the trap is later elevated into an oxidizing zone, several processes can convert the oil to heavy oil. These processes include water washing, bacterial degradation and evaporation. In this case, the biodegradation is aerobic. A third proposal is that biodegradation can also occur at depth in subsurface reservoirs (Head, Jones, and Larter, 2003; Larter and others, 2003; Larter and others, 2006). This explanation permits biodegradation to occur in any reservoir that has a water leg and has not been heated to more than 176° F. The controls on the biodegradation depend on local factors rather than basin-wide factors. Because the purpose of this report is to describe the geologic basin setting of the known heavy oil and natural bitumen deposits, it is beyond the scope of this report to argue the source or genesis of heavy oil and natural bitumen for each basin of the world.

Data Sources

Data for heavy oil resource occurrences and quantities for individual oilfields and reservoirs have been compiled from many published reports and commercial data bases. The most important of these include Demaison (1977), IHS Energy Group (2004), NRG Associates (1997), Parsons (1973), Roadifer (1987), Rühl (1982), and the U.S. Department of Energy, National Energy Technology Laboratory (1983, 2005)

Data for natural bitumen deposits in the United States are summarized in U.S Department of Energy, National Energy Technology Laboratory (1991), but information for Utah is taken from Oblad and others (1987) and Ritzma (1979). Although there is no single data source for deposits outside the United States, there is a rich literature, particularly for Russia and the countries of the Former Soviet Union. For Canada, reliance is placed on reports of the Alberta Energy and Utilities Board (2004) and Saskatchewan Industry and Resources (2003).

Resource Estimates

We consider the total original oil in place (OOIP) to be the most useful parameter for describing the location and volume of heavy oil and natural bitumen resources. Resource quantities reported here are based upon a detailed review of the literature in conjunction with available databases, and are intended to suggest, rather than define the resource volumes that could someday be of commercial interest. If only a recoverable volume of heavy oil for the accumulation was published, the discovered OOIP was computed according to the protocol set forth in table 3.

Natural bitumen originally in place is often reported in the literature. Where only a recoverable estimate is published, the in-place volumes were calculated according to the protocols given for heavy oil; this is especially the case for bitumen deposits above 4°API gravity, to which we arbitrarily refer as extra-heavy oil.

Poorly known deposits of heavy oil and natural bitumen are included in the category of prospective additional resources, as described in table 3. In no case are values for prospective additional resource volumes calculated as in the case of discovered resources but were taken directly from the published literature.

Table 4 summarizes the resources and essential physical parameters of the heavy oil and natural bitumen contained in each of the basin types. These characteristics affect heavy oil and natural bitumen occurrence and recovery. Recovery can be primary, as in the case of cold production without gravel packing, if the gas to oil ratio is high enough to provide necessary reservoir energy. Otherwise, recovery generally necessitates the application of enhanced recovery methods, such as thermal energy or the injection of solvents.

Recovery Methods

How the reservoir parameters apply to enhanced recovery is summarized from Taber, Martin, and Seright (1997a, 1997b) in table 5, which covers the most commonly used, or at least attempted enhanced oil recovery (EOR) methods. Of these methods, immiscible gas injection, polymer flooding, and *in situ* combustion (fireflood) have met with limited success for heavy oil and natural bitumen. Steam injection (cyclic steam, huff ‘n puff) has been most successful, frequently by use of cyclic steam, followed by steam flooding. Surface mining and cold *in situ* production are usually considered to be primary recovery methods. They can be suited to the extraction of heavy oil and natural bitumen under proper conditions.

Most of the process descriptions which follow are taken from Taber, Martin, and Seright (1997b). Many processes may result in the process agent, such as nitrogen or carbon dioxide, remaining immiscible with the reservoir hydrocarbon or else becoming miscible with it. The miscibility is dependent upon the minimum miscibility pressure (MMP) and determines the way in which the process agent achieves EOR. While this summary discussion shows the breadth of the EOR processes operators have tried and continue to try as experimental projects, thermal EOR methods account for most of the heavy oil that is commercially produced. Data on the frequency of the applications are taken, unless otherwise cited, from the Oil and Gas Journal Historical Review, 1980-2006 (2006), particularly the Oil and Gas Journal 2000 and 2006 EOR Surveys.

Nitrogen gas drive is low in cost and therefore may be used in large amounts. It is commonly used with light oils for miscible recovery. However, it may also be used for an immiscible gas flood. The Oil and Gas Journal 2000 Survey includes one immiscible nitrogen gas drive in a sandstone reservoir with 16˚API oil at 4,600 feet depth. It was reported to be producing 1,000 barrels per day (b/d) of enhanced production. The Journal’s 2006 Survey reports one each heavy oil nitrogen miscible and nitrogen immiscible projects. The miscible project is 19˚API, located in the Bay of Campeche, with 19 wells, but with no report of production capacity. The immiscible project has oil of 16˚API at 4,600 feet in sandstone. For this project total production is reported to be 1,500 b/d of which 1,000 b/d is enhanced by immiscible nitrogen injection.

Of the 77 CO2 projects in the Journal 2000 Survey, 70 are for miscible CO2 and none entails heavy oil. This is true also in the Journal 2006 Survey, where all 86 CO2 projects are devoted to light oil, above 28˚API. In the Journal 2000 Survey, five of the seven immiscible CO2 projects are applied to heavy oil reservoirs, four in clastics and one in limestone. The latter, in the West Raman field in Turkey, involves oil of 13°API, lies at 4,265 feet, and produces 8,000 b/d. The reservoir contains nearly two billion barrels of original oil in place. Recoverable reserves remain low because of the recalcitrance of the reservoir. Steam flooding has been unsuccessful. By the date of the Journal 2006, there are eight immiscible CO2 projects, with five of them entailing heavy oil amounting to 7,174 b/d. The

two largest projects are light oil and heavy oil and are each in carbonate reservoirs.

Polymer/chemical flooding includes micellar/polymer, alkaline-surfactant-polymer (ASP), and alkaline fluids (Taber, Martin, and Seright, 1997a, 1997b). Recovery is complex, leading to the lowering of interfacial tension between oil and water, solubilization of oil in some micellar systems, emulsification of oil and water, wettability alteration, and enhancement of mobility. Limitations and costs indicate for these floods the desirability of clean clastic formations. The Journal 2000 Survey shows five heavy oil polymer/chemical floods of 15°API in sandstone reservoirs at about 4,000 feet. They were producing about 366 b/d and the projects were deemed successful or promising. Projects such as these are below the desirable gravity limits and are more viscous than desired at 45 cP.

Polymer floods improve recovery over untreated water flood by increasing the viscosity of the water, decreasing thus the mobility of the water, and contacting a larger volume of the reservoir. The advantages of a polymer flood over a plain water flood are apparent. The Journal 2000 Survey lists 22 polymer flood projects, of which five involve heavy oil. These five are within the range of the polymer screen, although the gravities are marginal, lying from 13.5°API to a bit above 15°API. The five were producing 7,140 b/d, of which 2,120 b/d were attributed to EOR. The Journal 2006 Survey shows 20 polymer floods, with five exploring heavy oil reservoirs. Three of the five are producing 7,140 b/d total oil and 2,120 b/d of enhanced production.

The Journal 2000 Survey shows four hot water floods, one of which is heavy oil with a gravity of 12°API, viscosity of 900 cP, and starting saturation of only 15 percent. Project production was 300 b/d. Two of three hot water floods included in the Journal 2006 Survey are intended to enhance production of heavy oil. The two yield about 1,700 b/d of total oil and 1,700 b/d of enhanced hot water flood oil.

In situ combustion (fire flood) is theoretically simple, setting the reservoir oil on fire and sustaining the burn by the injection of air. Usually, the air is introduced through an injector well and the combustion front moves toward to the production wells. A variant is to include a water flood with the fire, the result being forward combustion with a water flood. Another variant is to begin a fire flood, then convert the initial well to a producer and inject air from adjacent wells. The problem with this reverse combustion is that it doesn't appear to work.

In situ combustion leads to oil recovery by the introduction of heat from the burning front, which leads to reduction in viscosity. Further, the products of steam distillation and thermal cracking of the reservoir oil are carried forward to upgrade the remaining oil. An advantage of the process is that the coke formed by the heat itself burns to supply heat. Lastly, the injected air adds to the reservoir pressure. The burning of the coke sustains the process so that the process would not work with light oil deficient in asphaltic components. The process entails a number of problems, some severe, but the Journal 2000 Survey shows 14 combustion projects, of which five are light oil and the remaining nine are heavy, between 13.5°API and 19°API. Viscosities and starting oil saturations are relatively high. It is notable that the heavy oil projects are in sandstones and the light oil in carbonates. The heavy oil *in situ* combustion projects were producing about 7,000 b/d. The Journal 2006 Survey includes nine heavy oil combustion projects among a total of twenty-one. The heavy oil projects yield about 7,000 b/d of combustion-enhanced oil, which ranges from 13.5˚API to 19˚API.

Steam injection for EOR recovery is done in two ways, either by cyclic steam injection (huff 'n puff) or continuous steam flood. Projects are frequently begun as cyclic steam, whereby a high quality steam is injected and soaks the reservoir for a period, and the oil, with lowered viscosity from the heat, is then produced through the injection well. Such soak cycles may be repeated up to six times, following which a steam flood is initiated. In general, steam projects are best suited to clastic reservoirs at depths no greater than about 4,000 feet, and with reservoir thicknesses greater than 20 feet and oil saturations above 40% of pore volume. For reservoirs of greater depth the steam is lowered in quality through heat loss to the well bore to where the project becomes a hot water flood. Steam is seldom applied to carbonate reservoirs in large part due to heat loss in fractures.

The Journal 2000 Survey lists 172 steam drive projects. Of these, four in Canada give no gravity reading, thirteen are medium oil from 22°API to 25°API, and the rest are heavy oil. The largest of all is at Duri field in Indonesia and this oil is 22°API. For the project list as a whole, the average gravity is 14°API, with a maximum value of 30°API and a minimum of 4°API. The average viscosity is 37,500 cP, with maximum and minimum values of 5,000,000 cP and 6 cP. Oil saturations range from 35% to 90%, the average being 68%. Most importantly, production from the project areas was 1.4 million b/d and of this, 1.3 million b/d was from steam drive EOR.

All but three of the 120 steam projects found in the Journal 2006 Survey entail recovery of heavy oil. The oil averages 12.9˚API, with a low value of 8˚API and a high of 28˚API (one of the three light oil reservoirs). The viscosity averages 58,000 cP, with a high value of 5 million cP and a low of 2 cP. The projects are yielding over 1.3 million b/d, virtually all being steam EOR.

Maps

The geographic distribution of basins reporting heavy oil and natural bitumen, as identified by their Klemme basin types, appears on Plate 1. A diagram of the Klemme basin classification illustrates the architectural form and the geological basin structure by type. This plate also includes histograms of the total original oil in place resource volumes of both heavy oil and natural bitumen. Plates 2 and 3, respectively, depict the worldwide distribution of heavy oil and natural bitumen resources originally in place. Each map classifies basins

by the reported volumes of total original oil in place. A table ranks the basins by total original oil in place volumes besides indicating Klemme basin type and reporting discovered original oil in place and prospective additional oil in place. Plates 2 and 3 also include an inset map of the geographic distribution of original heavy oil or natural bitumen by 10 world regions (see table 6 for regional listing of countries reporting heavy oil or natural bitumen.)

Basin outlines of the sedimentary provinces are digitally reproduced from the AAPG base map compiled by St. John (1996). The basin outlines of St. John (1996) are unaltered. However, the reader should note that the basin outlines are considered to be generalizations useful for displaying the resource distributions but are less than reliable as a regional mapping tool. Also, some basin names have been changed to names more commonly used by geologists in the local country. These equivalent names and the original names from Bally (1984) and St. John (1996) are detailed in table 1-1 in Appendix 1. The basin outline for Eastern Venezuela as shown does not include the island of Trinidad where both heavy oil and natural bitumen resources occur. For this report, resources from Trinidad and Tobago are reported in the Eastern Venezuela basin totals. In a few cases a single basin as outlined on the plates is composed of multiple basins to provide more meaningful local information. This is particularly true in the United States, where the AAPG-CSD map was employed (Meyer, Wallace, and Wagner, 1991). In each case, the individual basins retain the same basin type as the basin shown on the map and all such basins are identified in Appendix 1.

Basins having heavy oil or natural bitumen deposits are listed in table 2-1 in Appendix 2 along with the Klemme basin type, countries and U.S. states or Canadian provinces reporting deposits and other names cited in literature. The Klemme basin classification diagram in Plate 1 is reprinted in fig. 3-1 in Appendix 3 for the reader's convenience. The tables from Plates 2 and 3 are reprinted as table 4-1 and table 4-2 for the reader's convenience.

Klemme Basin Classification

Many classifications of petroleum basins have been prepared. In one of the earliest, Kay (1951) outlined the basic architecture of geosynclines, with suggestions as to their origins. Kay's work preceded the later theory of plate tectonics. Klemme (1977, 1980a, 1980b, 1983, 1984) gives a summary description of petroleum basins together with their classification, based upon basin origin and inherent geological characteristics. This classification is simple and readily applicable to the understanding of heavy oil and natural bitumen occurrence. The Klemme basin types assigned to the heavy oil and natural bitumen basins described in this report correspond to the assignments made in St. John, Bally, and Klemme (1984). In some cases of multiple type designations in St. John, Bally, and Klemme (1984) a unique type designation was resolved by reference to Bally (1984) or Bally and Snelson (1980). Only a few of the basins originally designated as multiple types in St. John, Bally and Klemme (1984) appear to contain heavy oil and natural bitumen.

Table 7 summarizes the criteria upon which Klemme based his classification. The general description of the resource endowment associated to the Klemme basin classification is based upon oilfield (and gasfield) data of the world as of 1980 without regard to the density or other chemical attributes of the hydrocarbons they contain (Klemme, 1984). At the time of Klemme's work, the average density U.S. refinery crude oil was about 33.7°API (Swain, 1991). A decline in the average to about 30.6°API by 2003 perhaps signifies the increasing importance of heavy oil in the mix (Swain, 2005).

Generally, basins may be described as large or small and linear or circular in shape. They may also be described by the ratio of surface area to sedimentary volume. The basement profile or basin cross-section, together with the physical description, permits the interpretation of the fundamental basin architecture. The basin can then be placed within the relevant plate tectonic framework and assigned to one of four basin types, of which two have sub-types. A diagram of the Klemme basin types appears on Plate 1, color-coded to the basins on the map.

In the following section we provide descriptions of the basin types from Klemme (1980b, 1983, 1984) followed by discussion of the heavy oil and natural bitumen occurrences within those same basin types, summary data for which are given in table 4. Because most heavy oil and natural bitumen deposits have resulted from the alteration of conventional and medium oil, the factors leading to the initial conventional and medium oil accumulations are relevant to the subsequent occurrence of heavy oil and natural bitumen.

Type I. Interior Craton Basins

The sediment load in these basins is somewhat more clastic than carbonate. Reservoir recoveries are low and few of the basins contain giant fields. Traps are generally related to central arches, such as the Cincinnati arch, treated here as a separate province (Plates 1-3), or the arches of the Siberian platform (see below for further explanation). Traps also are found in smaller basins over the craton, such as the Michigan basin. The origin of these depressions is unclear although most of them began during the Precambrian (Klemme, 1980a, 1980b).

The six Type I basins having heavy oil contain less than 3 billion barrels of oil in place and of this 93% occurs in the Illinois basin alone. Four Type I basins that contain natural bitumen have 60 billion barrels of natural bitumen in place, with nearly 99% in the Tunguska basin in eastern Siberia and the rest in the Illinois basin. The Tunguska basin covers most of the Siberian platform, around the borders of which are found cratonic margin basins of Type IIA. For convenience all the resource is assigned to the Tunguska basin. The prospec-

tive additional resource of 52 billion barrels is almost certainly an absolute minimum value for this potentially valuable but difficult to access area (Meyer and Freeman, 2006.)

Type II. Continental Multicyclic Basins

Type IIA. Craton margin (composite)

These basins, formed on continental cratonic margins, are generally linear, asymmetrical in profile, usually beginning as extensional platforms or sags and ending as compressional foredeeps. Therefore they are multicyclic basins featuring a high ratio of sediment volume to surface area. Traps are mainly large arches or block uplifts and may be found in rocks of either the lower (platform) or upper (compression) tectonic cycle. About 14% of conventional oil discovered in the world by 1980 is from marginal cratonic basins (Klemme, 1980a, 1980b).

Type IIA basins are of moderate importance with respect to heavy oil, with about 158 billion barrels of oil in place distributed among 28 basins. Three Type IIA basins, the Western Canada Sedimentary, Putumayo, and Volga-Ural, have combined total heavy oil resource of 123 billion barrels of oil in place, or 78% of the total for Type IIA basins.

In comparison, natural bitumen in 24 Type IIA basins accounts for 2,623 billion barrels of natural bitumen in place, or nearly 48% of the world natural bitumen total. The Western Canada Sedimentary basin accounts for 2,334 billion barrels of natural bitumen in place, or about 89%. Of the Canadian total, 703 billion barrels of natural bitumen in place is prospective additional oil, largely confined to the deeply buried bitumen in the carbonate that underlie the Peace River and part of the Athabasca oil sand deposit in an area known as the Carbonate Triangle. The significance of the Canadian deposits lies in their concentration in a few major deposits: Athabasca, from which the reservoir is exploited at or near the surface and shallow subsurface, and Cold Lake and Peace River, from which the bitumen is extracted from the subsurface. Two other basins contain much less but still significant amounts of natural bitumen, the Volga-Ural basin in Russia (263 billion barrels of natural bitumen in place) and the Uinta basin in the United States (12 billion barrels of natural bitumen in place). The Volga-Ural deposits are numerous, but individually are small and mostly of local interest. The Uinta deposits are much more concentrated aerially, but are found in difficult terrain remote from established transportation and refining facilities.

Type IIB. Craton accreted margin (complex)

These basins are complex continental sags on the accreted margins of cratons. Architecturally, they are similar to Type IIA basins, but begin with rifting rather than sags. About three-quarters of Type IIA and IIB basins have proven productive, and they contain approximately one-fourth of the world's total oil and gas (Klemme, 1980a, 1980b).

The 13 Type IIB basins contain a moderate amount of heavy oil (193 billion barrels of oil in place). The two most significant basins are in Russia, West Siberia and Timan-Pechora. These, together with most of the other Type IIB heavy oil basins, are of far greater importance for their conventional and medium oil resources.

Five Type IIB basins hold 29 billion barrels of natural bitumen in place. Only the Timan-Pechora basin contains significant natural bitumen deposits, about 22 billion barrels of natural bitumen in place. Unfortunately, this resource is distributed among a large number of generally small deposits.

Type IIC. Crustal collision zone (convergent plate margin)

These basins are found at the crustal collision zone along convergent plate margins, where they are downwarped into small ocean basins. Although they are compressional in final form, as elongate and asymmetrical foredeeps, they begin as sags or platforms early in the tectonic cycle. Type IIC downwarp basins encompass only about 18 percent of world basin area, but contain nearly one-half of the world's total oil and gas. These basins are subdivided into three subtypes, depending on their ultimate deformation or lack thereof: Type IICa, closed; Type IICb, trough; and Type IICc, open (Klemme, 1980a, 1980b).

Although basins of this type begin as downwarps that opened into small ocean basins (Type IICc), they may become closed (Type IICa) as a result of the collision of continental plates. Upon closing, a large, linear, asymmetric basin with sources from two sides is formed, resembling a Type IIA basin. Further plate movement appears to destroy much of the closed basin, leaving a narrow, sinuous foredeep, that is, a Type IICb trough. Relatively high hydrocarbon endowments in the open and the closed types may be related to above-normal geothermal gradients, which accentuates hydrocarbon maturation and long-distance ramp migration. Traps are mostly anticlinal, either draping over arches or compressional folds, and are commonly related to salt flowage.

Type IICa basins, with their architectural similarity to Type IIA basins, are the most important of the three Type IIC heavy oil basins. The 15 basins account for 1,610 billion barrels of the heavy oil in place, with the Arabian, Eastern Venezuela, and Zagros basins containing 95% of the total. Of particular interest is the Eastern Venezuela basin which includes large accumulations of conventional and medium oil, while at the same time possessing an immense resource of both heavy oil and natural bitumen.

Type IICa basins also are rich in natural bitumen, with a total of 2,507 billion barrels of natural bitumen in place among the six. About 83% of this occurs in Venezuela, mostly in the southern part of the Eastern Venezuelan basin known as the Orinoco Oil Belt. Here the reservoir rocks impinge upon the

Guyana craton in much the same fashion as the reservoir rocks of the Western Canada Sedimentary basin lap onto the Canadian shield. The only other significant Type IICa accumulation of natural bitumen is found in the North Caspian basin (421 billion barrels of natural bitumen in place).

Fourteen Type IICb basins contain modest amounts of heavy oil (32 billion barrels of oil in place) and even less of natural bitumen (5 billion barrels of natural bitumen in place in seven basins). Much of this resource is found in the Caltanisetta and Durres basins, on either side of the Adriatic Sea. Durres basin resources are aggregated with the South Adriatic and the province is labeled South Adriatic on the plates. Significant amounts of the Caltanisetta resource occurs offshore.

The amount of heavy oil in the 12 Type IICc basins is substantial (460 billion barrels of oil in place). The Campeche, by far the largest, and Tampico basins in Mexico and the North Slope basin in the United States account for 89% of the heavy oil. The Campeche field, which is actually an assemblage of closely associated fields, is found about 65 miles offshore of the Yucatan Peninsula in the Gulf of Mexico. The North Slope basin, on the north coast of Alaska, occurs in an area of harsh climate and permafrost, which makes heavy oil and natural bitumen recovery by the application of thermal (steam) methods difficult both physically and environmentally. The U.S. fields in the East Texas, Gulf Coast, and Mississippi Salt Dome basins account for only 5% of the heavy oil in basins of this type.

Only a small amount of natural bitumen (24 billion barrels) has been discovered in eight Type IICc basins. Two of these, the North Slope and South Texas Salt Dome basins, are significant for possible future development.

Type III. Continental Rifted Basins

Type IIIA. Craton and accreted zone (rift)

These are small, linear continental basins, irregular in profile, which formed by rifting and simultaneous sagging in the craton and along the accreted continental margin. About two-thirds of them are formed along the trend of older deformation belts and one-third are developed upon Precambrian shields. Rifts are extensional and lead to block movements so that traps are typically combinations. Oil migration was often lateral, over short distances. Rift basins are few, about five percent of the world's basins, but half of them are productive. Because of their high recovery factors, Type IIIA basins accounted for 10% of the world's total recoverable oil and gas in 1980 (Klemme, 1980a, 1980b).

Globally, there are 28 Type IIIA heavy oil basins, containing 222 billion barrels of oil in place The Bohai Gulf basin in China accounts for 63% of the heavy oil, with an additional 11% derived from the Gulf of Suez and 10% from the Northern North Sea. Outside of these, most Type IIIA basins contain just a few deposits. The five basins in Type IIIA have almost 22 billion barrels of natural bitumen in place, but half of that is located in the Northern North Sea basin.

Type IIIB. Rifted convergent margin (oceanic consumption)

Type IIIBa basins are classified as back-arc basins on the convergent cratonic side of volcanic arcs. They are small, linear basins with irregular profiles (Klemme, 1980a, 1980b).

Not unlike Type IIIA basins, the volume of heavy oil found in the Type IIIBa basins is small. Seventeen heavy oil basins contain 49 billion barrels of oil in place and 83% of this amount is in Central Sumatra.

Just 4 billion barrels of natural bitumen in place are identified in the Type IIIA basin called Bone Gulf. Small amounts are also known to occur in the Cook Inlet and Tonga basins.

Type IIIBb basins are associated with rifted, convergent cratonic margins where wrench faulting and subduction have destroyed the island arc. They are small, linear, and irregular in profile.

The 14 Type IIIBb basins containing heavy oil account for only 134 billion barrels of oil in place. These basins are only moderately important on a global scale, but have been very important to the California oil industry. The seven such basins of California - Central Coastal, Channel Islands, Los Angeles, Sacramento, San Joaquin, Santa Maria, and Ventura – equal 129 billion barrels of oil in place or 96%.

There are nine Type IIIBb basins that report natural bitumen deposits. They contain 4 billion barrels of natural bitumen in place, about half of which is in the Santa Maria basin.

Types IIIBa and IIIBb basins comprise about seven percent of world basin area, but only one-quarter of the basins are productive for oil of all types. However, the productive ones, which represent only two percent of world basin area, yield about seven percent of total world's oil and gas (Klemme, 1983). Some of these productive basins, particularly those located in California, have high reservoir recovery factors.

Type IIIBc basins are small and elongate, irregular in profile, and occupy a median zone either between an oceanic subduction zone and the craton or in the collision zone between two cratonic plates. They result from median zone wrench faulting and consequent rifts. Such basins make up about three and one-half percent of world basin area and contribute two and one-half percent of total world oil and gas.

Type IIIBc basins are important to the occurrence of heavy oil (351 billion barrels of oil in place). Although there are nine basins of this type, 92% of the heavy oil is concentrated in the Maracaibo basin. The Maracaibo basin also yields 95% of the 178 billion barrels of natural bitumen in place in the five basins containing this type of oil. This makes the Maracaibo basin unique: no other basin type is so completely dominated by a single basin.

Type IIIC. Rifted passive margin (divergence)

These basins, often aptly called pull-apart basins, are extensional, elongate, and asymmetric. Located along major oceanic boundaries of spreading plates, they are divergent and occupy the intermediate zone between thick continental crust and thin oceanic crust. They appear to begin with a rifting stage, making possible the later sedimentary fill from the continent. Type IIIC basins, comprising 18 percent of the world's basin area, are mostly offshore and are often in water as deep as 5,000 feet. For this reason their development has been slow but is accelerating as traditional, easily accessible basins reach full development and world demand for petroleum increases (Klemme, 1980a, 1980b).

Twenty-eight Type IIIC basins yield 158 billion barrels of heavy oil in place, but one, the offshore Campos basin, contains 66% of this heavy oil. These continental margin basins must at some point in their histories have been sufficiently elevated to permit their generated conventional oil to be degraded. It is possible that the heavy oil could be very immature, having undergone only primary migration and later elevation. The geologic history of such basins does not encourage this view. However, the oil could well have been degraded bacterially at depth according to the recently proposed mechanisms suggested by Head, Jones, and Larter (2003) and Larter and others (2006). In a pull-apart basin the sediments would have accumulated rapidly and at depth, the expressed oil then was subject to degradation. The problem with degradation at depth is the loss of mobility unless it can be demonstrated that the oil was never elevated and, in fact, the Campos basin oil is deep, occurring at an average depth of nearly 8,400 feet.

The bitumen resource in Type IIIC basins is small (47 billion barrels of natural bitumen in place in seven basins), as are nearly all bitumen occurrences in comparison with the Western Canada Sedimentary and Eastern Venezuela basins. But the 38.3 billion barrels of natural bitumen in place in the Ghana basin of southwestern Nigeria is exploitable and the amount of the resource may be understated. Like many bitumen deposits it awaits more detailed evaluation.

Type IV. Delta (Tertiary to recent)

Deltas form along continental margins as extensional sags, are circular to elongate, and show an extremely high ratio of sediment fill to surface area. Architecturally, they are modified sags comprised of sediment depocenters and occur along both divergent and convergent cratonic margins. Although by 1980 delta basins provide two and one-half percent of world basin area and perhaps six percent of total oil and gas (Klemme, 1980a, 1980b), they account for more of the conventional resource endowment with the recent successful exploration in frontier deep water areas.

The three Type IV delta basins produce scant heavy oil (37 billion barrels of oil in place) and no natural bitumen. This is related to the extremely high ratio of sediment fill to surface area and that these basins exhibited rapid burial of the source organic matter. Burial is constant and uninterrupted, providing very limited opportunity for degradation of the generated petroleum.

Type V. Fore-Arc Basins

Fore-arc basins are located on the ocean side of volcanic arcs. They result from both extension and compression, are elongate and asymmetrical in profile, and architecturally are the result of subduction. Fore-arc basins are few in number and generally not very productive (Klemme, 1980a, 1980b).

Very small amounts of heavy oil are found in the Barbados basin. Although a natural bitumen deposit is reported in the Shumagin basin, volume estimates are not available.

Essentially no heavy oil or natural bitumen is found in fore-arc basins because these basins do not generate large quantities of petroleum of any type and therefore provide relatively little material to be degraded.

Regional Distribution of Heavy Oil and Natural Bitumen

The preceding discussion has been concerned with the distribution of heavy oil and natural bitumen in the world's geological basins. This is of paramount interest in the exploration for the two commodities and for their exploitation. The chemical and physical attributes of the fluids and the reservoirs which contain them do not respect political boundaries.

At the same time it is necessary to understand the geography of the heavy oil and natural bitumen for both economic and political reasons. These factors will be dealt with in detail in a subsequent report. The bar graphs on Plates 2 and 3 give the regional distribution of total and discovered original oil in-place for heavy oil and natural bitumen, respectively. The distribution of the resources is given in table 8. The western hemisphere accounts for about 52 percent of the world's heavy oil and more than 85 percent of its natural bitumen. The Middle East and South America have the largest in-place volumes of heavy oil, followed by North America. North and South America have, by far, the largest in-place volumes of natural bitumen. Very large resource deposits are also known in eastern Siberia but insufficient data are available to make more than nominal size estimates.

Summary

From the preceding basin discussion, Klemme basin Type IICa is by far the most prolific in terms of heavy oil. For natural bitumen Klemme basin Type IIA and Type IICa are the most prolific. The basin types involved are architecturally analogous, beginning with depositional platforms or sags

and ending up as foredeeps. They differ only in their modes of origin. What they have in common is truncation against cratonic masses updip from rich source areas. This situation permitted immense accumulations of conventional oil at shallow depths, with near ideal conditions for oil entrapment and biodegradation resulting in formation of heavy oil and bitumen accumulations. The prospective resources from the prospective additional resource deposits in these basins are larger than the discovered resources of many basin types.

The Klemme basin classification system includes elements of basin development and architecture that control basin type. The observed pattern of the heavy oil and natural bitumen occurrences across basin types is consistent with the formation of heavy oil and natural bitumen through the process of degradation of conventional oil. Only relatively small quantities of heavy oil were found in the Interior Craton (Type I), Deltas (Type IV) and Fore-Arc basins (Type V).

Type IICa basins, including the Arabian, Eastern Venezuela, and Zagros, have the largest endowments of heavy oil and also contain the largest amounts of conventional oil. Large volumes of heavy oil are also found in both Type IICc basins, notably, the Campeche, Tampico, and North Slope basins, and in Type IIIBc basins, primarily Maracaibo basin. For natural bitumen, the Western Canada Sedimentary and Eastern Venezuela basins have similar development histories and basin architectural features. Some basin development patterns promote the formation of greater volumes of heavy oil and natural bitumen than others. This is seen most clearly in present occurrences of heavy oil and natural bitumen in the Type IICa and Type IICc basins, with their rich source areas for oil generation and up-dip migration paths to entrapment against cratons. Conventional oil may easily migrate through the tilted platforms until the platforms are breached at or near surface permitting deveopment of asphaltic seals.

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Tables 1–8

Table 1. Some chemical and physical attributes of crude oils (averages).

[cP, centipoise; wt%, weight percent; mgKOH/g, milligrams of potassium hydroxide per gram of sample; sp gr, specific gravity; vol%, volume percent; ppm, parts per million; Concarbon, Conradson carbon; VOC, volatile organic compounds; BTEX, benzene, toluene, ethylbenzene, and xylenes]

Attribute	Unit	Conventional oil (131 basins, 8148 deposits)	Medium oil (74 basins, 774 deposits)	Heavy oil (127 basins, 1199 deposits)	Natural bitumen (50 basins, 305 deposits)
API gravity	degrees	38.1	22.4	16.3	5.4
Depth	feet	5,139.60	3,280.20	3,250.00	1,223.80
Viscosity (77°F)	cP	13.7	34	100,947.00	1,290,254.10
Viscosity (100°F)	cP	10.1	64.6	641.7	198,061.40
Viscosity (130°F)	cP	15.7	34.8	278.3	2,371.60
Conradson Carbon	wt%	1.8	5.2	8	13.7
Coke	wt%	2.9	8.2	13	23.7
Asphalt	wt%	8.9	25.1	38.8	67
Carbon	wt%	85.3	83.2	85.1	82.1
Hydrogen	wt%	12.1	11.7	11.4	10.3
Nitrogen	wt%	0.1	0.2	0.4	0.6
Oxygen	wt%	1.2		1.6	2.5
Sulfur	wt%	0.4	1.6	2.9	4.4
Reid vapor pressure	psi	5.2	2.6	2.2	
Flash point	°F	17	20.1	70.5	
Acid number	mgKOH/g	0.4	1.2	2	3
Pour point	°F	16.3	8.6	19.7	72.9
C1-C4	vol%	2.8	0.8	0.6	
Gasoline + naphtha	vol%	31.5	11.1	6.8	4.4
Gasoline + naphtha	sp gr	0.76	0.769	0.773	0.798
Residuum	vol%	22.1	39.8	52.8	62.2
Residuum	sp gr	0.944	1.005	1.104	1.079
Asphaltenes	wt%	2.5	6.5	12.7	26.1
Asphaltenes + resins	wt%	10.9	28.5	35.6	49.2
Aluminum	ppm	1.174	1.906	236.021	21,040.03
Copper	ppm	0.439	0.569	3.965	44.884
Iron	ppm	6.443	16.588	371.05	4,292.96
Mercury	ppm	19.312	15	8.74	0.019
Nickel	ppm	8.023	32.912	59.106	89.137
Lead	ppm	0.933	1.548	1.159	4.758
Titanium	ppm	0.289	0.465	8.025	493.129
Vanadium	ppm	16.214	98.433	177.365	334.428
Residue Concarbon	wt%	6.5	11.2	14	19
Residue Nitrogen	wt%	0.174	0.304	0.968	0.75
Residue Nickel	ppm	25.7	43.8	104.3	
Residue Sulfur	ppm	1.5	3.2	3.9	
Residue Vanadium	ppm	43.2	173.7	528.9	532
Residue viscosity (122°F)	cP	1,435.80	4,564.30	23,139.80	
Total BTEX volatiles	ppm	10,011.40	5,014.40	2,708.00	
Total VOC volatiles	ppm	15,996.30	8,209.20	4,891.10	

Table 2. Conversion factors and equivalences applied to standardize data.

Standard unit in this report	Units as reported in literaure	Formula
	API gravity	
°API (degrees)	specific gravity (sp gr), (g/cm³)	= (141.5/(sp gr))-131.5
	Area	
acre	square mile (mi²)	= (1/640) mi²
	square kilometer (km^2)	= 0.00405 km^2
	hectare (ha)	= 0.405 ha
	Asphalt in crude	
weight percent (wt%)	Conradson Carbon Residue (CCR)	= 4.9× (CCR)
	Barrels of oil	
barrel (bbl), (petroleum, 1 barrel=42 gal)	cubic meter (m³)	= 0.159 m³
	metric tonne (t)	= 0.159× (sp gr) ×t
	Coke in crude	
weight percent (wt%)	Conradson Carbon Residue (CCR)	= 1.6× (CCR)
	Gas-oil ratio	
cubic feet gas/barrel oil (ft³ gas/bbl oil)	cubic meters gas/cubic meter oil (m³ gas/m³ oil)	= 0.18× (m³gas/m³oil)
	Parts per million	
parts per million (ppm)	gram/metric tonne (g/t)	= g/t
	milligram/kilogram (mg/kg)	= mg/kg
	microgram/gram (µg/g)	= µg/g
	milligram/gram (mg/g)	= 0.001 mg/g
	weight percent (wt%)	= 0.0001 wt%
	Parts per billion	
parts per billion (ppb)	parts per million (ppm)	= 0.001 ppm
	Permeability	
millidarcy (md)	micrometer squared (μm^2)	= 1,000 μm^2
	Pressure	
pound per square inch (psi)	kilopascal (kPa)	= 6.89 kPA
	megapascal (Mpa)	= 0.00689 MPa
	bar	= 0.0689 bar
	kilograms/square centimeter (kg/cm^2)	= 0.0703 kg/cm^2
	Specific gravity (density)	
specific gravity (sp gr), (g/cm³)	°API (degrees)	= 141.5/(131.5+°API)
	Temperature	
degrees Fahrenheit (°F)	degrees Celsius (°C)	= (1.8×°C)+32
degrees Celsius (°C)	degrees Fahrenheit (°F)	= 0.556×(°F-32)
	Viscosity (absolute or dynamic)	
centipoise (cP)	Pascal second (Pa·s)	= 0.001 Pa·s
	millipascal second (mPa·s)	= mPa·s

Table 2. Conversion factors and equivalences applied to standardize data.—Continued

Standard unit in this report	Units as reported in literaure	Formula
	Viscosity (absolute or dynamic)—Continued	
centipoise (cP)—cont.	kinematic viscosity[1]: centistroke (cSt), (mm²/sec)	= cSt × (sp gr)
	Saybolt Universal Seconds (SUS) at 100°F, for given density	= (SUS /4.632)× (sp gr)
	Saybolt Universal Seconds (SUS) at 100°F, for given °API	= (SUS /4.632)×(141.5/(131.5+°API))
	Weight percent	
weight percent (wt%)	parts per million (ppm)	= 10,000 ppm

[1] Kinematic viscosity is equal to the dynamic viscosity divided by the density of the fluid, so at 10°API the magnitudes of the two viscosities are equal.

Table 3. Total original in place resource calculation protocol when discovered oil in place is unavailable.

Define—

- OOIP-disc.: Original Oil In Place, discovered
- RF: Recovery factor (%)
- R: Reserves, known
- OR: Reserves, original sometimes called, known recovery, ultimate production if so reported
- AP: Production, annual
- CP: Production, cumulative
- PA: Prospective additional oil in place resource
- TOOIP = Total original oil in place

Calculations are based given data, which always receives priority; CP, AP and PA are never calculated and must be from published sources. (Assume CP, AP, PA are given)—

- R = 20×AP. This assumes a 20-year life or production plan for the viscous oil.
- OR = R+CP
- RF = 0.1 for clastic reservoirs or if no lithology is reported
- RF = 0.05 for carbonate reservoirs
- OOIP-disc. = OR/RF
- TOOIP = OOIP-disc. + PA

Table 4. Heavy oil and natural bitumen resources in billions of barrels of oil (BBO) and average characteristics of heavy oil and natural bitumen by basin type. Average values for gravity, viscosity, depth, thickness permeability are weighted by volume of oil in place discovered in each heavy oil or natural bitumen deposit by basin type; except for API gravity of heavy oil Type I, where because of relatively few deposits and several outlier values, a trimmed weighted mean value is shown.

[Volumes may not add to totals due to independent rounding; BBO, billions of barrels of oil; cP, centipoise]

Basin type	Total original oil in place (BBO)	Discovered oil in place (BBO)	API gravity (degrees)	Viscosity (cP @ 100°F)	Depth (feet)	Thickness (feet)	Porosity (percent)	Permeability (millidarcy)	Temperature (°F)
Heavy oil									
I…….	3	2	15.9	724	1,455	11	15.3	88	122
IIA…….	158	157	16.3	321	4,696	36	22.8	819	102
IIB…….	181	181	17.7	303	3,335	96	27.2	341	82
IICa…...	1,610	1,582	15.5	344	3,286	150	24	242	144
IICb…...	32	32	15.4	318	3,976	161	16.9	2,384	126
IICc…...	460	460	17.8	455	6,472	379	19.6	1,080	159
IIIA……	222	222	16.3	694	4,967	279	24.9	1,316	159
IIIBa…..	49	49	19.2	137	558	838	24.9	2,391	122
IIIBb…..	134	134	15.8	513	2,855	390	31.9	1,180	116
IIIBc…..	351	351	13.5	2,318	4,852	142	20.1	446	145
IIIC……	158	158	17.2	962	7,227	273	25.1	868	159
IV……..	37	37	17.9	-	7,263	1,195	27.9	1,996	155
V……	<1	<1	18	-	1,843	135	30	-	144
All types	3,396	3,366	16	641	4,213	205	23.7	621	134
Natural bitumen									
I…….	60	8		-	20	317	5.5	100	
IIA…….	2,623	1,908	6.8	185,407	223	53	0.4	611	173
IIB…….	29	26	4.5	-		209	13.1	57	113
IICa…...	2,509	2,319	4.4	31,789	806	156	29.8	973	174
IICb…...	5	5	6.8	-	8,414	1,145	4.7	570	181
IICc…...	24	23	5	1,324	3,880	82	32.4	302	263
IIIA……	22	22	8.7	-	4,667	882	30.3	1,373	85
IIIBa…..	4	4	-	-	-	-	-	-	-
IIIBb…..	3	3	6.7	500,659	3,097	586	28.6	2,211	89
IIIBc…..	178	178	9.5	1,322	8,751	52	34	751	139
IIIC……	47	14	7.3	-	900	103	23.1	2,566	117
IV……..	0	0							
V……	0	0							
All types	5,505	4,512	4.9	198,061	1,345	110	17.3	952	158

Table 5. Enhanced oil recovery (EOR) methods for heavy oil showing primary reservoir threshold criteria.

[modified from Taber, Martin, and Seright (1997a,b); cP, centipoises; PV, pore volume; ft, feet; md, millidarcy; °F, degrees Fahrenheit, wt%, weight percent]

Method	Gravity (°API)	Viscosity (cP)	Oil composition	Oil saturation (%PV)	Lithology	Net thickness (ft)	Average permeability (md)	Depth (ft)	Temperature (°F)
Immiscible gases									
Immiscible gases[a]	>12	<600	Not critical	>35	Not critical	Not critical	Not critical	>1,800	Not critical
Enhanced waterflood									
Polymer	>15	<150	Not critical	>50	Sandstone preferred	Not critical	>10[b]	<9,000	>200-140
Thermal/mechanical									
Combus-tion	>10	<5,000	Asphaltic compo-nents	>50	Highly porous sandstone	>10	>50[c]	<11,500	>100
Steam	>8	<200,000	Not critical	>40	Highly porous sandstone	>20	>200[d]	<4500	Not critical
Surface mining	>7	0 cold flow	Not critical	>8 wt% sand	Mineable oil sand	>10[e]	Not critical	>3:1 over-burden: sand ratio	Not critical

[a] Includes immiscible carbon dioxide flood.

[b] >3 md for some carbonate reservoirs if the intent is to sweep only the fracture systems.

[c] Transmissibility > 20md-ft/cP.

[d] Transmissibility > 50md-ft/cP.

[e] See depth.

Table 6. Listing of countries reporting deposits of heavy oil and/or natural bitumen grouped by region. (See inset maps of regional distribution on Plates 2 and 3.)

North America	South America	Europe	Africa	Transcaucasia	Middle East	Russia	South Asia	East Asia	Southeast Asia and Oceania
Canada	Argentina	Albania	Algeria	Azerbaijan	Bahrain	Russia	Bangladesh	China	Australia
Mexico	Barbados	Austria	Angola	Georgia	Iran		India	Japan	Brunei
United States	Bolivia	Belarus	Cameroon	Kazakhstan	Iraq		Pakistan	Taiwan	Indonesia
	Brazil	Bosnia	Chad	Kyrgyzstan	Israel				Malaysia
	Colombia	Bulgaria	Congo (Brazzaville)	Tajikistan	Jordan				Myanmar
	Cuba	Croatia	Democratic Republic of Congo (Kinshasa)	Turkmenistan	Kuwait				Philippines
	Ecuador	Czech Republic	Egypt	Uzbekistan	Neutral Zone				Thailand
	Guatemala	France	Equatorial Guinea		Oman				Tonga
	Peru	Germany	Gabon		Qatar				Vietnam
	Suriname	Greece	Ghana		Saudi Arabia				
	Trinidad & Tobago	Hungary	Libya		Syria				
	Venezuela	Ireland	Madagascar		Turkey				
		Italy	Morocco		Yemen				
		Malta	Nigeria						
		Moldova	Senegal						
		Netherlands	South Africa						
		Norway	Sudan						
		Poland	Tunsia						
		Romania							
		Serbia							
		Slovakia							
		Spain							
		Sweden							
		Switzerland							
		Ukraine							
		United Kingdom							

Table 7. Attributes of Klemme basin types.

[Sources for attributes 1-15 are Klemme (1980a, 1980b, 1984) and attributes 16 and 17 are from this report]

	Type I	Type IIA	Type IIB	Type IICa
	Craton interior	**Continental multicycle basins, craton margin**	**Continental multicycle basins: craton/acreted zone rift-faulted**	**Continental interior multicycle basins: close collision zone at paleoplate margin**
1. Crustal zone	Continental craton	Continental craton	Contnental craton and accreted zone	Ocean crust early stages then continental crust of craton and accreted zone
2. Tectonic setting	Continenal crust within interior of craton, near or upon Precambrian sheld areas	Continental crust on exterior margin of craton, basins become multicylic ion Paleozoic or Mesozoic when a second cycle of sediments derived from uplife encroaches	Continental crust, or on margin of craton	Convergent margin along collision zone of paleoplates
3. Regional stress	Extensional	1st cycle: extension, 2nd cycle: compression	(1st) extension with rifting, (2nd) extensional sag	(1st) regional extension and platform deposits, then rifting, formation of linear sag, (2nd) compression with creation of foredeep
4. Basin size, shape	Large, circular to elongate	Moderate to large, circular to elongate	Large, circular	Large, elongate
5. Basin profile	Symmetrical	Asymmetrical	Irregular to asymmetrical	Asymmetrical
6. Sediment ratio[1]	Low	High	High	High
7. Architectural sequence	Sag	1st cycle: platform or sag, 2nd cycle: foredeep	(1st) rift, (2nd) large circular sag	(1st) platform or sag, (2nd) foredeep
8. Special features	Unconformities, regional arches, evaporite caps	Large traps, basins and arches, evaporite caps	Large traps, basins and arches, evaporite caps	Large traps and basins, evaporite caps, regional arches, regional source seal, fractured reservoirs
9. Basin lithology[2]	Clastic 60%, carbonate 40%	Clastic 75%, carbonate 25%	Clastic 75%, carbonate 25%	Clastic 35%, carbonate 65%
10. Depth of production[3]	Shallow	Shallow 55%, moderate 25%, deep 5%[5]	Shallow 55%, moderate 25%, deep 5%[5]	Shallow 45%, moderate 30%, deep 25%
11. Geothermal gradient	Low	Low	High	High
12. Temperature	Cool	Cool	Cool	High
13. Age	Paleozoic	Paleozoic, Mesozoic	Paleozoic, Mesozoic	Upper Paleozoic, Mesozoic, Tertiary
14. Oil and gas recovery[4]	Low, few giant fields	Average	Generally average	High
15. Traps	Associated with central arches and stratigraphic traps along basin margins	Basement uplifts, mostly arches or blocks	Basement uplifts, mostly combination of structural stratigraphic	Basement uplifts, arches and fault blocks
16. Propensity for heavy oil	Low	Low	Low	High
17. Propensity for natural bitumen	Low	High	Low	High

[1]Sediment ratio: ratio of sediment volume to basin surface area.

[2]Basin lithology: percentages apply to reservoir rocks, not to the basin fill.

[3]Depth of production: shallow, 0-6000 ft.; medium, 6000-9000 ft.; deep, >9000 ft.

[4]Oil and gas recovery (barrels of oil equivalent per cubic mile of sediment): low, <60,000; average, >=60,000 but <300,000; high, >=300,000.

[5]Does not add to 100% in source, Klemme (1980a,b).

Table 7. Attributes of Klemme basin types.—Continued

	Type IICb	Type IICc	Type IIIA	Type IIIBa
	Continental interior multicycle basins: foredeep portion of collision zone at paleoplate margin	**Continental interior multicycle basins: open collision zone at paleoplate margin**	**Continental rifted basins: craton/accreted zone, rift-faulted, with small linear sag**	**Continental rifted basins: back arc rift-faulted convergent margin**
1. Crustal zone	Ocean crust early stages then continental crust of craton and accreted zone	Ocean crust early stages then continental crust of craton and accreted zone	Continental craton and accreted zone	Contintental accreted zone with oceanic crust in early stages
2. Tectonic setting	Convergent margin along collision zone of paleoplates, but retain only proximal or foredeep portion of original sediment suite	Convergent margin along collision zone of paleoplates	Continental, on margin of craton. About two-thirds of Type IIIA basins form along trend of older deformation; remainder on Precambrian shields	Back arc basins along accreted zone of continent, with continental crust involved in later stages of development and ocean crust in the initial stages
3. Regional stress	(1st) regional extension and platform deposits, then rifting, formation of linear sag, (2nd) compression with creation of foredeep	(1st) regional extension and platform deposits, then rifting, formation of linear sag, (2nd) compression with creation of foredeep	(1st) extension with local wrench faulting during rifting, (2nd) sag	(1st) extension with local wrench faulting compression, (2nd) extension and compression
4. Basin size, shape	Large, elongate	Large, elongate	Small to moderate, fault controlled, elongate	Small, elongate
5. Basin profile	Asymmetrical	Asymmetrical	Irregular	Irregular
6. Sediment ratio[1]	High	High	High	High but variable
7. Architectural sequence	(1st) platform or sag, (2nd) foredeep	(1st) platform or sag, (2nd) foredeep	(1st) extension with local wrench faulting druing rifting, (2nd) sag	Rift faulting leading to linear sag, may be followd by wrench faulting
8. Special features	Large traps and basins, evaporite caps, regional arches, regional source seal, fractured reservoirs	Large traps and basins, evaporite caps, regional arches, regional source seal, fractured reservoirs, unconformities	Large traps, evaporite caps, unconformities, regional source seal	Large traps, and unconformities
9. Basin lithology[2]	Clastic 50%, carbonate 50%	Clastic 35%, carbonate 65%	Clastic 60%, carbonate 40%	Clastic 90%, carbonate 10%
10. Depth of production[3]	Shallow 45%, moderate 30%, deep 25%	Shallow 45%, moderate 30%, deep 25%	Moderate 55%, shallow 30%, deep 15%	Shallow 70%, moderate 20%, deep 10%
11. Geothermal gradient	High	High	High	High
12. Temperature	High	High	Normal to high	Normal to high
13. Age	Upper Paleozoic, Mesozoic, Tertiary	Upper Paleozoic, Mesozoic, Tertiary	Upper Paleozoic, Mesozoic, Paleogene, Neogene	Upper Mesozoic, Paleogene and Neogene
14. Oil and gas recovery[4]	Generally low	High	Generally high	Variable
15. Traps	Basement uplifts, arches and fault blocks	Basement uplifts, arches and fault blocks	Basement uplifts, combination structural/stratigraphic; result in fault block movement	Basement uplifts, fault blocks and combination
16. Propensity for heavy oil	Low	Moderate	Moderate	Low
17. Propensity for natural bitumen	Low	Low	Low	Low

Table 7. Attributes of Klemme basin types.—Continued

	Type IIIBb	Type IIIBc	Type IIIC	Type IV	Type V
	Continental rifted basins: transverse rift-faulted convergent margin	**Continental rifted basins: median rift-faulted convengent margin**	**Continental rifted basins: rift-faulted divergent margin, may be subdivided into (a) parallel, or (b) transverse basins**	**Deltas**	**Fore-arc basins**
1. Crustal zone	Contintental accreted zone with oceanic crust in early stages	Contintental accreted zone with oceanic crust in early stages	Ocean crust in early stage, then continental crust of craton and accreted zone	Ocean crust in early stage, then continental crust of craton and accreted zone	Continetal accreted crust and oceanic crust
2. Tectonic setting	Back arc basins along accreted zone of continent, with continental crust involved in later stages of development and ocean crust in the initial stages	Back arc basins along accreted zone of continent, with continental crust involved in later stages of development and ocean crust in the initial stages	Rift faulting along a divergent, passive or pull-apart continental margin	Almost any location: divergent and convergent margins along open or confined coastal areas	Fore-arc basins located on oceanward side of the volcanic arc in subduction or consumption zone
3. Regional stress	(1st) extension and wrench compression, (2nd) extension and compression	(1st) extension and wrench compression, (2nd) extension and compression	Extension leading to rift or wrench faulting	Extension as sag develops but uncertain as to the initial cause of sag, roots being deeply buried	Compression and extension
4. Basin size, shape	Small, elongate	Small, elongate	Small to moderate, elongate	Moderate, circular to elongate	Small, elongate
5. Basin profile	Irregular	Irregular	Asymmetrical	Depocenter	Asymmetrical
6. Sediment ratio[1]	High but variable	High but variable	High	Extremely high	High
7. Architectural sequence	Rift faulting leading to linear sag, may be followd by wrench faulting	Rift faulting leading to linear sag, may be followd by wrench faulting	Linear sage with irregular profile	Roots of deltas deeply buried; extension leads to half-sag with sedimentary fill thickening seaward.	Small linear troughs
8. Special features	Large traps, and unconformities	Large traps, unconformities, and regional arches	Possible unconformities and regional source seals	None	Large traps, and unconformities
9. Basin lithology[2]	Clastic 90%, carbonate 10%	Clastic 90%, carbonate 10%	Clastic 70%, carbonate 30%	Clastic 100%	Clastic 90%, carbonate 10%
10. Depth of production[3]	Shallow 70%, moderate 20%, deep 10%	Shallow 70%, moderate 20%, deep 10%	Deep 60%, moderate 30%, shallow 10%	Deep 65%, moderate 30%, shallow 5%	Shallow 70%, deep 20%, moderate 10%
11. Geothermal gradient	High	Normal to high	Low	Low	High
12. Temperature	Normal to high	Normal to high	Cool	Normal to low	High to normal
13. Age	Upper Mesozoic, Paleogene and Neogene	Upper Mesozoic, Paleogene and Neogene	Upper Mesozoic, Paleogene and Neogene	Paleogene, Neogene, and Quaternary	Upper Mesozoic, Tertiary
14. Oil and gas recovery[4]	Variable	Variable	Low	High	High but variable
15. Traps	Basement uplifts, fault blocks and combination	Basement uplifts, fault blocks and combination	Fault blocks and combination	Primarily tensional growth (roll-over) anticlines and flowage: basement not involved	Fault blocks and combination
16. Propensity for heavy oil	Low	Moderate	Low	Low	Nil
17. Propensity for natural bitumen	Low	Low	Low	Nil	Nil

Table 8. Regional distribution of heavy oil and natural bitumen (billion barrels).

[Volumes may not add to totals due to independent rounding]

Region[1]	Discovered orginal oil in place	Prospective additional	Total original oil in place
		Heavy oil	
North America……	650	2	651
South America……	1099	28	1127
Europe…….	75	0	75
Africa……..	83	0	83
Transcaucasia……..	52	0	52
Middle East…….	971	0	971
Russia……..	182	0	182
South Asia……...	18	0	18
East Asia…….	168	0	168
Southeast Asia and Oceania……	68	0	68
Total……..	3366	29	3396
		Natural bitumen	
North America……	1671	720	2391
South America……	2070	190	2260
Europe…….	17	0	17
Africa……..	13	33	46
Transcaucasia……..	430	0	430
Middle East…….	0	0	0
Russia……..	296	51	347
South Asia……...	0	0	0
East Asia…….	10	0	10
Southeast Asia and Oceania……	4	0	4
Total……..	4512	993	5505

[1] See table 6 for a list of countries reporting deposits of heavy oil and/or natural bitumen grouped by regions.

Appendixes 1–4

Appendix 1. Map Basin Name Conventions

Table 1-1. List of geologic provinces where province names used in this report differ from names used in St. John, Bally and Klemme (1984).

Geological province name in this report	Geological province name in St. John, Bally, and Klemme (1984)
Amu Darya	Tadzhik
Arkla	Louisiana Salt Dome
Baikal	Lake Baikal
Barinas-Apure	Llanos de Casanare
Carnarvon	Dampier
Central Montana Uplift	Crazy Mountains
Central Sumatra	Sumatra, Central
East Java	Java, East
East Texas	East Texas Salt Dome
Eastern Venezuela	Maturin
Forest City	Salina-Forest City
Gulf of Alaska	Alaska, Gulf of
Gulf of Suez	Suez, Gulf of
Guyana	Guiana
Junggar	Zhungeer
Kutei	Mahakam
Mae Fang	Fang
Minusinsk	Minisinsk
North Caspian	Caspian, North
North Caucasus-Mangyshlak	Caucasus, North
North Egypt	Western Desert
North Sakhalin	Sakhalin, North
North Sumatra	Sumatra, North
North Ustyurt	Ust Urt
Northern North Sea	North Sea, Northern
Northwest Argentina	Argentina, Northwest
Northwest German	German, Northwest
Northwest Shelf	Dampier
Ordos	Shanganning
Progreso	Guayaquil
Sacramento	Sacramento/San Joaquin
Salinas	Salinas (Mexico)
San Joaquin	Sacramento/San Joaquin
South Adriatic	Adriatic, South
South Palawan	Palawan, South
South Sumatra	Sumatra, South
Timan-Pechora	Pechora
Turpan	Tulufan

Table 1-1. List of geologic provinces where province names used in this report differ from names used in St. John, Bally and Klemme (1984).—Continued

Geological province name in this report	Geological province name in St. John, Bally, and Klemme (1984)
Upper Magdalena	Magdalena, Upper
West Java	Java, West, Sunda
West of Shetlands	Shetlands, West
Western Canada Sedimentary	Alberta
Yukon-Kandik	Yukon/Kandik

The following basins listed in bold type are from the digital mapping file of St. John (1996) and require further explanation:

- **Anadarko**: includes provinces more commonly known as the *Anadarko,* Central Kansas Uplift, Chautauqua Platform, *Las Animas Arch,* Nemaha Anticline-Cherokee Basin, *Ozark Uplift,* Sedgwick, and South Oklahoma Folded Belt (provinces in italics report neither heavy oil nor natural bitumen.)
- **Sacramento/San Joaquin**: separated into two distinct provinces, Sacramento and San Joaquin.
- **North Sea, Southern**: : includes both the Anglo-Dutch and Southern North Sea basins.
- **South Adriatic**: includes both the Durres and South Adriatic basins.

Other comments:

Three separate outlines for Marathon, Ouachita, and Eastern Overthrust are shown as a common province Marathon/Ouachita/Eastern Overthrust in the original St John (1996) but only Ouachita Basin had reported volumes of natural bitumen resources.

Deposits reported for Eastern Venezuela basin include deposits on the island of Trinidad, which are a likely extension of the rock formations from the surface expression of the basin outline.

The plates attach the name of Barinas Apure to the polygonal province labeled Llanos de Casanare in St. John (1996). Barinas Apure is the province name commonly used in Venezuela and Llanos de Casanare is the province name commonly used in Colombia for the same geologic province.

Appendix 2. Basins, Basin Type and Location of Basins having Heavy Oil and Natural Bitumen Deposits

Table 2-1. List of geological basin names, the Klemme basin type, countries, U.S. states or Canadian provinces reporting deposits of heavy oil and/or natural bitumen, and other names cited in literature.

Geological province	Klemme basin type	Country	State/Province	Other names
Aegian	IIIBc	Greece		North Aegean Trough (North Aegean Sea Basin)
Akita	IIIBa	Japan		Akita Basin, Japan Accreted Arc/Accreted Terrane
Amu-Darya	IICa	Tajikistan, Uzbekistan		Tadzhik, Surkhan-Vaksh, Badkhyz High (Murgab Basin), Afghan-Tajik
Amur	IIIBc	Georgia		
Ana Maria	IIIBb	Cuba		Zaza Basin, Greater Antilles Deformed Belt
Anabar-Lena	IIA	Russia		
Anadarko	IIA	United States	Kans.	
Anadyr	IIIBb	Russia		
Angara-Lena	IIA	Russia		
Anglo-Dutch	IIB	Netherlands		Central Graben, North Sea, Southern
Appalachian	IIA	United States	Ky., N.Y.	
Aquitaine	IIIA	France		Ales, Aquitaine, Lac Basin, Parentis, Massif Central, Pyrenean Foothills-Ebro Basin
Arabian	IICa	Bahrain, Iran, Iraq, Jordan, Kuwait, Neutral Zone, Oman, Qatar, Saudi Arabia, Syria		Arabian Basin, Rub Al Khali, Aneh Graben, Aljafr Sub-basin, Oman Platform, Mesopotamian Foredeep, Palmyra Zone, Oman Sub-Basin, Euphrates/Mardin, Ghaba Salt Basin, Greater Ghawar Uplift, Haleb, Qatar Arch, South Oman Salt Basin, Widyan Basin
Arkla	IICc	United States	Ark., La.	Louisiana Salt Dome
Arkoma	IIA	United States	Ark., Okla.	
Assam	IICb	India		
Atlas	IICb	Algeria		Moroccan-Algerian-Tunisian Atlas, Hodna-Constantine
Bahia Sul	IIIC	Brazil		J Equitinhonha
Baikal	IIIA	Russia		Lake Baikal
Balearic	IIIA	Spain		Western Mediterranean, Gulf of Valencia, Barcelona Trough (Catalano-Balearic Basin), Iberic Cordillera
Baltic	I	Sweden		
Baluchistan	IICb	Pakistan		Sulaiman-Kirthar
Barbados	V	Barbados		Lesser Antilles, Northeast Caribbean Deformed Belt
Barinas-Apure	IIA	Venezuela, Colombia		Barinas-Apure Basin, Llanos de Casanare
Barito	IIIBa	Indonesia		Barito Basin
Bawean	IIIBa	Indonesia		
Beibu Gulf	IIIBa	China		Beibuwan (Gulf of Tonkin) Basin
Bengal	IICa	Bangladesh, India		Bengal (Surma Sub-basin), Tripura-Cachar, Barisal High (Bengal Basin), Ganges-Brahmaputra Delta
Beni	IIA	Bolivia		Foothill Belt
Big Horn	IIA	United States	Mont., Wyo.	
Black Mesa	IIB	United States	Ariz.	Dry Mesa, Dineh Bi Keyah
Black Warrior	IIA	United States	Ala., Miss.	
Bohai Gulf	IIIA	China		Bohai Wan (Huabei-Bohai) Basin, Huabei, Pohal, Luxi Jiaoliao Uplift

Table 2-1. List of geological basin names, the Klemme basin type, countries, U.S. states or Canadian provinces reporting deposits of heavy oil and/or natural bitumen, and other names cited in literature.—Continued

Geological province	Klemme basin type	Country	State/Province	Other names
Bombay	IIIC	India		
Bonaparte Gulf	IIIC	Australia		Berkeley Platform (Bonaparte Basin)
Bone Gulf	IIIBa	Indonesia		Bone
Bresse	IIIA	France		Jura Foldbelt
Browse	IIIC	Australia		
Brunei-Sabah	IICc	Brunei, Malaysia		Baram Delta
Cabinda	IIIC	Angola, Congo (Brazzaville), Democratic Republic of Congo (Kinshasa)		Lower Congo Basin, West-Central Coastal
Caltanisetta	IICb	Italy, Malta		Caltanissetta Basin, Ibleian Platform, Sicilian Depression
Cambay	IIIA	India		Cambay North, Bikaner-Nagam, Bombay (in part)
Campeche	IICc	Mexico		Tabasco-Campeche, Yucatan Boderland and Platform, Tobasco, Campeche-Sigsbee Salt, Villahermosa Uplift
Campos	IIIC	Brazil		Cabo Frio High (Campos Basin)
Cantabrian	IIIA	Spain		Offshore Cantabrian Foldbelt (Cantabrian Zone), Spanish Trough-Cantabrian Zone
Carnarvon	IIIC	Australia		Dampier, Northwest Shelf, Carnarvon Offshore, Barrow-Dampier Sub-Basin
Carpathian	IICb	Austria, Czech Republic, Poland, Ukraine		Carpathian Flysch, Carpathian Foredeep, Bohemia, Carpathian-Balkanian
Celtic	IIIA	Ireland		Celtic Sea Graben System, Ireland-Scotland Platform
Central Coastal	IIIBb	United States	Calif.	Coastal, Santa Cruz, Salinas Valley, Northern Coast Range
Central Kansas Uplift	IIA	United States	Kans.	Anadarko
Central Montana Uplift	IIA	United States	Mont.	Crazy Mountains
Central Sumatra	IIIBa	Indonesia		Central Sumatra Basin
Ceram	IICa	Indonesia		North Seram Basin, Banda Arc
Channel Islands	IIIBb	United States		Southern California Borderlands
Chao Phraya	IIIA	Thailand		Phitsanulok Basin, Thailand Mesozoic Basin Belt
Chautauqua Platform	IIA	United States	Okla.	Anadarko
Cincinnati Arch	I	United States	Ky., Ohio	
Cook Inlet	IIIBa	United States	Alaska	Susitna Lowlands
Cuanza	IIIC	Angola		Kwanza Basin, West-Central Coastal
Cuyo	IIB	Argentina		Alvear Sub-basin (Cuyo Basin), Cuyo-Atuel
Dead Sea	IICa	Israel, Jordan		Syrian -African Arc, Levantine, Jafr-Tabuk, Sinai
Denver	I	United States	Colo., Nebr.	Denver-Julesberg
Diyarbakir	IICa	Syria, Turkey		Bozova-Mardin High (Southeast Turkey Fold Belt), Euphrates/Mardin, Zagros Fold Belt
Dnieper-Donets	IIIA	Ukraine		Dnepr-Donets Graben
Doba	IIIA	Chad		
Durres	IICb	Albania		Ionian Basin (zone), South Adriatic, Pre-Adriatic
East China	IIIBa	China, Taiwan		Diaoyu Island Depression (East China Sea Basin)
East Java	IIIBa	Indonesia		Bawean Arch (East Java Basin)
East Texas	IICc	United States	Tex.	East Texas Salt Dome, Ouachita Fold Belt
Eastern Venezuela	IICa	Venezuela, Trinidad and Tobago		Maturin, Eastern Venezuela Basin, Orinoco Oil Belt, Guarico Sub-basin, Trinidad-Tabago

Table 2-1. List of geological basin names, the Klemme basin type, countries, U.S. states or Canadian provinces reporting deposits of heavy oil and/or natural bitumen, and other names cited in literature.—Continued

Geological province	Klemme basin type	Country	State/Province	Other names
Espirito-Santo	IIIC	Brazil		Abrolhos Bank Sub-Basin (Espirito Santo Basin)
Fergana	IIIBc	Kyrgyzstan, Tajikistan, Uzbekistan		
Florida-Bahama	IIIC	Cuba, United States	Fla.	Almendares-San Juan Zone, Bahia Honda Zone, Llasvvillas Zone, Florida Platform, Greater Antilles Deformed Belt
Forest City	I	United States	Kans., Nebr.	Salina-Forest City, Salina, Chadron Arch
Fort Worth	IIA	United States	Tex.	Bend Arch, Fort Worth Syncline, Llano Uplift, Ouachita Overthrust
Gabon	IIIC	Gabon		Gabon Coastal Basin (Ogooue Delta), West-Central Coastal
Gaziantep	IICa	Syria, Turkey		
Ghana	IIIC	Ghana, Nigeria		Benin-Dahomey, Dahomey Coastal
Gippsland	IIIA	Australia		Gippsland Basin
Green River	IIA	United States	Colo., Wyo.	
Guangxi-Guizou	IIB	China		Bose (Baise) Basin, South China Fold Belt
Gulf Coast	IICc	United States	La., Tex.	Mid-Gulf Coast, Ouachita Folded Belt, Burgos
Gulf of Alaska	V	United States	Alaska	
Gulf of Suez	IIIA	Egypt		Gulf of Suez Basin, Red Sea Basin
Guyana	IIIC	Suriname		Guiana, Bakhuis Horst, Guyana-Suriname
Illinois	I	United States	Ill., Ky.	
Indus	IICb	India		Punjab (Bikaner-Nagaur Sub-basin), West Rajasthan
Ionian	IICb	Greece		Epirus, Peloponesus
Irkutsk	IIA	Russia		
Jeanne d'Arc	IIIC	Canada	N.L.	Labrador-Newfoundland Shelf
Jianghan	IIIA	China		Tung-T'Ing Hu
Junggar	IIIA	China		Zhungeer, Anjihai-Qigu-Yaomashan Anticlinal Zone (Junggar)
Kansk	IIA	Russia		
Krishna	IIIC	India		Krishna-Godavari Basin
Kura	IIIBc	Azerbaijan, Georgia		Kura Basin
Kutei	IIIBa	Indonesia		Mahakam
Kuznets	IIB	Russia		
Laptev	IIB	Russia		
Los Angeles	IIIBb	United States	Calif.	
MacKenzie	IV	Canada	N.W.T.	Beaufort Sea, MacKenzie Delta
Mae Fang	IIIA	Thailand		Fang, Mae Fang Basin, Tenasserim-Shan
Maracaibo	IIIBc	Venezuela, Colombia		Maracaibo Basin, Catatumbo
Mauritius-Seychelles	IIIC	Seychelles		
Mekong	IIIC	Vietnam		Mekong Delta Basin
Michigan	I	United States	Mich.	
Middle Magdalena	IIIBc	Colombia		Middle Magdalena Basin
Minusinsk	IIB	Russia		Minisinsk
Mississippi Salt Dome	IICc	United States	Ala., Miss.	
Moesian	IICb	Bulgaria, Moldova, Romania		Moesian Platform-Lom Basin, Alexandria Rosiori Depression (Moesian Platform), Carpathian-Balkanian, West Black Sea

Table 2-1. List of geological basin names, the Klemme basin type, countries, U.S. states or Canadian provinces reporting deposits of heavy oil and/or natural bitumen, and other names cited in literature.—Continued

Geological province	Klemme basin type	Country	State/Province	Other names
Molasse	IICb	Austria, Germany, Italy, Switzerland		Molasse Basin
Morondava	IIIC	Madagascar		
Mukalla	IIIC	Yemen		Sayhut Basin, Masila-Jeza
Natuna	IIIA	Indonesia		
Nemaha Anticline-Cherokee Basin	IIA	United States	Kans., Mo.	Anadarko
Neuquen	IIB	Argentina		Agrio Fold Belt (Neuquen Basin)
Niger Delta	IV	Cameroon, Equatorial Guinea, Nigeria		Abakaliki Uplift (Niger Delta)
Niigata	IIIBa	Japan		Niigata Basin, Yamagata Basin, Japan Volcanic Arc/Accreted Terrane
Nile Delta	IV	Egypt		Nile Delta Basin
North Caspian	IICa	Kazakhstan, Russia		Akatol' Uplift, Alim Basin, Beke-Bashkuduk Swell Pri-Caspian, Kobyskol' Uplift, South Emba, Tyub-Karagan
North Caucasus-Mangyshlak	IICa	Russia		Indolo-Kuban-Azov-Terek-Kuma Sub-basins, North Buzachi Arch, Middle Caspian, North Caucasus
North Egypt	IICa	Egypt		Western Desert, Abu Gharadiq
North Sakhalin	IIIBb	Russia		Sakhalin North
North Slope	IICc	United States	Alaska	Arctic Coastal Plains, Interior Lowlands, Northern Foothills, Southern Foothills, Colville
North Sumatra	IIIBa	Indonesia		North Sumatra Basin
North Ustyurt	IIB	Kazakhstan		Ust-Urt
Northern North Sea	IIIA	Norway, United Kingdom		Viking Graben, North Sea Graben
Northwest Argentina	IIA	Argentina		Carandaitycretaceous Basin
Northwest German	IIB	Germany		Jura Trough, West Holstein
Olenek	I	Russia		
Ordos	IIA	China		Shanganning, Qinling Dabieshan Fold Belt
Oriente	IIA	Peru		Acre, Maranon, Upper Amazon
Otway	IIIC	Australia		
Ouachita Overthrust	IIA	United States	Ark.	
Palo Duro	IIA	United States	N. Mex.	Tucumcari
Pannonian	IIIBc	Bosnia and Herzegovina, Croatia, Hungary, Romania, Serbia		Backa Sub-basin (Pannonian Basin)
Paradox	IIB	United States	Utah	
Paris	IIB	France		Anglo-Paris Basin
Pearl River	IIIC	China		Dongsha Uplift (Pearl River Basin), Pearl River Mouth, South China Continental Slope
Pelagian	IICa	Tunisia, Libya		
Permian	IIA	United States	N. Mex., Tex.	Ouachita Fold Belt, Bend Arch, Delaware, Midland
Peten-Chiapas	IICc	Guatemala		Chapayal (South Peten) Basin, North Peten (Paso Caballos), Sierra De Chiapas-Peten, Yucatan Platform
Piceance	IIA	United States	Colo.	
Po	IICb	Italy		Crema Sub-Basin (Po Basin)
Polish	IIIA	Poland		Danish-Polish Marginal Trough, German-Polish

Table 2-1. List of geological basin names, the Klemme basin type, countries, U.S. states or Canadian provinces reporting deposits of heavy oil and/or natural bitumen, and other names cited in literature.—Continued

Geological province	Klemme basin type	Country	State/Province	Other names
Potiguar	IIIC	Brazil		Boa Vista Graben (Potiguar Basin), North-Northeastern Region
Potwar	IICb	Pakistan		Bannu Trough (Potwar Basin), Kohat-Potwar
Powder River	IIA	United States	Mont., Wyo.	
Pripyat	IIIA	Belarus		Pripyat Graben
Progreso	IIIBb	Ecuador		Guayaquil, Gulf Of Gayaquil, Jambeli Sub-basin of Progresso Basin, Santa Elena
Putumayo	IIA	Colombia, Ecuador		Napo, Cuenca Oriente Ecuatoriana
Rhine	IIIA	France, Germany		Upper Rhine Graben
Sacramento	IIIBb	United States	Calif.	Sacramento-San Joaquin
Salawati	IICa	Indonesia		Salawati Basin, Bintuni-Salawati
Salinas	IICc	Mexico		Isthmus Of Tehuantepec, Salinas Sub-basin, Isthmus Saline, Saline Comalcalco
San Joaquin	IIIBb	United States	Calif.	Sacramento-San Joaquin
San Jorge	IIIA	Argentina		Rio Mayo, San Jorge Basin
San Juan	IIB	United States	Ariz., Colo., N. Mex.	
Santa Maria	IIIBb	United States	Calif.	
Santos	IIIC	Brazil		
Sarawak	IICc	Malaysia		Central Luconia Platform
Sedgwick	IIA	United States	Kans.	Anadarko
Senegal	IIIC	Senegal		Bove-Senegal Basins
Sergipe-Alagoas	IIIC	Brazil		Sergipe-Alagoas Basin
Shumagin	V	United States	Alaska	
Sirte	IIIA	Libya		Agedabia Trough (Sirte Basin)
Songliao	IIIA	China		
South Adriatic	IICb	Italy		Adriatic, Marche-Abruzzi Basin (Pede-Apenninic Trough), Plio-Pleist Foredeep, Scaglia
South African	IIIC	South Africa		Agulhas Arch (South African Coastal Basin)
South Burma	IIIBb	Burma		Central Burma Basin, Irrawaddy
South Caspian	IIIBc	Azerbaidjan		South Caspian OGP (Apsheron-Kobystan Region), Emba, Guriy Region
South Oklahoma Folded Belt	IIA	United States	Okla., Tex.	Anadarko
South Palawan	IIIBa	Philippines		China Sea Platform, Palawan Shelf
South Sumatra	IIIBa	Indonesia		Central Palembang Depression (South Sumatra Basin)
South Texas Salt Dome	IICc	United States	Tex.	
South Yellow Sea	IIIA	China		Central Uplift (South Huanghai Basin), Subei Yellow Sea
Southern North Sea	IIB	United Kingdom		Central Graben (North Sea Graben system), Dutsh Bank Basin (East Shetland Platform), Witch Ground Graben
Sudan	IIIA	Sudan		Kosti Sub-Basin (Melut Basin), Muglad Basin, Sudd Basin
Sunda	IIIBa	Indonesia		
Surat	IIB	Australia		
Sverdrup	IICc	Canada	N.W.T.	Mellville
Taiwan	IIIBa	Taiwan		Taihsi Basin

Table 2-1. List of geological basin names, the Klemme basin type, countries, U.S. states or Canadian provinces reporting deposits of heavy oil and/or natural bitumen, and other names cited in literature.—Continued

Geological province	Klemme basin type	Country	State/Province	Other names
Talara	IIIBb	Peru		Talara Basin
Tampico	IICc	Mexico		Tampico-Tuxpan Embayment, Chicontepec, Tampico-Misantla
Tarakan	IIIBa	Indonesia		Bera Sub-basin (Tarakan Basin), Pamusian-Tarakan
Taranto	IICb	Italy		Abruzzi Zone (Apennine Range). Marche-Abruzzi Basin (Pede-Apenninic Trough), Latium, Calabrian
Tarfaya	IIIC	Morocco		Aaiun-Tarfaya
Tarim	IIIA	China		
Thrace	IIIBc	Turkey		Thrace-Gallipoli Basin, Zagros Fold Belt
Timan-Pechora	IIB	Russia		Belaya Depression (Ural Foredeep), Brykalan Depression, Pechora-Kozhva Mega-Arch, Varendey-Adz'va
Timimoun	IIB	Algeria		Sbaa
Tonga	IIIBa	Tonga		
Tunguska	I	Russia		Baykit Antecline
Turpan	IIIA	China		Tulufan
Tyrrhenian	IIIA	Italy		
Uinta	IIA	United States	Utah	
Upper Magdalena	IIIBc	Colombia		Upper Magdalena Basin
Ventura	IIIBb	United States	Calif.	Santa Barbara Channel
Veracruz	IIIC	Mexico		
Verkhoyansk	IIA	Russia		
Vienna	IIIBc	Austria, Slovakia		Bohemia
Vilyuy	IIA	Russia		
Volga-Ural	IIA	Russia		Aksubayevo-Nurlaty Structural Zone, Bashkir Arch, Belaya Depression, Melekess Basin, Tatar Arch, Vishnevo-Polyana Terrace
Washakie	IIA	United States	Wyo.	
West Java	IIIBa	Indonesia		Arjuna Sub-Basin (West Java Basin), Northwest Java
West of Shetlands	IIIC	United Kingdom		Faeroe, West of Shetland
West Siberia	IIB	Russia		West Siberia
Western Canada Sedimentary	IIA	Canada, United States	Alta., Mont., Sask.	Alberta, Western Canada Sedimentary, Sweetgrass Arch
Western Overthrust	IIA	United States	Ariz., Mont., Nev., Utah	Central Western Overthrust, Great Basin Province, Southwest Wyoming, South Western Overthrust
Williston	I	Canada, United States	N. Dak., Sask.	Sioux Uplift
Wind River	IIA	United States	Wyo.	
Yari	IIA	Colombia		Yari Basin
Yenisey-Khatanga	IIA	Russia		
Yukon-Kandik	IIIBb	United States	Alaska	Yukon-Koyukuk
Zagros	IICa	Iran, Iraq		Zagros Fold Beltzagros or Iranian Fold Belt, Sinjar Trough, Bozova-Mardin High, Euphrates/Mardin

Appendix 3. Klemme Basin Classificaton Figure from Plate 1

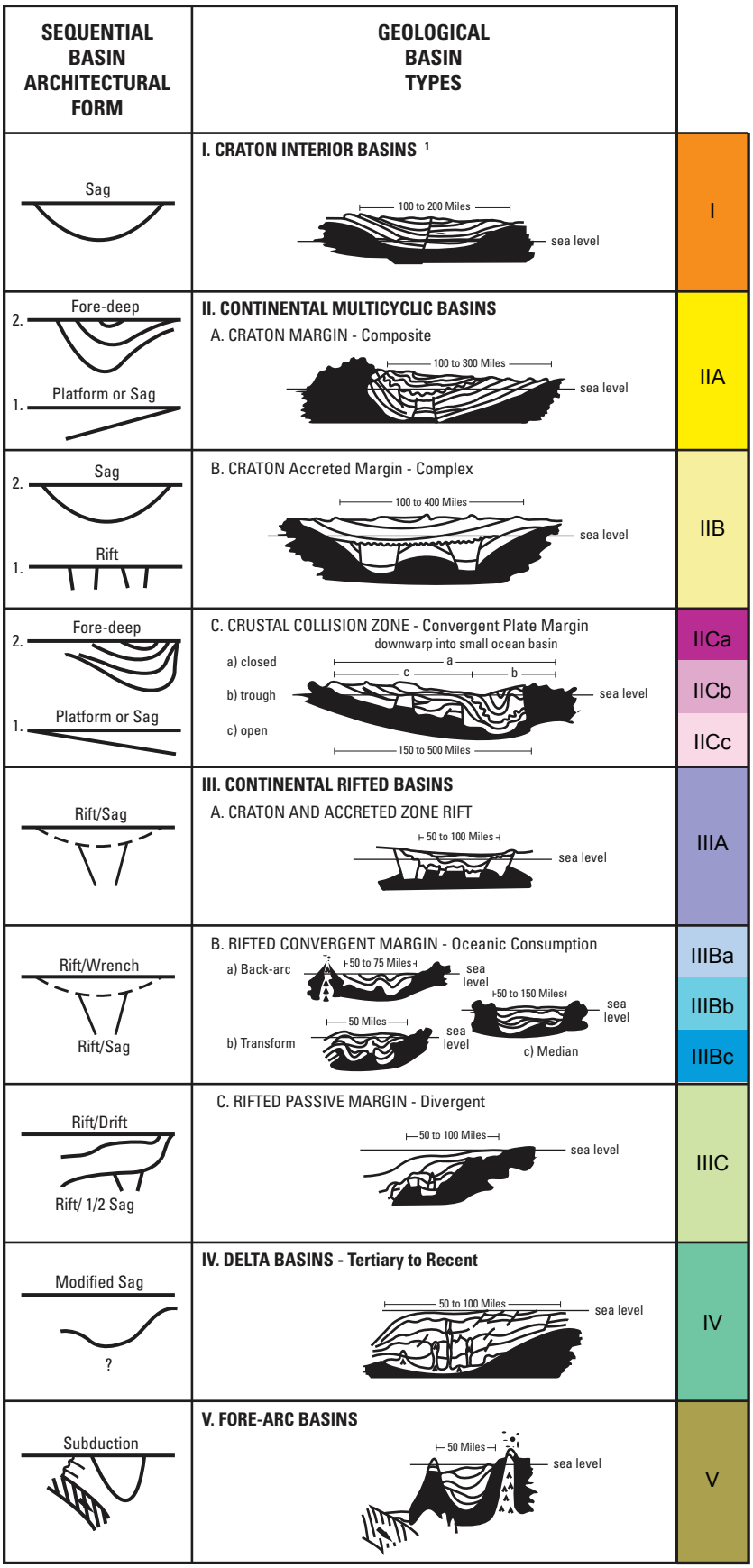

Figure 2-1. Diagram of Klemme basin types from plate 1. Modified from St. John, Bally, and Klemme (1984).
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[1] Cincinati Arch is classified as I-Arch

Appendix 4. Tables from the Plates

Table 4-1. 50 heavy oil basins ranked by volumes of total original heavy oil in place (TOHOIP), showing natural bitumen volumes where reported. Table repeated from plate 2.

[billions of barrels, BBO, 10^9 barrels]

Rank	Geological province	Klemme basin type	Total original heavy oil in place	Original heavy oil in place-discovered	Prospective additional heavy oil in place	Total original natural bitumen in place	Original natural bitumen in place-discovered	Prospective additional natural bitumen in place
1	Arabian	IICa	842	842				
2	Eastern Venezuela	IICa	593	566	27.7	2,090	1,900	190
3	Maracaibo	IIIBc	322	322		169	169	
4	Campeche	IICc	293	293		0.060	0.060	
5	Bohai Gulf	IIIA	141	141		7.63	7.63	
6	Zagros	IICa	115	115				
7	Campos	IIIC	105	105				
8	West Siberia	IIB	88.4	88.4				
9	Tampico	IICc	65.3	65.3				
10	Western Canada Sedimentary	IIA	54.9	54.9		2,330	1,630	703
11	Timan-Pechora	IIB	54.9	54.9		22.0	22.0	
12	San Joaquin	IIIBb	53.9	53.9		< 0.01	< 0.01	
13	Putumayo	IIA	42.4	42.4		0.919	0.919	
14	Central Sumatra	IIIBa	40.6	40.6				
15	North Slope	IICc	37.0	37.0		19.0	19.0	
16	Niger Delta	IV	36.1	36.1				
17	Los Angeles	IIIBb	33.4	33.4		< 0.01	< 0.01	< 0.01
18	North Caspian	IICa	31.9	31.9		421	421	
19	Volga-Ural	IIA	26.1	26.1		263	263	
20	Ventura	IIIBb	25.2	25.2		0.505	0.505	
21	Gulf of Suez	IIIA	24.7	24.7		0.500	0.500	
22	Northern North Sea	IIIA	22.8	22.8		10.9	10.9	
23	Gulf Coast	IICc	19.7	19.7				
24	Salinas	IICc	16.6	16.6				
25	Middle Magdalena	IIIBc	16.4	16.4				
26	Pearl River	IIIC	15.7	15.7				
27	North Ustyurt	IIB	15.0	15.0				
28	Brunei-Sabah	IICc	14.7	14.7				
29	Diyarbakir	IICa	13.5	13.5				

Table 4-1. 50 heavy oil basins ranked by volumes of total original heavy oil in place (TOHOIP), showing natural bitumen volumes where reported. Table repeated from plate 2.—Continued

[billions of barrels, BBO, 10^9 barrels]

Rank	Geological province	Klemme basin type	Total original heavy oil in place	Original heavy oil in place-discovered	Prospective additional heavy oil in place	Total original natural bitumen in place	Original natural bitumen in place-discovered	Prospective additional natural bitumen in place
30	Northwest German	IIB	9.48	9.48				
31	Barinas-Apure	IIA	9.19	9.19		0.38	0.38	
32	North Caucasus-Mangyshlak	IICa	8.60	8.60		0.060	0.060	
33	Cambay	IIIA	8.28	8.28				
34	Santa Maria	IIIBb	8.06	8.06		2.03	2.02	< 0.01
35	Central Coastal	IIIBb	8.01	8.01		0.095	0.025	0.070
36	Big Horn	IIA	7.78	7.78				
37	Arkla	IICc	7.67	7.67				
38	Moesian	IICb	7.39	7.39				
39	Assam	IICb	6.16	6.16				
40	Oriente	IIA	5.92	5.92		0.250	0.250	
41	Molasse	IICb	5.79	5.79		0.010	0.010	
42	Doba	IIIA	5.35	5.35				
43	Morondava	IIIC	4.75	4.75		2.21	2.21	
44	Florida-Bahama	IIIC	4.75	4.75		0.48	0.48	
45	Southern North Sea	IIB	4.71	4.71				
46	Durres	IICb	4.70	4.70		0.37	0.37	
47	Caltanisetta	IICb	4.65	4.65		4.03	4.03	
48	Neuquen	IIB	4.56	4.56				
49	North Sakhalin	IIIBb	4.46	4.46		< 0.01	< 0.01	
50	Cabinda	IIIC	4.43	4.43		0.363	0.363	

Table 4-2. 33 natural bitumen basins ranked by volumes of total original natural bitumen in place (TONBIP). Table repeated from plate 3.

[billions of barrels, BBO, 10^9 barrels]

Rank	Geological province	Klemme basin type	Total original natural bitumen in place	Original natural bitumen in place-discovered	Prospective additional natural bitumen in place
1	Western Canada Sedimentary	IIA	2,330	1,630	703
2	Eastern Venezuela	IICa	2,090	1,900	190
3	North Caspian	IICa	421	421	
4	Volga-Ural	IIA	263	263	
5	Maracaibo	IIIBc	169	169	
6	Tunguska	I	59.5	8.19	51.3
7	Ghana	IIIC	38.3	5.74	32.6
8	Timan-Pechora	IIB	22.0	22.0	
9	North Slope	IICc	19..0	19.0	
10	Uinta	IIA	11.7	7.08	4.58
11	Northern North Sea	IIIA	10.9	10.9	
12	South Caspian	IIIBc	8.84	8.84	
13	Bohai Gulf	IIIA	7.63	7.63	
14	Paradox	IIB	6.62	4.26	2.36
15	Black Warrior	IIA	6.36	1.76	
16	South Texas Salt Dome	IICc	4.88	3.87	1.01
17	Cuanza	IIIC	4.65	4.65	
18	Bone Gulf	IIIBa	4.46	4.46	
19	Caltanisetta	IICb	4.03	4.03	
20	Nemaha Anticline-Cherokee Basin	IIA	2.95	0.70	2.25
21	Morondava	IIIC	2.21	2.21	
22	Yenisey-Khatanga	IIA	2.21	2.21	
23	Santa Maria	IIIBb	2.03	2.02	<0.01
24	Junggar	IIIA	1.59	1.59	
25	Tarim	IIIA	1.25	1.25	
26	West of Shetlands	IIIC	1.00	1.00	
27	Putumayo	IIA	0.919	0.919	
28	Illinois	I	0.890	0.300	0.590
29	South Oklahoma Folded Belt	IIA	0.885	0.058	0.827
30	South Adriatic	IICb	0.510	0.510	
31	Ventura	IIIBb	0.505	0.505	
32	Gulf of Suez	IIIA	0.500	0.500	
33	Florida-Bahama	IIIC	0.477	0.477	

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ORIGINAL PAPER

Evaluating the effectiveness of road mitigation measures

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Abstract The last 20 years have seen a dramatic increase in efforts to mitigate the negative effects of roads and traffic on wildlife, including fencing to prevent wildlife-vehicle collisions and wildlife crossing structures to facilitate landscape connectivity. While not necessarily explicitly articulated, the fundamental drivers behind road mitigation are human safety, animal welfare, and/or wildlife conservation. Concomitant with the increased effort to mitigate has been a focus on evaluating road mitigation. So far, research has mainly focussed on assessing the use of wildlife crossing structures, demonstrating that a broad range of species use them. However, this research has done little to address the question of the effectiveness of crossing structures, because use of a wildlife crossing structure does not necessarily equate to its effectiveness. The paucity of studies directly

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examining the effectiveness of crossing structures is exacerbated by the fact that such studies are often poorly designed, which limits the level of inference that can be made. Without well performed evaluations of the effectiveness of road mitigation measures, we may endanger the viability of wildlife populations and inefficiently use financial resources by installing structures that are not as effective as we think they are. In this paper we outline the essential elements of a good experimental design for such assessments and prioritize the parameters to be measured. The framework we propose will facilitate collaboration between road agencies and scientists to undertake research programs that fully evaluate effectiveness of road mitigation measures. We discuss the added value of road mitigation evaluations for policy makers and transportation agencies and provide recommendations on how to incorporate such evaluations in road planning practices.

Keywords Wildlife · Population viability · Road mitigation · Crossing structures · Monitoring · Effectiveness · Guidelines

Introduction

In recent decades, transportation agencies have become increasingly aware of the effects of roads, railroads and other linear infrastructure on wildlife (Forman and Alexander 1998; Trombulak and Frissell 2000; Coffin 2007). Roads and traffic may increase mortality of wildlife due to wildlife-vehicle collisions, act as barriers to animal movement and migration, and affect both the amount and quality of wildlife habitat (Spellerberg 2002; Forman et al. 2003). Consequently, roads and road networks potentially jeopardize the long-term persistence of wildlife populations, communities and ecosystems (van der Grift et al. 2003; Jaeger and Fahrig 2004; Fahrig and Rytwinski 2009; van der Ree et al. 2009; Benítez-López et al. 2010; Borda-de-Agua et al. 2010; Kociolek et al. 2011).

Concern for the impacts of roads on wildlife has resulted in efforts to mitigate these effects (Forman et al. 2003). Mitigation measures include wildlife warning signs, measures to reduce traffic volume and/or speed, animal detection systems, wildlife reflectors, wildlife repellents, modified road designs/viaducts/bridges, changes in road-verge

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management, wildlife fences, wildlife crosswalks, and wildlife crossing structures (Iuell et al. 2003; Clevenger and Ford 2010; Huijser and McGowen 2010). Wildlife crossing structures, combined with wildlife fences that prevent animals from accessing roads and that guide animals towards the crossing structures, are gaining attention by transportation agencies because they provide safe wildlife passages without affecting traffic flow. Hence they improve human safety, reduce property damage and decrease the risk of local population extinction due to wildlife mortality and/or population isolation. Wildlife crossing structures include both underpasses (e.g., amphibian tunnel, badger pipe, ledges in culvert) and overpasses (e.g., land bridge, rope bridge, glider pole).

Road mitigation measures are common in some parts of the world (Trocmé et al. 2003). Mitigation measures are most likely to be considered when new roads, road extensions or road upgrades are proposed (Evink 2002). Occasionally, existing roads may be retrofitted (van der Grift 2005). Investments in road mitigation measures can be substantial. For example, in the Netherlands 70 million euros (10 % of road project budget) were spent on the construction of 85 wildlife crossing structures, 80 km of wildlife fences and 185 ha of habitat restoration, to counteract the expected impacts of a 42-km highway extension (Kusiak and Hamerslag 2003). The Netherlands has also allocated about 410 million euros to a national defragmentation program that aims to retrofit crossing structures to existing highways, railroads and waterways (van der Grift 2005). In the USA, 94 million dollars were spent by the federal government on road mitigation measures between 1992 and 2008 (National Transportation Enhancements Clearinghouse 2009) and currently 10 million dollars—7.5 % of the road project budget—is invested in road mitigation at U.S. Highway 93 at the Flathead Indian Reservation, Montana, USA, including 41 wildlife and/or fish crossing structures (Becker and Basting 2010; P.B. Basting, personal communication).

But to what extent are such measures effective? Most research has focussed on assessing the use of wildlife crossing structures (e.g., Hunt et al. 1987; Foster and Humphrey 1995; Yanes et al. 1995; Rodriguez et al. 1996; van Wieren and Worm 2001; Ng et al. 2004). Such studies have demonstrated that a broad range of species use wildlife crossing structures, that the optimal design and placement of crossing structures is often species-specific and that crossing rates depend on both landscape and structural features (Rodriguez et al. 1997; McDonald and St-Clair 2004; Clevenger and Waltho 2005; van Vuurde and van der Grift 2005; Grilo et al. 2008). On the other hand, comparatively few studies (see overview in van der Ree et al. 2007) have addressed the extent to which the barrier effect of roads and road-related mortalities is reduced (Lehnert and Bissonette 1997; Dodd et al. 2004; Klar et al. 2009) or gene flow between populations has been enhanced by road mitigation measures (Corlatti et al. 2009; Clevenger and Sawaya 2010). Empirical studies that examine population-level effects of crossing structures are even rarer (but see, e.g., Mansergh and Scotts 1989; van der Ree et al. 2009). Clearly, estimates of the extent to which a structure is used does not directly answer the question of to what extent the impacts of the road and traffic on wildlife have been mitigated.

The paucity of studies directly examining the effectiveness of crossing structures on wildlife populations is exacerbated by the fact that such studies invariably permit, at best, weak inference. For example, many studies are of too short duration to distinguish transient from long-term effects. Only a small number of studies have employed a before-after design or included comparisons between treated and untreated sites (van der Ree et al. 2007; Glista et al. 2009). Consequently, transportation agencies can rarely assess whether mitigation objectives have been met. Without well performed evaluations of the effectiveness of road mitigation measures, we may endanger the viability of wildlife populations and waste financial resources by installing structures that are not as effective as we think

they are. Furthermore, we cannot establish a set of best mitigation practices nor evaluate cost-benefits and consider what mitigation strategies are most efficient until effectiveness has been quantified.

Here we propose a methodological framework for evaluating the effectiveness of wildlife crossing structures. First, we identify the principle ecological objectives of crossing structures and discuss what needs to be measured to evaluate how well these objectives are being met. Second, we provide guidelines for study design, the selection of appropriate research sites, survey methods and the development of suitable/feasible sampling schemes. For cases where the mitigation is intended to benefit many species, we identify criteria to prioritise species for evaluation. Finally, we discuss the value of road mitigation evaluation for policy makers and transportation agencies and provide recommendations on how to incorporate evaluations into road planning practice.

Guidelines for evaluating road mitigation effectiveness

The first step in setting up a monitoring plan for evaluating the effectiveness of wildlife crossing structures (Fig. 1) is to determine the species targeted by the mitigation and to explicitly identify mitigation goals. The second step is to identify the species and goals that will actually be evaluated, in cases where it is not feasible to evaluate all species or goals. Steps three to five address the selection of variables to measure, the selection of a study design, and the development of a suitable sampling scheme. Steps six to eight address the selection of appropriate study sites, the determination of appropriate covariates, and the selection of appropriate survey methods. The final step is an assessment of the costs of evaluation and the feasibility of monitoring.

Although the steps in Fig. 1 are suggested as a logical sequence, in reality it may sometimes be necessary to revisit earlier steps to reconsider prior decisions. For example, if no appropriate study sites can be found for a selected species, an alternative study design, measure or species must be selected. Or if the cost of a study surpasses the available budget, alternative decisions on, e.g., study design or survey method should be made. Such iterations in the process may occur from step five onward (Fig. 1), but should be kept to a minimum.

Step 1: Identify species and goals for mitigation

The first step is to identify the target species that prompted the mitigation and formulate the specific goals for mitigation. A list of target species is usually presented by the road authority responsible for the mitigation, often prepared in cooperation with other stakeholders such as wildlife managers and environmental planners. These lists may be based on (1) empirical studies, e.g., on road-kill or road-related changes in animal movements; (2) predictive (modeling) studies in which potential effects of mitigation measures are explored; and/or (3) expert-opinion. Occasionally, groups of species are targeted for mitigation, e.g., “small mammals”, “butterflies”, or “frogs”. This typically occurs as a result of expert opinion or when information is lacking. In such cases, a first step should be to specify targeted species to allow for an effective monitoring plan (van der Grift et al. 2009a).

Selection of target species for mitigation is based on considerations of human safety, animal welfare, and wildlife conservation. Human safety issues dominate when animal-vehicle collisions pose a significant risk to motorists. These species need not be of conservation concern. For example the construction of fences and wildlife crossing structures on Swedish highways is motivated primarily by concerns for human health risks associated

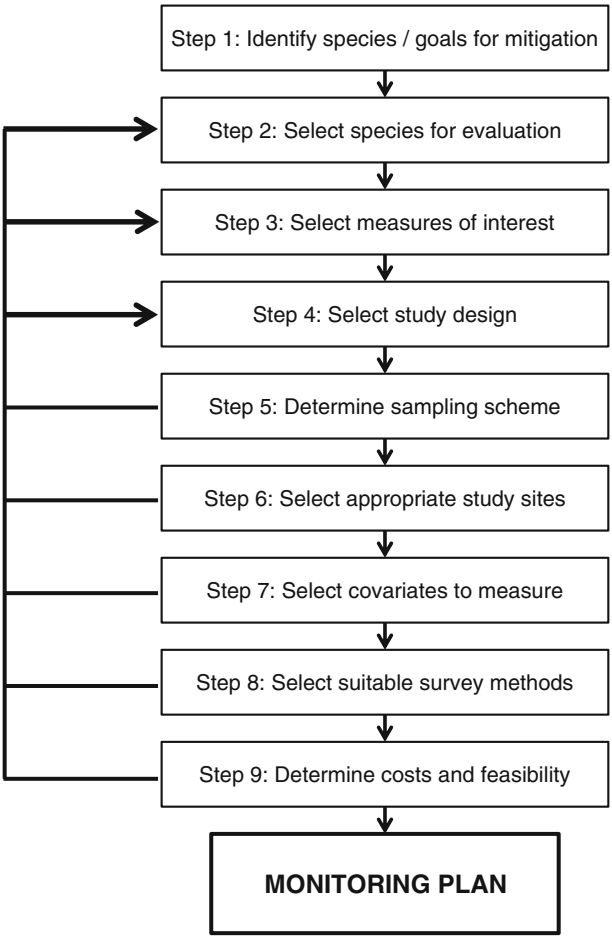

Fig. 1 Process for setting up a monitoring plan for evaluating the effectiveness of wildlife crossing structures

with moose-vehicle collisions rather than a concern with the impacts of traffic mortality on the viability of moose populations (Seiler 2003). When animal welfare drives the selection of species, the motivation is that each animal affected by the road is one too many. For example, the death of high numbers of hedgehogs on Dutch roads is—although the survival probability of local populations may be affected (Huijser and Bergers 2000)—usually not believed to affect the existence of the species in the country, but if animal welfare is a concern, wildlife fences and crossing structures may be warranted. If wildlife conservation is the goal, target species for mitigation are selected on the basis of the potential impact of the road and traffic on species viability, e.g., determined through population modelling. This can include species with protected status as well as species of general conservation concern. Such species selection is generally directed by conservation legislation or environmental policies.

We distinguish two potential targets in road mitigation goals: (1) no net loss, and (2) limited net loss. No net loss implies that road impacts will be entirely mitigated, i.e., the

post-mitigation situation for the targeted species and goals is identical to the pre-road construction situation. Limited net loss implies that a limited road impact will be accepted (van der Grift et al. 2009a). The target level should be decided in advance and will depend on the local situation. For example, in one jurisdiction a species may be common and its survival not significantly harmed by a small loss in cross-road movements, whereas somewhere else it may be essential to its survival, justifying a no net loss target. In case a limited net loss target level is selected, it should be carefully determined how much loss, relative to pre-road conditions, is acceptable. If this appears hard to pin-point, precautionary principles should be followed, i.e., no net loss should be selected as target level.

Currently, road mitigation studies rarely specify mitigation goals (see van der Ree et al. 2007). When goals are made explicit they are often too imprecise to allow for an evaluation of whether indeed they have been achieved, e.g., "allowing animal movement", "restoring connectivity" and/or "promoting gene flow". Effective evaluation of road mitigation measures requires a clear definition of success. We recommend the SMART-approach to develop goals that are Specific, Measurable, Achievable, Realistic and Time-framed (Doran 1981; examples in Table 1). The goals should ideally: specify what road impact(s) is/are addressed; quantify the reduction in road impact(s) aimed for; be agreed upon by all stakeholders; match available resources; and specify the time-span over which the reductions in road impact(s) have to be achieved. Well-described mitigation goals will channel the choices in the next steps towards an effective monitoring plan (Fig. 1).

Table 1 Examples of SMART defined goals for mitigation for each target level in road mitigation and some of the main road effects addressed by the construction of wildlife crossing structures

Road effect	Target level in road mitigation	
	No net loss	Limited net loss
Wildlife mortality	In year X after mitigation all traffic-related mortality of species Y is prevented	In year X after mitigation Z % of traffic-related mortality of species Y is prevented
Barrier effect	In year X after mitigation the number of between-population movements across the road of species Y is similar to pre-road construction movement numbers	In year X after mitigation the number of between-population movements across the road of species Y is Z % of pre-road construction movement numbers
	Or, if before mitigation the species occurs on only one side of the road: In year X after mitigation the empty habitat is permanently colonised by species Y	*Or, if before mitigation the species occurs on only one side of the road:* In year X after mitigation the empty habitat is used Z % of the time by species Y
	Or, if before mitigation the populations on both sides of the road show significant genetic differences: In year X after mitigation no genetic difference occurs between populations of species Y across the road	*Or, if before mitigation the populations on both sides of the road show significant genetic differences:* In year X after mitigation the genetic difference between populations of species Y across the road is reduced by Z %
Population reduction	In year X post-mitigation population density of species Y is similar to pre-road construction population density	In year X post-mitigation population density of species Y reaches Z % of pre-road construction population density
	Or, if pre-road construction situation is unknown: In year X post-mitigation population density of species Y is similar to population density in a control population	*Or, if pre-road construction situation is unknown:* In year X post-mitigation population density of species Y reaches Z % of population density in a control population

Step 2: Select species for evaluation

The preferred approach is to study the responses of all species targeted for mitigation. However, the list of targeted species is often long and resources may not be sufficient to evaluate them all. It may also not be necessary to evaluate all targeted species, as some may be similar to others in their responses to roads and road mitigation. Hence, the species for evaluation need to be chosen, and a random sampling approach may be required if the general performance of a wildlife crossing structure needs to be assessed. However, studies of the performance of wildlife crossing structures usually target threatened species, i.e., species that are rare, in decline or both. If limited resources prevent an evaluation of all threatened species, one may choose species that are most likely to demonstrate statistically significant effects with comparatively little sampling effort in space and/or time. We suggest using the following criteria to select those species: (1) Select species that have shown strong responses to roads and traffic, e.g., species that are frequently killed by traffic, or species that have proven to be unable/reluctant to cross roads or who avoid the road corridor altogether (see also Jaeger et al. 2005). (2) Select species that are expected to show short response times to road mitigation, e.g., species that quickly habituate to wildlife crossing structures. (3) Select species that are relatively widespread, as this will increase opportunities to find suitable replication and control sites. (4) Select species with low natural variability in population densities over time, as high variability in population densities will decrease the statistical power to detect road mitigation effects. (5) Select species that can be readily and easily surveyed. If the list of selected species for evaluation, after applying these criteria, still exceeds available resources, further selections of species can be made on the basis of preferences, for example, even representation of different animal taxa, habitats and/or trophic levels.

Step 3: Select measures of interest

As Table 2 shows there are many ways to measure road mitigation effectiveness, depending on the concern, i.e., human safety, animal welfare or wildlife conservation. The best measures, i.e., measurement endpoints, are those which are most closely related to the outcome(s) of real concern, i.e., the assessment endpoint (Suter 1990; Roedenbeck et al. 2007). For example, (changes in) population viability cannot be directly measured in the field, hence we measure attributes of the population that are known to be related to population viability and predict future likelihood of persistence.

Four measurement endpoints are suggested to assess effects of road mitigation measures on human casualties (Table 2). The best is the actual number of people killed or injured due to animal-vehicle collisions or due to collision avoidance. Alternative measurement endpoints include the amount of insurance money spent, number of hospitalizations due to animal-vehicle collisions or collision avoidance, or number of wildlife-vehicle collisions concerning species that potentially impact human safety, regardless of whether they resulted in human injury or death. Two measurement endpoints are suggested to assess effects of road mitigation measures on wildlife health and mortality, i.e., the number of animals killed or injured while crossing roads and the number of animals killed or with ill-health due to isolation from needed resources through the barrier effect of roads (Table 2). These measurement endpoints seem to complement each other as each endpoint addresses a different mechanism through which wildlife health and mortality can be positively affected by wildlife crossing structures, i.e., through a reduction in animal-vehicle collisions or through increased road permeability and hence increased access to resources. Therefore, we suggest to always use these endpoints together.

Table 2 Overview of possible measurement endpoints (list is not complete) for each driver of road mitigation and assessment endpoint, and the extent of extrapolation needed from measurement endpoint to assessment endpoint

Driver of road mitigation	Assessment end point *What we want to know*	Measurement endpoint *What we measure*	Extent of extrapolation needed from measurement to assessment endpoint
Human safety	Human casualties	Number of humans killed or injured due to wildlife-vehicle collisions or due to collision avoidance	0
		Insurance money spent on material/immaterial damage due to wildlife-vehicle collisions	**
		Number of hospitalizations due to vehicle-animal collisions	**
		Number of wildlife-vehicle collisions, concerning species that potentially impact human safety, regardless of whether they resulted in human injury or death	****
Animal welfare	Wildlife health and mortality	Number of animals killed or injured while crossing roads	0
		Number of animals killed or with ill-health due to isolation from needed resources through the barrier effect of roads	0
Wildlife conservation	Population viability	Trend in population size/density	*
		Number of animals killed	**
		Reproductive success	**
		Age structure	***
		Sex ratio	***
		Between-population movements	***
		Genetic differentiation	****
		Genetic variability	****

Needed extrapolation is classified as not needed (0), low (*), moderate (**), high (***), or very high (****)

Eight measurement endpoints are suggested to assess effects of road mitigation measures on population viability (Table 2). The most informative measurement endpoint is the trend over time in the size (or density) of the local population. Trend in population size is fundamental to understanding how the species has responded to the road mitigation. For example, if existing roads are having population-level effects and crossing structures are successful in mitigating those effects we would expect to see increases in population size after the structures are installed. If the crossing structures are installed on a new road, successful mitigation would be indicated by no change in the size of the wildlife population. Population size itself is also related to population persistence, since smaller populations are more likely to go extinct by chance.

When it is not possible to estimate population size or trend, a reduction in road-kill numbers following mitigation may provide an indicator for mitigation effectiveness at population level, but only if compared with road-kill numbers at control sites (see also Step 4) and if assumed (which may not hold) that (1) mortality is the main mechanism through which roads affect the population, and (2) road-induced mortality is not counteracted by,

e.g., increased reproduction or immigration. As both assumptions may not apply (but see Hels and Buchwald 2001), changes in road-kill numbers should be seen as less indicative than estimates of population size or trend. Similarly, reproductive success as an indicator for mitigation effectiveness at the population level should be used with care, as no increase in reproductive success following mitigation may be the result of higher reproduction levels pre-mitigation as a response to loss of individuals due to road mortality.

Age structure and sex-ratio within the population may provide additional information to supplement the estimate of trends in population size because roads may impact individuals of different age classes or sexes differently. A positive feature of these measurement endpoints is that changes may be detected sooner in population structure than in population trend. However, they are less closely tied to population viability so more extrapolation is necessary, and they are only applicable to species that show differential age or sex responses to the road or traffic.

Road permeability measurement endpoints, such as between-population movement and gene flow may also allow inferences to population-level mitigation, if the main population-level effect of the road is through movement (rather than, say, mortality). Increased movements between populations divided by roads may affect, e.g., dispersal success or access to mates (see, e.g., Mansergh and Scotts 1989) and consequently population dynamics. Migrations across wildlife crossing structures may restore gene flow and reduce road-related genetic differences between the populations (Gerlach and Musolf 2000; Vos et al. 2001; Epps and McCullough 2005; Arens et al. 2007; Björklund and Arrendal 2008; Balkenhol and Waits 2009; Corlatti et al. 2009). Although both measurement endpoints directly address the extent to which the barrier effect of roads is reduced, endpoint extrapolation is rather high because demographic and genetic connectivity between populations are not necessarily related to population viability.

An even less direct indicator of a change in population viability is a change in genetic variability within the population. Genetic variability is thought to be positively correlated with population viability (Frankham 1996, 2005; Lacy 1997; Reed and Frankham 2003; Reed et al. 2007). Small populations that result from increased mortality or habitat fragmentation lose genetic variability as a result of genetic drift or inbreeding (Keller and Largiader 2003). The disadvantage of genetic variability as an endpoint is that the correlation between genetic variability and population persistence is not well understood. However, changes in genetic diversity—as an important part of biodiversity—may in itself be considered as an assessment endpoint.

Step 4: Select study design

Appropriate study design, i.e., the spatial and temporal sampling scheme, is critical for determining the effectiveness of road mitigation. It is the responsibility of the ecologists involved in the research and monitoring process to ensure the design is rigorous and provides useful information. As argued by Roedenbeck et al. (2007), the optimal study design is a replicated BACI (Before–After–Control–Impact), where data are collected before and after road mitigation, both at sites where mitigation measures are being taken (impact sites—hereafter referred to as mitigation sites) and at sites that are similar to these sites but where no mitigation measures are taken (control sites).

Control sites are important to ensure that changes to the measurement endpoint can reasonably be attributed to the mitigation measures. For example, mitigation may reduce road-kill, but an observed reduction in road-kill could also be caused by other factors, such as a decrease in population density, increased road avoidance behavior or changes in traffic

volume. An important assumption here is that mitigation and control sites are similar in all relevant respects (see also Step 6). As this assumption is rarely met, replication is strongly recommended for both the mitigation and control sites. We also recommend including unconventional controls or benchmarks that may further help to interpret observed changes, such as reference areas that are characterized by the absence of roads, or measurements of (national) trends in the selected measurement endpoints over time.

In some situations, there may be no suitable control sites available. Under these conditions, a replicated BA study design (Before–After) may be an alternative, where measurements are taken at multiple sites before and after the treatment. The fundamental limitation of this design is that an observed change in the measurement endpoint may have been caused by some factor other than the road mitigation. Since the BA design fails to distinguish other sources of temporal variability from effects of the mitigation measures, other potential impact factors (e.g., climate variability, increasing traffic volume over time) should be considered when interpreting the results (Roedenbeck et al. 2007).

In some other situations, such as when the effectiveness of an existing wildlife crossing structure is to be quantified, it may be impossible to collect any 'before' data. Under these conditions, a replicated CI study design (Control–Impact) may be possible, where measurements are taken at multiple mitigation and control sites after mitigation. The inference in a CI design is that differences between the mitigation and control sites are due to the mitigation measure. However, as no two sites are identical, this inference may be invalid if the observed effect arises from other systematic differences between control and impact sites, or possibly even random inter-site variation. Replication of both the mitigation and control sites increases the strength of the inference that observed differences are indeed due to the mitigation. Note that the level of replication required for a CI study is higher than the level of replication required for a BACI type of study.

When selecting an appropriate study design, opportunities for experimental manipulations should be explored, as this may provide higher inferential strength. For example, if the construction of wildlife crossing structures along one road can be staged, the temporarily non-mitigated stretch can be used as control site. Or when a time gap can be planned between the construction of wildlife fences and the construction of crossing structures or some of the crossing structures can be closed intentionally for a while after construction, the individual effects of both measures can be evaluated. Such an approach requires that goals and plans for evaluations are incorporated into the construction schedule.

Step 5: Determine sampling scheme

Several key questions related to data collection should now be addressed: (1) How long should sites be monitored before and after road mitigation? (2) How often should sites be monitored? (3) How many replicates are needed? As these decisions are unlikely to be independent, we recommend conducting model-based power analyses to optimize the sampling design (see, e.g., van der Grift et al. 2009b). For example, Fig. 2 illustrates the relationship between mitigation effectiveness (the expected effect size) on the degree of temporal replication needed for adequate statistical power. Similar graphs can be produced for other design variables such as sampling frequency and the number of replicate sites. Note that either pilot studies or pre-existing data on anticipated effect sizes are needed to conduct this type of analysis.

The sampling scheme is related to the chosen measurement endpoint and the characteristics of the studied species. For example, for a highly mobile species with a long

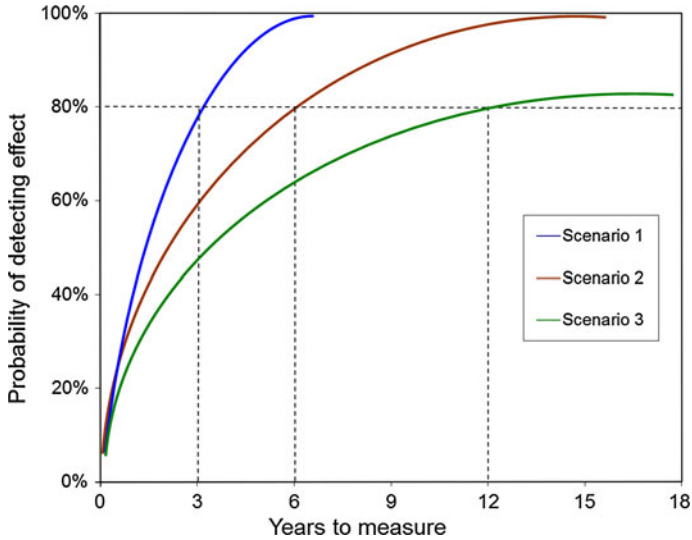

Fig. 2 Hypothetical relation between the probability of detecting an effect of road mitigation and the duration of monitoring after the mitigation measures are put in place. The three scenarios illustrate variations in the expected effectiveness of mitigation, e.g. road mitigation is expected to reduce the road effect by 100, 75 or 50 %. The figure shows that if we want to achieve statistical power of 80 % we should measure the response variable for 3, 6 and 12 years in scenarios 1, 2, and 3, respectively. This figure assumes that the effect of the mitigation measure on the population is immediate. However, response times of the population to both the road and the mitigation measures also have to be considered

lifespan, monitoring over a longer period would be required to assess a change in population density than that required to detect a change in movement. Similarly, a shorter monitoring period would be required to assess a change in road-kill numbers for a species that crosses roads frequently than for a species that crosses roads infrequently. For some measurement endpoints, such as changes in population size/density, higher levels of replication will allow a quicker evaluation of effectiveness. A study with three replicates will need to be continued for longer than a study with ten replicates, because with more replication the uncertainty in effect size will be reduced, thus allowing a reliable decision to be reached sooner.

The rate of use of wildlife crossing structures often increases over time (e.g., Clevenger and Waltho 2003; Ford et al. 2010) due to habituation or gradual improvement in the quality of the crossing structure (e.g., vegetation succession on wildlife overpasses). If usage and effectiveness are positively correlated, it is also likely that effectiveness will increase with time since mitigation. Therefore, if monitoring ceases too quickly, an incorrect inference that a crossing structure is ineffective may be drawn. In fact, in some cases monitoring resources may be more effectively allocated by waiting for a few years after installation of the mitigation measure before starting the 'after' monitoring. This may be particularly true when the assessment endpoint is population viability. Similarly, monitoring a site for too long commits resources after they are needed. Thus, sampling should not begin before an effect is expected to have occurred and should continue long enough to detect lagged and/or transient effects. A worst-case scenario is that the sampling duration is too short to detect a real effect and that future mitigation projects reject the use of a measure that is, in fact, successful.

Step 6: Select appropriate study sites

Selection of mitigation sites

If a road mitigation evaluation is to assess the effectiveness of multiple wildlife crossing structures along a road or hundreds of mitigation sites at multiple roads, it may be necessary to sample a subset of the available mitigation sites. The method for selecting an appropriate subset of mitigation sites depends on the overall objective of the evaluation. If the objective is to evaluate the extent to which a road mitigation plan is effective for a target species, one should choose a random sample of mitigation sites from the total number of available mitigation sites. Such evaluation aims to provide insight into the average effectiveness of the road mitigation. If the objective is, however, to evaluate whether wildlife crossing structures potentially mitigate road impacts for the target species, one should choose sites that are most likely to demonstrate statistically significant effects with comparatively little sampling effort in time. The following criteria provide a framework to select mitigation sites in this context: (1) Select sites where the road effect is known or expected to be high. (2) Select sites where the planned construction of the mitigation measures allows for sufficient time for repeated measurements before construction. (3) Select sites for which sufficient replicate sites can be found. (4) Select sites where multiple mitigation measures are planned for a relatively long section of road as this may allow for phasing or manipulating mitigation in an experimental design (see Step 4 above).

A mitigation effect is most likely to be detectable where a significant positive shift in population viability—e.g., estimated through a PVA (see, e.g., van der Grift and Pouwels 2006)—can be expected as a result of the road mitigation measures (Fig. 3). This implies selecting sites where on at least one side of the road the amount of habitat available is sufficient for only a small, non-viable population that needs an influx of animals from the opposite side of the road (Fig. 3b; see also van der Grift et al. 2002). An impact site with non-viable populations on both sides of the road may be appropriate as well, but only if the combined amount of habitat on both sides of the road is sufficient for a viable overall population in the mitigated situation (Fig. 3c).

The size of a mitigation site, in terms of road length, may vary. Preferably, the mitigation site is delineated where the studied road effect no longer occurs. These boundaries typically occur where suitable habitat ceases. Hence, if more than one target species is studied at one mitigation site, the size of that site, in terms of road length, may differ for each species as habitat preferences differ among species. The size of mitigation sites should not be based on the length over which wildlife fences are planned—as they may only be planned for limited sections of the road. Limiting measurements to only fenced road sections may mean that the conclusions drawn about the effectiveness of the road mitigation measures may be overly positive (Fig. 4).

Selection of control sites

Control sites require some consideration to ensure the comparison between the mitigation and control sites is valid. The goals for mitigation (see Step 1) determine which type of control site is needed, i.e., either a control site where the road is present but there is no mitigation, or control sites where there is no road present. The former applies when post-mitigation conditions have to be compared with pre-mitigation conditions, e.g., when the aim is to compare between-population movements before and after road mitigation. The

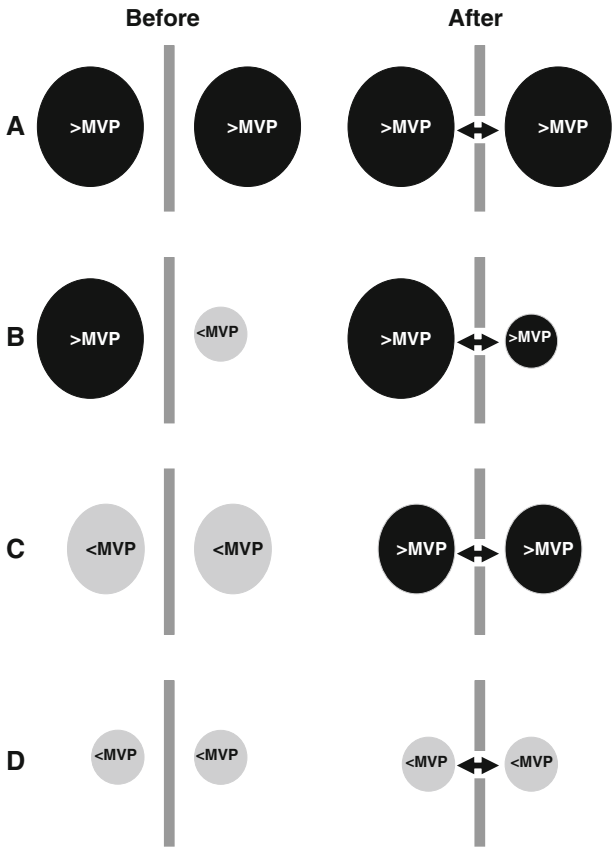

Fig. 3 Schematic overview of consequences for population viability when populations of different size, above or below the threshold of a minimum viable population (MVP), are merged due to road mitigation measures. Viable populations are depicted in *black*, non-viable populations in *grey*. Populations in which a significant effect of road mitigation on population viability is expected, here in situation *B* and *C*, should preferably be selected as research sites

latter applies when post-mitigation conditions have to be compared with pre-road construction conditions. For example, when a no net loss in population size/density is the target. If, in such cases, only control sites where the road is present but without mitigation are selected, no final conclusions can be drawn on the extent to which the full effect of the road has been mitigated.

Figure 5 illustrates measured (changes in) population density over time at mitigation and control sites where there is mitigation of an existing road. Scenarios 1 and 2 show that population density increased with the installation of road mitigation measures. However, proper assessments of the extent to which population density improves can only be made if we include no-road control sites. The other scenarios show no improvement (scenario 3) or even a decline in population density (scenario 4) after mitigation, due to mitigation measures that are ineffective (e.g., not located, designed or managed properly, or too few; compare for example Fig. 4II, IV). Proper assessments of the extent to which population density declines have been mitigated can only be made if we include no-mitigation control sites. Similar scenarios can be constructed for cases where the construction of the road and

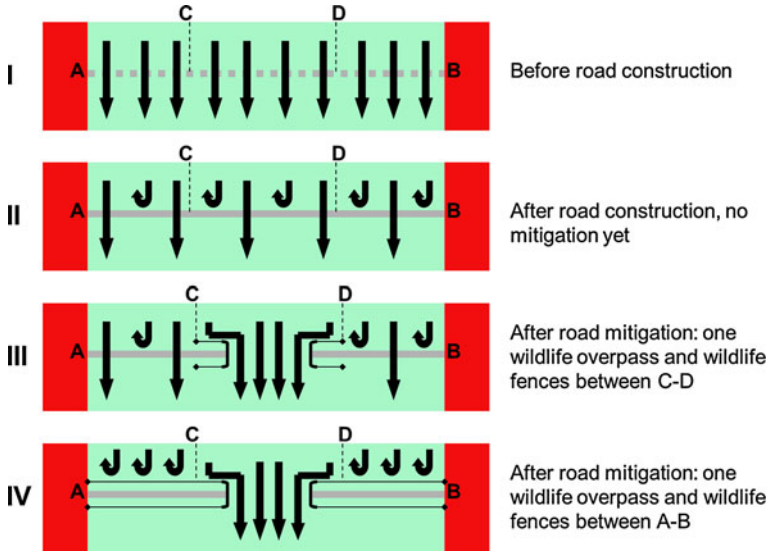

Fig. 4 Example of how the size of a mitigation site, i.e., road length where measurements are carried out, affects conclusions about crossing structure effectiveness. The studied road effect is the reduction of between-population movement. The *green area* symbolizes suitable habitat for the studied species. *Red areas* are non-suitable habitat, e.g., urban areas. Road construction (*II*) has decreased the number of movements by 50 %, compared to pre-road conditions (*I*). If only the mitigated road stretch (*C–D*) is included in the evaluation (*III*), the conclusion would be that the crossing structure is 100 % effective, as the number of movements across the road pre-road construction and post-mitigation are equal ($n = 4$). However, if the whole road stretch (*A–B*) is included in the evaluation, the conclusion would be that the crossing structure is only 70 % effective, as the crossing structure does not provide a solution for all potential movements across the road. Because the aim of the road mitigation was to fully prevent the barrier effect of the road between *A* and *B*, a delineation of the mitigation site between *C* and *D* will overestimate crossing structure effectiveness. Finally, the situation is shown where the full road length is fenced in (*IV*). In this case the effectiveness of the road mitigation measures is 40 %, illustrating that road mitigation, if not properly implemented, i.e., with sufficient numbers of crossing structures along the road, may result in less connectivity between populations on opposite sides of the road in comparison with the situation before mitigation (*II*). Again, like in situation *III*, wrong conclusions on mitigation effectiveness would be drawn if only road section *C–D* was monitored

road mitigation take place simultaneously, except that the trajectories would have a different starting point, i.e., at the level of the no-road control at $t = 0$ (Fig. 6).

All control sites need to be far enough away from the mitigation sites and each other to ensure statistical independence, yet still be as similar as possible. If possible, control sites should be sited along the same road as the mitigation site(s), as road age, design and traffic characteristics of the same section of road are probably similar. Such control sites should never immediately border the mitigation site(s), as possible edge effects of mitigation measures, e.g., an unnaturally high number of road-kill just at the end of the wildlife fencing, may influence the measurements.

Select appropriate spatial scale of study

Two factors need to be considered when determining the spatial scale of a study. First, the spatial scale of the study should match the spatial scale of the effect being mitigated. Stipulating a one-size fits all approach to determine the spatial scale of the study is not

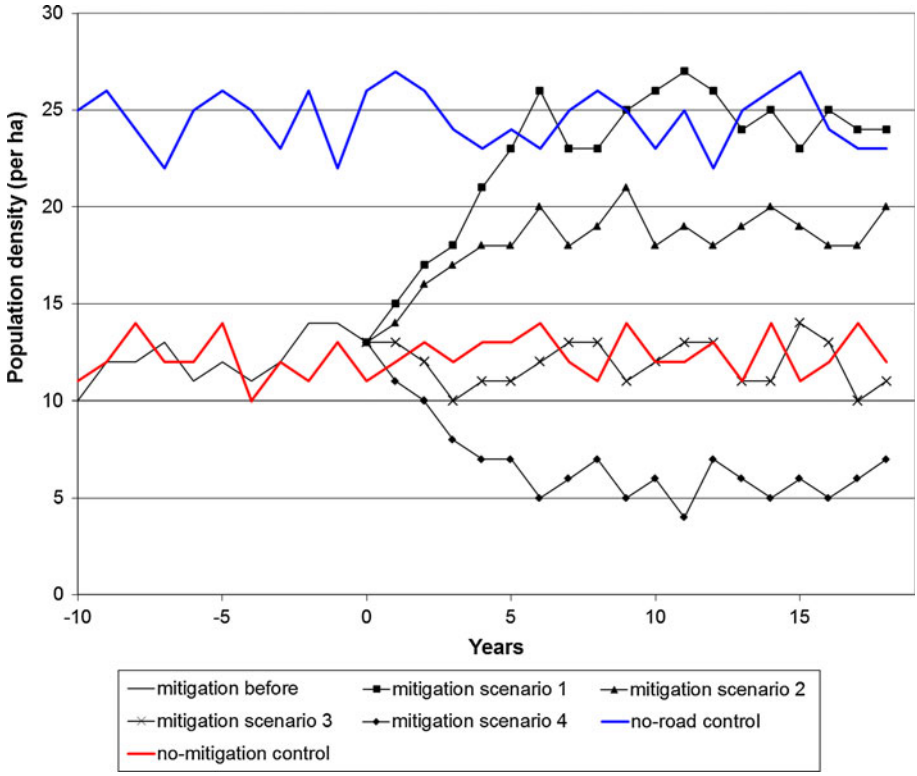

Fig. 5 Hypothetical result when evaluating the effectiveness of road mitigation measures at an existing road. Mitigation measures are installed at time zero. In addition to the mitigation site, measurements are carried out—before and after mitigation—at a no-mitigation control site and a no-road control site. Generally, there are four possible scenarios *1* the road mitigation measures are 100 % effective and population density increases to the level of the no-road control site, *2* the road mitigation measures are only partly effective and population density increases compared to the unmitigated situation but does not reach the level of the no-road control site, *3* the road mitigation measures are not effective and population density remains similar to the density in the unmitigated situation, *4* the road mitigation measures are not effective and even worsen the situation by reducing population density compared to the unmitigated situation

possible because the size of the road effect zone (Forman and Deblinger 2000; Forman et al. 2003) varies depending on the effect, the species of concern, and the local situation (e.g., habitat type, topography). Second, the sampling effort should be apportioned equally across the road effect zone, as the road effect of concern may vary significantly within this zone. The effect-size of the road—and consequently the effect-size of road mitigation measures—will be often at its maximum in close proximity to the road. However, situations occur where the opposite is true, e.g., due to an increase in suitable edge habitat at the roadside (Mumme et al. 2000) or due to home range pile-up adjacent to the road due to barrier effects (Riley et al. 2006).

It is often necessary to do a best guess about where the road effect zone ends. The distance over which an individual moves—on a daily basis or over its life span—may be helpful here, but should not be viewed as a characterization of the appropriate spatial scale of all studies. If changes in between-population movements are studied, mean individual movement distances may well indicate the effect-distance, as individuals that live farther

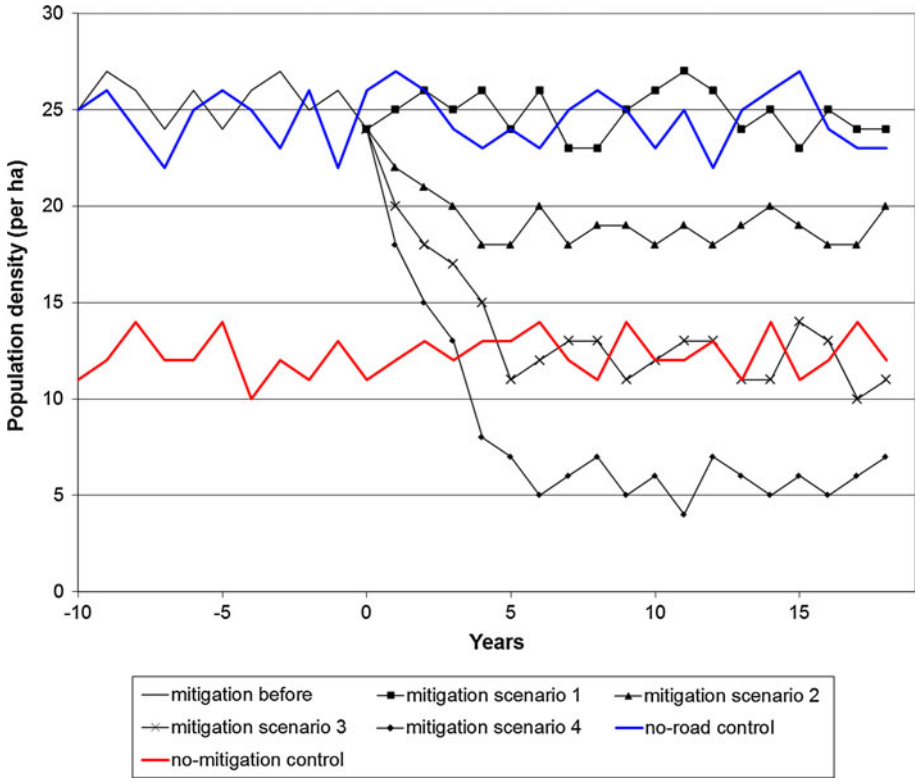

Fig. 6 Hypothetical result when evaluating the effectiveness of road mitigation measures at a new road with mitigation. The new road with mitigation is constructed at time zero. In addition to the mitigation site, measurements are carried out—before and after road construction—at a no-mitigation control site and a no-road control site. Generally, there are four possible scenarios *1* the road mitigation measures are 100 % effective and population density remains at the level of the no-road control site, *2* the road mitigation measures are only partly effective and population density decreases compared to the no-road control site but does not reach the level of the no-mitigation control site, *3* the road mitigation measures are not effective and population density decreases to the level of the no-mitigation control site, *4* the road mitigation measures worsen the situation and population density decreases below the level of the no-mitigation control site

from the road than the mean individual movement distance will not likely reach the road corridor and road mitigation measures. However, if genetic features are studied, individual movement distances are not suitable indicators for the effect-distance, as the genetic changes will diffuse from the local area adjacent to the road and indirectly affect the broader population over time. The same applies if population size/density is the selected measurement endpoint. In cases where little is known about the spatial extent of road or road mitigation effects, as will often be the case, or where cumulative effects of multiple roads are expected, sampling should be done at multiple spatial scales.

Step 7: Select covariates to measure

Sampling should not just be limited to the selected measurement endpoint. Other variables should also be measured to improve interpretation of the results, provide better comparisons among study sites, and allow for stronger inferences concerning the causes of

observed differences. We recommend documenting spatial (among sites, where appropriate) and/or temporal (within sites over time, where appropriate) variability in: (1) road design and traffic, (2) crossing structure design and use, and (3) structural features of the surrounding landscape, all of which have been shown to influence the use of road mitigation measures (Clevenger and Waltho 2000; McDonald and St-Clair 2004; Ng et al. 2004; Clevenger and Waltho 2005; van Vuurde and van der Grift 2005; Ascensão and Mira 2007; Grilo et al. 2008).

Road design covariates should include road width, road surface elevation (elevated road bed or road bed in cut), presence and type of pavement, presence and type of street lights, presence and type of fences, presence and type of noise screens, presence and width of median strip, presence and type of barriers in the median strip, presence and width of road verges, and presence and type of vegetation in road verges. Traffic volume and speed should be documented at several temporal scales (e.g., daily, seasonally, annually). Road mitigation covariates should include size and characteristics of the crossing structures, the type and size of wildlife fences, passage use by the target species and non-target species, and presence and frequency of use by humans and domestic animals. Information on the duration of the construction period that marks the transition from the 'before' to the 'after' situation and the date that road mitigation measures were ready for use may also be important. Finally, landscape covariates should include the altitude, topography, land use, type and amount of vegetation and the occurrence of characteristic landscape elements (e.g., river, pond, hedge row).

Step 8: Select suitable survey methods

For most measurement endpoints, several survey methods exist (Table 3) but not all methods are equally effective for all species or species groups. We recommend survey methods that monitor multiple species simultaneously to provide more information for similar effort. We also recommend using more than one survey method for each species, because combining methods can decrease bias and provide better estimates of the variable of interest. Consistent use of the same methods and personnel over time and across control/mitigation sites is important to provide comparable results.

Step 9: Determine costs and feasibility

A comprehensive evaluation of road mitigation measures will require a substantial budget. However, other resources that may not have direct costs are equally important, e.g., sufficient time, or stakeholder support. The need for both economic and non-economic resources demands detailed organization and planning, including clear deadlines for decisions, and strong consensus among the research team, the funding organization and other stakeholders. For example, if a land owner refuses access to a sampling site during a long-term study, resources spent on sampling that location will have been wasted.

If all necessary resources cannot be guaranteed before commencing the project, carrying out the study should be seriously reconsidered. Hence, we recommend conducting a comprehensive risk assessment before the start of a study, to judge its feasibility. Such risk assessment should not only address costs, but all types of resources needed for the study, including risks related to the research itself. As road mitigation evaluation studies are ambitious, especially those that aim for measuring effects on population viability, unexpected complications are likely to arise and thus uncertainties should be incorporated into cost and scheduling estimates. For example, a selected study site may become unsuitable

Table 3 Potential survey method(s) for each measurement endpoint

Assessment endpoint	Measurement endpoint	Potential survey methods
Human casualties	Number of humans killed or injured due to wildlife-vehicle collisions or due to collision avoidance	Questionnaire
	Insurance money spent on material/immaterial damage due to wildlife-vehicle collisions	Questionnaire
	Number of hospitalizations due to vehicle-animal collisions	Questionnaire
	Number of wildlife-vehicle collisions, concerning species that potentially impact human safety, regardless of whether they resulted in human injury or death	Road surveys
Wildlife health and mortality	Number of animals killed or injured while crossing roads	Road surveys
	Number of animals killed or with ill-health due to isolation from needed resources through the barrier effect of roads	Field surveys
Population viability	Trend in population size/density	Capture-mark-recapture, Point/Transect counts or calling surveys, Pellet counts, Nest/den counts, Tracking arrays, e.g. photo/video cameras, track pads
	Number of animals killed	Road surveys
	Reproductive success	Counts of eggs/young
	Age structure	Capture, Direct observation
	Sex ratio	Capture, Direct observation
	Between-population movements	Capture-Mark-Recapture, Radio-tracking, Direct observation, Tracking arrays
	Genetic differentiation	Invasive DNA sampling after capture, Non-invasive DNA sampling, e.g. through hair traps, scat collection, antler/skin collection
	Genetic variability	Invasive DNA sampling after capture, Non-invasive DNA sampling

The list provides primarily some examples of frequently used survey methods and is not aimed at being complete

during the study due to changes in land use, or a positive trend in population size due to road mitigation may be observed but more years of measurement than planned seem to be needed to provide statistically significant results. Preferably, the monitoring plan includes an analysis of such risks and presents practical solutions on how to avoid them and what to do when they are unavoidable. For example, if our sampling scheme is based on ten replicates, we may select and sample at two more sites (i.e., for a total of 12), as a back-up for sites that may unexpectedly become unsuitable during the study.

The feasibility of a study can be easily increased using the protocol described in this paper, as at most steps there is choice on how to proceed (Fig. 1). Hence, when one or more resources are expected to be limiting, a different decision at one or more steps (e.g., choice of target species or measurement endpoint) may provide a practical solution. We do not recommend, however, leaving out essential components of an evaluation, such as the measurement of covariates, an often underestimated part of evaluation studies in

terms of effort and budget, as this will considerably reduce the inferential strength of the study, limit the possibilities to compare study sites or extrapolate, and decrease the ability to explain the results. Hence, if choices have to be made, we recommend conducting one scientifically rigorous study that is more likely to contribute new knowledge than numerous poorly-designed studies.

Added value of road mitigation evaluations

Road mitigation measures have become integral components of major road construction projects in developed countries—and are becoming so in developing countries—where environmental impacts are likely to be large and unavoidable. Increasingly, mitigation attempts are also common as part of regional or national defragmentation strategies for existing road networks (e.g., Hlavac 2005; Holzgang et al. 2005; Böttcher et al. 2005; Grau 2005; Tillmann 2005; van der Grift 2005; van der Grift et al. 2008). These trends emphasize the need for proper evaluations of the effectiveness of road mitigation measures. Such evaluations produce considerable added value for policy makers and transportation planners because they are necessary to enhance the effectiveness of existing and future road mitigation projects. Demonstrable financial and environmental benefits will provide stronger justification for the construction of future mitigation measures. Thorough evaluation of road mitigation projects will answer two questions: What additions or changes in mitigation measures need to be made to improve effectiveness? And: What mitigation measures use the fewest resources? Hence, road mitigation evaluations will help us to provide cheaper but more effective ways of mitigating road effects on wildlife.

Incorporating proper evaluations in road planning

The evaluation of the effectiveness and efficiency of road mitigation is a unique collaboration between those who plan, design, construct and manage the road, and scientists who study the responses of flora and fauna to the road and mitigation measures. Achieving a productive partnership between these groups is a significant challenge that must be overcome to move mitigation from the realm of assumed best practices into good science.

Successful evaluation studies are likely to require collaboration between researchers and road planners commences at the very earliest stages of road planning. A proper evaluation is characterized by a BACI study design, which includes several years of measurements before the road mitigation takes place. This is in contrast to current practice where discussion about the evaluation of road mitigation works typically begins after the road mitigation has already been installed. A change in this practice can, in our opinion, be best accomplished if the preparation of a monitoring plan for the evaluation of planned road mitigation measures is made an inseparable part of the legal processes that must be followed during the road planning stage (e.g., similar to the EIA process). Practical experience (van der Grift, pers. obs.) has shown that even in a country like The Netherlands where road mitigation is high on the political agenda, there is little effort to incorporate studies that evaluate effectiveness until late in the planning and construction process, probably because there is no legal requirement for the early development of a monitoring plan. Education of road planners, or presentation of guidelines for road mitigation evaluation during road planning may be helpful, but are not likely to be as effective as statutory duties and associated regulations.

Another important factor in the success of an evaluation study is that all necessary resources are secured beforehand. Currently, road mitigation construction and road mitigation evaluation are often organized and administered as two different projects. The result is that construction can easily proceed without evaluation and that the preparation of a proper monitoring plan and the provision of resources for evaluation studies do not occur simultaneously with the construction planning. A common outcome is that the road is built and road mitigation is in place, but there are insufficient resources allocated to fully evaluate road mitigation measures. We recommend that evaluation studies become an integral part of the road or road mitigation construction project. This will better ensure that such studies are budgeted in a timely manner, properly planned in relation to the planning of the construction, and better communicated with stakeholders.

Integration of evaluation studies with the construction project will not solve all problems. A major challenge is also the compartmentalization and project-based organization of most road projects and agencies. Responsibility for the funding, construction and management of roads and road mitigation may be split among international, national, state/province and local governments. And within levels, responsibilities may be further subdivided, with different sections or departments working on different road projects. Consequently, there may be little co-ordination among projects, even when building near-identical mitigation devices. As such, funding is usually associated with a particular project, and hence mitigation sites and appropriate controls are often restricted to those available on a project by project basis. There would be significant gains in efficiency and inferential strength if resources could be pooled—including funds and study sites—among projects to produce well-designed studies of road mitigation effectiveness as recommended by the guidelines in this paper.

Finally, one of the most powerful approaches used in science is that of the manipulative experiment. Depending on the specific question being addressed, this may include opening and closing wildlife crossing structures and measuring population density, mortality rate or gene flow. In the case of testing effectiveness of mitigation structures, it would be ideal to build, say, ten crossing structures, and periodically shut/open them so we can experimentally test what happens to local populations. However, there are many reasons (e.g., finances invested, risk to local populations, political support) why it may be difficult to periodically close the structures. Our paper has focused on detailing the parameters we believe need to be studied in order to evaluate road mitigation effectiveness. However, we also strongly suggest that road agencies consider the installation of mitigation measures in a truly experimental manner to maximize the insights gained about their influence on population dynamics.

Concluding remarks

A comprehensive evaluation of the extent to which mitigation programs reduce the risk of decline and extinction of local populations is essential to ensure that conservation funds are being allocated in the most cost-effective manner. However, only a handful of studies have studied the population-level effects of wildlife crossing structures (van der Ree et al. 2011). We point out three key areas requiring greater investment and political will to ensure that road mitigation effectiveness, and not just rate of use of crossing structures, is assessed.

First, road management and permitting agencies need to move beyond asking consultants or researchers to simply record use or measure rate of crossing by fauna, to insisting on evaluations of whether the crossing structure has mitigated the effect of the road on the

wildlife population. Second, researchers need to be involved in the design of the evaluation programs from the earliest stages of the road or road mitigation project. The researchers need to inform the road agency of the essential components of good study design and the need for (1) before data, (2) appropriate mitigation and control sites, (3) sufficient site replication, and (4) appropriate spatial scale and time-frame for evaluation. Finally, the importance and benefits of road mitigation measures should be better communicated to all stakeholders. Only then can the support and cooperation, which is indispensable for studies that are characterized by long-term monitoring efforts, be achieved. Although the set of guidelines we have presented is ambitious, we are convinced that they are necessary to improve our understanding of the effectiveness of road mitigation measures.

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Research, part of a Special Feature on Effects of Roads and Traffic on Wildlife Populations and Landscape Function

Wildlife Tunnel Enhances Population Viability

Rodney van der Ree [1], *Dean Heinze* [2], *Michael McCarthy* [3], *and Ian Mansergh* [4]

ABSTRACT. Roads and traffic are pervasive components of landscapes throughout the world: they cause wildlife mortality, disrupt animal movements, and increase the risk of extinction. Expensive engineering solutions, such as overpasses and tunnels, are increasingly being adopted to mitigate these effects. Although some species readily use such structures, their success in preventing population extinction remains unknown. Here, we use population viability modeling to assess the effectiveness of tunnels for the endangered Mountain Pygmy-possum (*Burramys parvus*) in Australia. The underpasses reduced, but did not completely remove, the negative effects of a road. The expected minimum population size of a "reconnected" population remained 15% lower than that of a comparable "undivided" population. We propose that the extent to which the risk of extinction decreases should be adopted as a measure of effectiveness of mitigation measures and that the use of population modeling become routine in these evaluations.

Key Words: *barrier effect; Burramys; population-level impacts; population viability analysis; road ecology; underpass; wildlife crossing structure*

INTRODUCTION

Roads, railways, utility easements, and other linear infrastructure are conspicuous and pervasive components of landscapes throughout the world. The ecological effects of roads and traffic are diverse and may extend hundreds of meters beyond the road (Reijnen et al. 1995, Forman and Deblinger 2000, Eigenbrod et al. 2009). The cumulative effect of the network of roads is potentially large; it has been estimated, for example, that approximately 20% of the land area of the continental USA is affected by roads and traffic (Forman 2000). Roads and traffic directly and indirectly affect wildlife in a variety of ways (Bennett 1991, Forman et al. 2002) and have contributed to the decline of many wildlife populations.

The barrier or filter effect of roads on wildlife has been the focus of many mitigation efforts, particularly in North America and western Europe (Forman et al. 2002, Irwin et al. 2005). The inclusion of wildlife-crossing structures (e.g., overpasses, tunnels, and culverts) in the design and construction of new roads and road upgrades around the world is becoming increasingly common. The effectiveness of wildlife-crossing structures is typically assessed by documenting their rate of use by wildlife, primarily through photographic records, and the detection of footprints in a suitable medium, such as sand or snow (Clevenger and Waltho 2000, Ng et al. 2004, van der Ree et al. 2007). Fewer studies have documented which individuals use the structure (e.g., age and sex parameters), the type of use (e.g., dispersal, migration, or daily foraging), the success of individuals following crossing (e.g., mating) or the reduction in the risk of extinction. These other parameters provide a greater insight into success and allow a more comprehensive assessment of effectiveness.

Use of an under-road tunnel by the mountain pygmy-possum (*Burramys parvus*) in southeastern Australia led to a demonstrable population-level effect (Mansergh and Scotts 1989). Using trapping and photography, the possum was shown to use the tunnel, and the overwinter survival and sex ratios of the population were "restored." However, despite

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the apparent success of this installation in restoring connectivity and improving survival rates for *B. parvus*, there has been no formal evaluation of the crossing structure on population levels using quantitative modeling.

Population viability analysis is an approach that can be used to evaluate the effectiveness of wildlife-crossing structures by comparing rates of birth, death, and migration before and after the construction of the road and mitigation structure. Excellent long-term data (annual census trapping over a 20-year period) on population parameters for *B. parvus* exist from populations affected by the road (before and after construction of the tunnel) as well as for a population distant from and unaffected by the road. In this study, we use population viability modeling to predict the likely effect of the road and tunnel on population size and the probability of decline. To our knowledge, this is the first instance where population viability analysis has been used to assess the effectiveness of such mitigation techniques.

Burramys parvus is a small (~45 g), highly endangered marsupial, endemic to high-altitude boulderfield habitat in southeastern Australia (Mansergh and Scotts 1990, Heinze et al. 2004). Much of its preferred habitat has been cleared, degraded, and fragmented by development associated with alpine ski resorts, and currently <1600 females survive in the wild. It is one of Australia's most threatened marsupials. The sexes are usually segregated, except during the mating season (October–December) when males move into the female territory, departing shortly after mating. This lowers the population density and reduces competition for food, allowing females to raise young and increase their body weight before the overwinter hibernation. A major road to the Mount Hotham ski resort obstructed this annual migration at Mount Higginbotham because males avoided crossing the road and the highly disturbed roadside vegetation (Mansergh and Scotts 1989). This resulted in increased population densities and altered sex ratios in the female-dominated area, and reduced overwinter survival. In 1985, two rock-lined tunnels were built under the road and an abutting 60 m of boulderfield corridor to mitigate this problem (Mansergh and Scotts 1989). The tunnels were concrete box culverts (0.9 x 1.2 m), approximately 16 m in length, traversing approximately 7 m of road and 9 m of cleared verge. Traffic volume along the road in autumn (April) 2001 was 400 vehicles per day (VicRoads, unpublished data). Winter estimates of traffic volume are unavailable due to logistical difficulties of using counters in the snow, but would have been significantly higher. However, winter traffic volume is somewhat irrelevant because the possums hibernate during winter. The site was important because it was central to the habitat that supported >50% of the world population of the species.

METHODS

The size and distribution of populations of *B. parvus* at Mount Higginbotham have been assessed annually since 1983 (Mansergh 1984). A capture-mark-release program was conducted over a series of trapping grids. Biological data were collected and animals fitted with ear tags. Here, we use a subset of the census data set (1982/83–2002/03) including one population that has been divided by the road for >25 years, for which data were collected before (1983–1985) and after (1986–2003) mitigation; and a second population unaffected by the road, approximately 0.5 km distant from the "road" population. Both populations experience similar climatic and environmental conditions, however, are separated by at least two ski runs, each 20–30 m, effectively isolating both populations from each other. Despite being physically capable of moving this distance, no individuals have been detected moving between the two populations.

The population was modeled using a Ricker (1975) function with an additional term to account for effects of changes in sex ratio. Thus, the expected logarithmic growth rate was

$$\ln[N_{t+1}/N_t] = a + b\times N_t + s\times S_t + \mathrm{norm}(0, \sigma),$$

where N_t is the population size (number of females) at time t, S_t is the sex ratio (ratio of females to males), norm(0, σ) is a normal random deviate with mean zero and standard deviation σ, and a, b, and s are parameters influencing the maximum population growth rate, and the rate at which this growth rate declines with increasing population density and sex ratio. The normal random deviate was included to model environmental stochasticity. The sex ratio was the observed ratio of females and males that were captured. This model is a simplified version of that developed by McCarthy and Broome (2000) for *B. parvus* in New South Wales, Australia. The simplified version was used because age-structure

data were unavailable, but it still provided similar predictions to the original model. Demographic stochasticity was modeled by drawing the population size from a Poisson distribution (Akçakaya 1991). Simulations were run for 20 years with 10 000 iterations of the model.

We modeled only linear changes in the logarithmic population growth rate with changes in the sex ratio. Sex ratio is used as a surrogate measure for the impacts of the road on dispersal ability. As population size declines, it is conceivable that the number of males will become limiting. However, *B. parvus* is polygynous, and the number of males is unlikely to be limiting except at very small population sizes. In the data and the model simulations, the population sizes of females were well above zero and a quadratic relationship for sex ratio did not improve the fit, so it was assumed that the linear form sufficed.

Parameter estimates for the model (Table 1) were obtained using Bayesian Markov chain Monte Carlo (MCMC) methods in WinBUGS (Spiegelhalter et al. 2003). A Bayesian approach was used because it provided a convenient method for accounting for uncertainty in the estimates of population size (measured by the standard error of the population estimate obtained from mark-recapture analysis), and for propagating uncertainty about parameter estimates through to predictions. Vague priors were used for the parameter estimates to reflect a lack of other useful information about the population dynamics of the species. Posterior distributions were obtained from 100 000 MCMC samples, after discarding the first 5000 samples as a burn-in. The code used in the WinBUGS analysis is given in Appendix 1.

The predicted effect of the tunnel in mitigating the impact of the road was assessed by substituting the average pre-tunnel sex ratio, post-tunnel sex ratio, and the sex ratio in the unaffected population into the model of predicted growth rate (9.5, 4.1, and 2.4, respectively). The sex ratio of the three populations was the primary input into the model because it best summarized the effect of the road on movement patterns and overwinter survival. Thus, the model predicts risk for a site affected by a road without mitigation, a road with mitigation, and a site without a road, assuming an equilibrium population size in the absence of the road of 82 females. This number was also used as the initial population size. The median population size over the 20-year period was predicted using the best parameter estimates (means of the posterior distributions of the parameter estimates). Additionally, the effect of parameter uncertainty was investigated by examining the posterior distribution of the expected minimum population size (EMP) over the 20-year period. The EMP is the smallest population size expected within a given time frame and summarizes the risk of decline (McCarthy and Thompson 2001). See McCarthy (2007) for the method for calculating EMP within WinBUGS.

RESULTS

Summary statistics of the posterior distribution of the model parameters indicate that population growth rates decline with increasing population size and sex ratio because the parameters b and s are both negative (Table 1).

Our model of the effectiveness of a tunnel for *B. parvus* predicted that the median population size at the unmitigated road was 40% lower than at a site without a road (median population size at site without road was about 80, 95% CI 48–125, compared with about 53, 95% CI 35–86 at the site with a road and tunnel) (Fig. 1). The probability of extinction (zero population size) within 20 years was predicted to be zero in all scenarios considered. We have used the word predicted because we have had to predict what the situation might be at a road that was unmitigated. The tunnel reduced the barrier effect of the road and adjacent disturbance, but there remained a 15% reduction in the median population size of females (Fig. 1). The influence on the EMP of females showed a similar pattern (Fig. 2), with the unmitigated road resulting in the fewest females after 20 years. Uncertainty in the parameter estimates of the population model led to uncertainty in the predictions, with the 95% credible intervals for the EMP being relatively wide (Fig. 2). The difference between the EMP in the absence of the road and a site with an unmitigated road is large (mean difference of 17 females with 95% credible interval of 1.5–35). In contrast, the difference between the predictions without a road and a mitigated road were relatively small (mean difference of 3.5 females with 95% credible interval of 0.5–8). These credible intervals are for the difference in EMP between two scenarios, which is different from the credible intervals in Fig. 2 that represent uncertainty in the EMP of individual scenarios.

Table 1. Mean, standard deviation (s.d.) and 95% credible interval for the posterior distributions of the parameters of the population model.

Parameter	mean	s.d.	95% credible interval
a	1.3	0.32	(0.62, 1.9)
b	–0.014	0.0035	(–0.0069, –0.021)
s	–0.054	0.025	(–0.0086, –0.10)
σ	0.21	0.065	(0.093, 0.35)

DISCUSSION

The original study on the effectiveness of the mitigation works for *B. parvus* (Mansergh and Scotts 1989) concluded that the tunnels and rock-lined corridor restored habitat continuity and population processes. Our simulation supports this assertion, and quantified the extent to which the tunnels mitigated the barrier effect of the road. Quantifying success in this way is a first because other evaluations typically assume success after recording the presence of animals using the underpass or overpass by footprint or camera. Our model suggests that although the tunnels did restore population processes for *B. parvus*, they did not completely eliminate the effects of the road. Even after mitigation, the median population size of females was predicted to be 15% lower than if the road had not been constructed. This reduction may be due to an insufficient number of tunnels, mortality due to collision with vehicles or natural variation in population size. The issue of even relatively small reductions in population size may not be trivial to population survival, especially for rare or uncommon species. For example, a genetically isolated population of approximately 350 individuals of *B. parvus* at Mount Buller declined by 90% in the 10 years to 2006 due to habitat destruction and fragmentation that compounded predation and restricted animal movement (Heinze 2006). If population modeling had been used at the impact-assessment stage, the population decline might have been avoidable. Subsequently, modeling has been used to evaluate the costs and benefits of proposed recovery actions for this Mount Buller population, resulting in an integrated predator-control program, extensive habitat restoration works, and the removal of wild animals for a captive breeding program.

Our modeling of the effects of the road and tunnels on *B. parvus* demonstrates one approach that explicitly and quantitatively incorporates population viability into the assessment of mitigation effectiveness. The broad aim of most mitigation projects is to “increase the permeability of a road corridor” (Forman et al. 2002: 161). According to this criterion, most overpasses and underpasses would be considered successful (see van der Ree et al. 2007). Interestingly, there is even a lack of evidence to assess whether wildlife overpasses and underpasses are able to effectively facilitate gene flow across potential barriers (Corlatti et al. 2009). However, we propose that a fundamental measure of the effectiveness of wildlife-crossing structures should also include the extent to which they increase the viability of local populations. This must be considered a key measure of success because the passage of animals under or over a road may not be sufficient to counteract the numerous deleterious effects of the road along its entire length (e.g., see Jaeger et al. 2005). Population modeling (using a range of different modeling methods) can be used before construction to evaluate the relative benefits of different mitigation options, as well as to evaluate effectiveness after completion. The greatest risk from a conservation perspective is that insufficient or poorly designed wildlife-crossing structures be installed while adjacent populations continue to decline in size.

We are not advocating that our specific modeling approach is the only way to evaluate effectiveness, as there are a range of different modeling

Fig. 1. Predicted population size of female *B. parvus* at Mount Higginbotham for 20 years in the presence of the road (A), after construction of tunnels to mitigate the barrier effect of a road (B), and in the absence of the road (C). The predictions are based on mean parameter estimates and show the median population size and the 95% prediction interval based on environmental and demographic stochasticity.

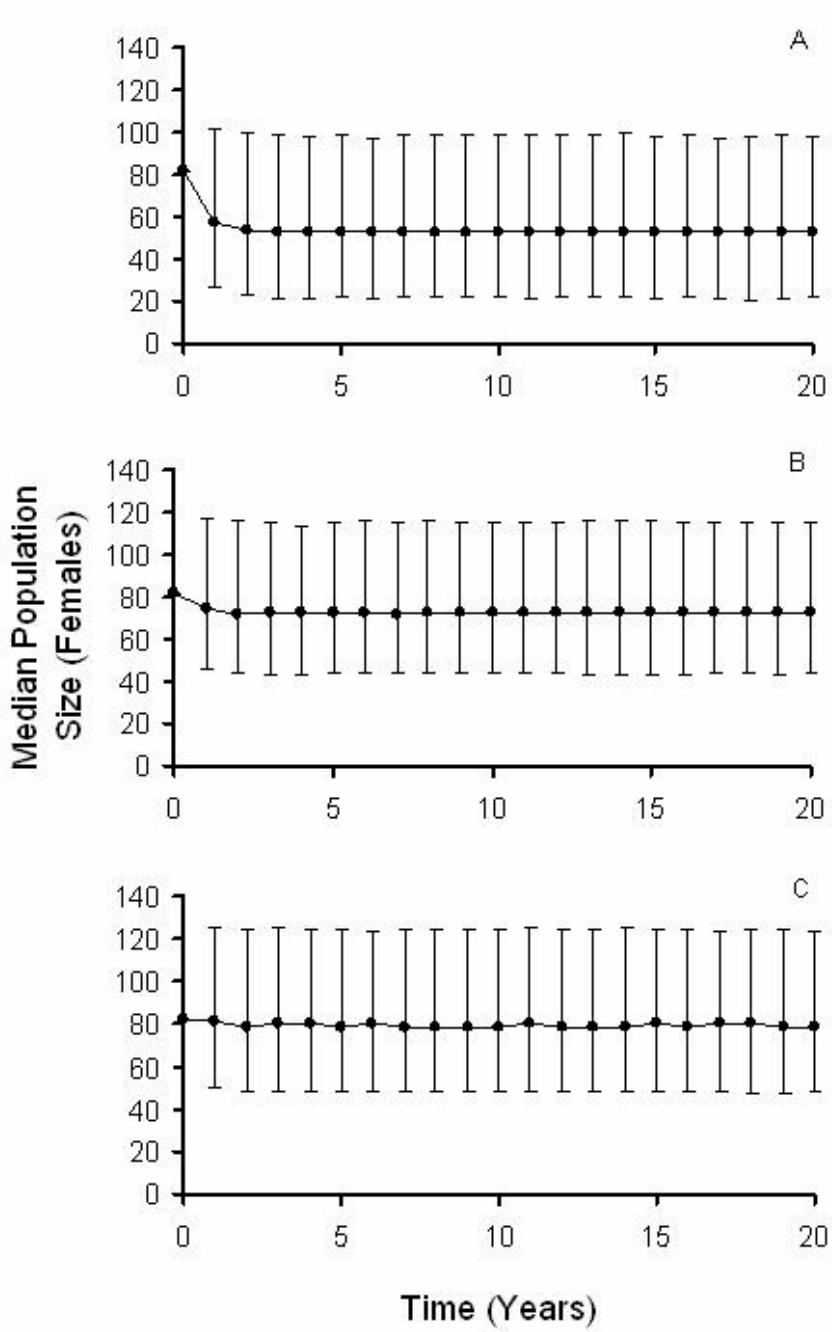
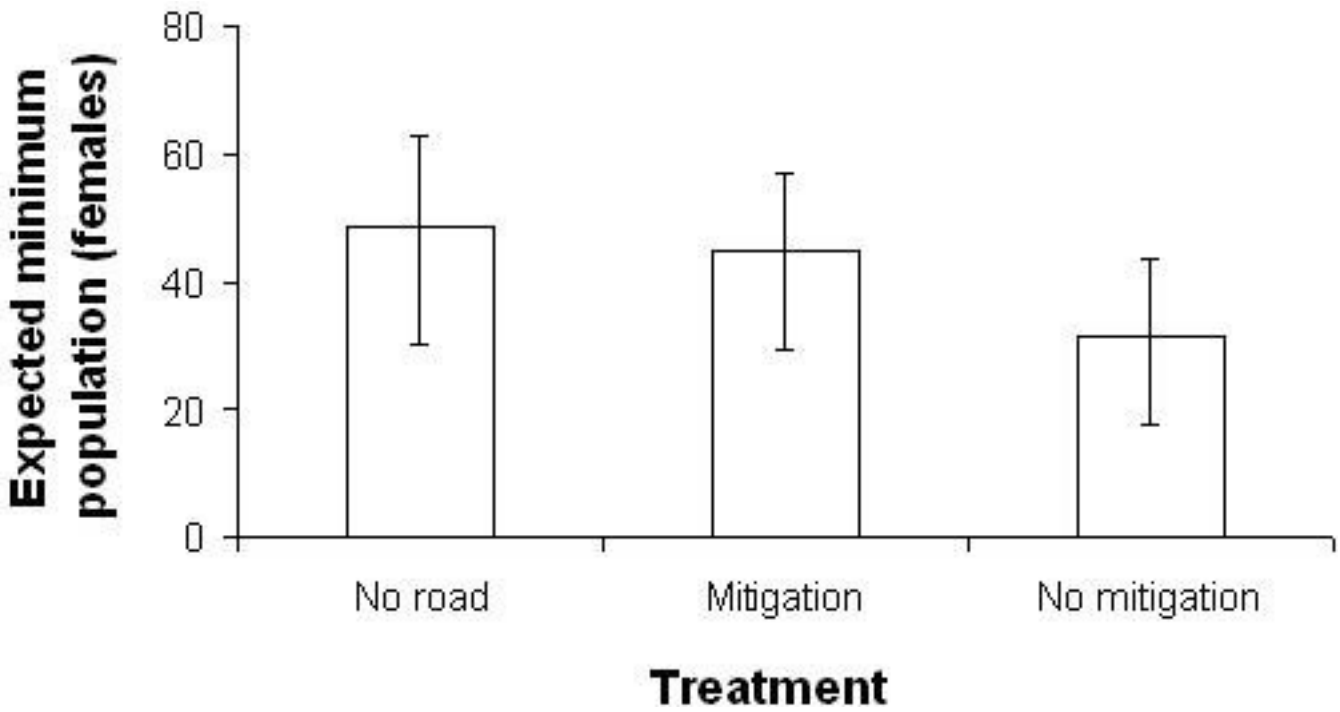


Fig. 2. Expected minimum female population size of *B. parvus* at Mount Higginbotham, 20 years after construction of tunnels and boulder corridor to mitigate the barrier effect of a road and adjacent habitat degradation. The error bars are 95% credible intervals that propagate the uncertainties in parameter estimates.



approaches available. The critical issue is that the effectiveness (and not just usage) of wildlife-crossing structures needs to be evaluated, and that population modeling provides a tool to achieve this. We were fortunate to have a 20-year data set with which to parameterize our model, and in most cases, such detailed information does not exist. However, parameters for our model are based on data collected after the road and mitigation measures were implemented. Nevertheless, a range of different model types are available that can incorporate a differing array of biological, ecological, and landscape information to evaluate effectiveness at reducing the risk of extinction, with each suited to different situations or conditions. For example, the spatially explicit population models used to quantify the effects of roads on the dispersal of the Eurasian lynx (*Lynx lynx*) in Germany (Kramer-Schadt et al. 2004) could be adapted to also evaluate the effectiveness of mitigation works. Optimal locations for crossing structures and crossing rates that are likely to be required to achieve desired population-level outcomes could be predicted using spatially explicit models of population dynamics (see van der Grift and Pouwels 2006). This will also permit an evaluation of cost effectiveness of different mitigation options. For example, sufficient rates of crossing under particular conditions might be achieved with three culverts, which may be cheaper to install than a single land bridge. Alternatively, modeling may predict that the only option to maintain a certain-sized population (and hence reduce the risk of extinction to an acceptable level) is to move or close the road and not fragment the habitat.

Evaluating the effectiveness of wildlife-crossing structures by measuring the rate of use by individuals is a first step to a comprehensive analysis of success. The risk in not evaluating effectiveness at the population level is that mitigation measures may only partially decrease the

barrier effect, without a satisfactory increase in population viability. It is imperative that mitigation measures increase population viability, given the large amounts of money required to install and maintain them. Road construction and management agencies may face legislative requirements to ensure that their actions do not further endanger species that are facing extinction. Finally, it is pertinent to remember that the barrier effect is just one of the potential impacts of roads on fauna, and mitigation that addresses this may only increase viability within the limits posed by other effects.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol14/iss2/art7/responses/

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APPENDIX 1. Supporting online material (code for population model for WinBugs)

Appendix 1. Code for population model for WinBugs. The data used to model the effectiveness of tunnels for *Burramys parvus* are available from Dean Heinze upon request.

```
model
{
 tau[1] <- 1 / (SE[1] * SE[1])
 # precision of the estimate in year 1
 # precision = 1/variance

 A[1] ~ dnorm(F[1], tau[1]) # initial population size

 for (i in 2:22) # for each subsequent year
 {
 F[i] ~ dnorm(A[i], tau[i])
 # estimate population size deviates from actual

 tau[i] <- 1/(SE[i]*SE[i])
 # precision of estimate

 A[i] ~ dpois(pred[i])
 # actual population size drawn from Poisson

 pred[i] <- A[i-1] * exp(a + bF*A[i-1] + bS*SR[i-1] + ann[i]) # Ricker model

 ann[i] ~ dnorm(0, t)
 # normal deviate representing environmental variation
 }

 ev <- 1/sqrt(t)
 # standard deviation for environmental variation

 # vague priors
 t ~ dgamma(0.001, 0.001) # precision of env. variation
 a ~ dnorm(0, 1.0E-6) # intercept of Ricker model
 bF ~ dnorm(0, 1.0E-6) # effect of density dependence
 bS ~ dunif(0, 1) # effect of sex ratio
}
ADD DATA HERE
END
```

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SEE COMMENTARY

A phantom road experiment reveals traffic noise is an invisible source of habitat degradation

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Decades of research demonstrate that roads impact wildlife and suggest traffic noise as a primary cause of population declines near roads. We created a "phantom road" using an array of speakers to apply traffic noise to a roadless landscape, directly testing the effect of noise alone on an entire songbird community during autumn migration. Thirty-one percent of the bird community avoided the phantom road. For individuals that stayed despite the noise, overall body condition decreased by a full SD and some species showed a change in ability to gain body condition when exposed to traffic noise during migratory stopover. We conducted complementary laboratory experiments that implicate foraging-vigilance behavior as one mechanism driving this pattern. Our results suggest that noise degrades habitat that is otherwise suitable, and that the presence of a species does not indicate the absence of an impact.

traffic noise pollution | songbird migration | habitat degradation | foraging-vigilance trade-off | perceived predation risk

Human infrastructure shapes animal behaviors, distributions, and communities (1, 2). A meta-analysis of 49 datasets from across the globe found that bird populations decline within 1km of human infrastructure, including roads (2). Observational studies of birds near roads implicate traffic noise as a primary driver of these declines (3). Road ecology research has also shown negative correlations between traffic noise levels and songbird reproduction (4, 5). Birds that produce low frequency songs, likely masked by traffic noise, show the strongest avoidance of roads (6).

There is now substantial evidence that anthropogenic noise has detrimental impacts on a variety of species (3, 7–10). For example, work in natural gas extraction fields has demonstrated that compressor station noise alters songbird breeding distribution and species richness (11–13). However, explicit experiments would help to further rule out other characteristics of infrastructure, such as visual disturbance, collisions, chemical pollution, and edge effects, which might be driving these patterns (3). In addition, although these studies implicate noise as a causal factor in population declines, many individuals remain despite noise exposure (3), but at what cost? Proposed causes of decreased fitness for birds in noise include song masking, interference with mate evaluation, nonrandom distribution of territorial individuals, disruption of parent-chick communication, reduced foraging opportunities, and/or alterations in the foraging/vigilance trade-off (3, 4).

Here we parse the independent role of traffic noise from other aspects of roads experimentally by playing traffic sounds in a roadless area, creating a 'phantom road'. We focus on birds during migratory stopover, because energy budgets are streamlined; foraging, vigilance, and rest dominate activity (14). To meet the amplified physiological needs of sustained nocturnal migratory flights, birds must increase foraging during periods of stopover while maintaining appropriate vigilance levels (14, 15). Any interference with foraging will decrease stopover efficiency and thus reduce migration speed, a likely surrogate for fitness (14), thereby increasing exposure to significant mortality risks during what can be the most perilous stage of a migratory bird's life cycle (16). Anthropogenic noise might disrupt the foraging-vigilance tradeoff by acting as a form of perceived predation risk (17, 18) or by reducing sensory awareness via distraction or acoustic masking (3, 19). Using the "phantom road" experimental approach, we previously conducted count surveys of bird distributions at this site, finding a decrease in overall bird numbers of more than 25% (20). We hypothesized that the subset of birds choosing to stay at the site would experience other negative effects of traffic noise, and we predicted that the birds that remained would exhibit lower body condition and reduced ability to increase body condition (i.e., reduced stopover efficiency) in noise.

To test these predictions we used an array of speakers to recreate the soundscape of a ∼0.5 km section of highway along a ridge in southwest Idaho. This approach enabled us to turn the traffic noise *on* and *off* throughout fall migration at our phantom road site, and compare it with a nearby quiet control site, creating a modified before-after-control-impact design (Fig. 1). Alternating noise on/off every four days, we sampled a different set of migrants during each block as birds arrived and departed from the stopover site (*SI Text*). We measured sound levels (hourly level-equivalent, or LEQ) continuously during the season using acoustic recording units placed at mist net locations (Fig. 1*A*). We compared mist-net capture rate (birds/net/hr) across site (control vs. phantom road) and noise treatment (on vs. off) to investigate whether birds were leaving or staying when exposed to traffic noise (*SI Text*). Similar to our survey work (20), our best-fitting model indicated that capture rate decreased by 31% during phantom traffic noise playback, demonstrating that anthropogenic noise, independent of other road forces, fundamentally shapes bird distributions. However, 69% of birds remained despite the noise (Table S1, Dataset S1, and *SI Text*).

Significance

Using landscape-scale traffic noise playbacks to create a "phantom road," we find that noise, apart from other factors present near roads, degrades the value of habitat for migrating songbirds. We found that nearly one third of the bird community avoided the phantom road. For some bird species that remained despite noise exposure, body condition and stopover efficiency (ability to gain body condition over time) decreased compared with control conditions. These findings have broad implications for the conservation of migratory birds and perhaps for other wildlife, because factors driving foraging behavior are similar across animals. For wildlife that remains in loud areas, noise pollution represents an invisible source of habitat degradation.

Author contributions: H.E.W., C.J.W.M., J.D.C., and J.R.B. designed research; H.E.W., C.J.W.M., J.D.C., and J.R.B. performed research; H.E.W. and C.J.W.M. analyzed data; H.E.W., C.J.W.M., J.D.C., and J.R.B. wrote the paper.

The authors declare no conflict of interest.

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See Commentary on page 11995.

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ECOLOGY

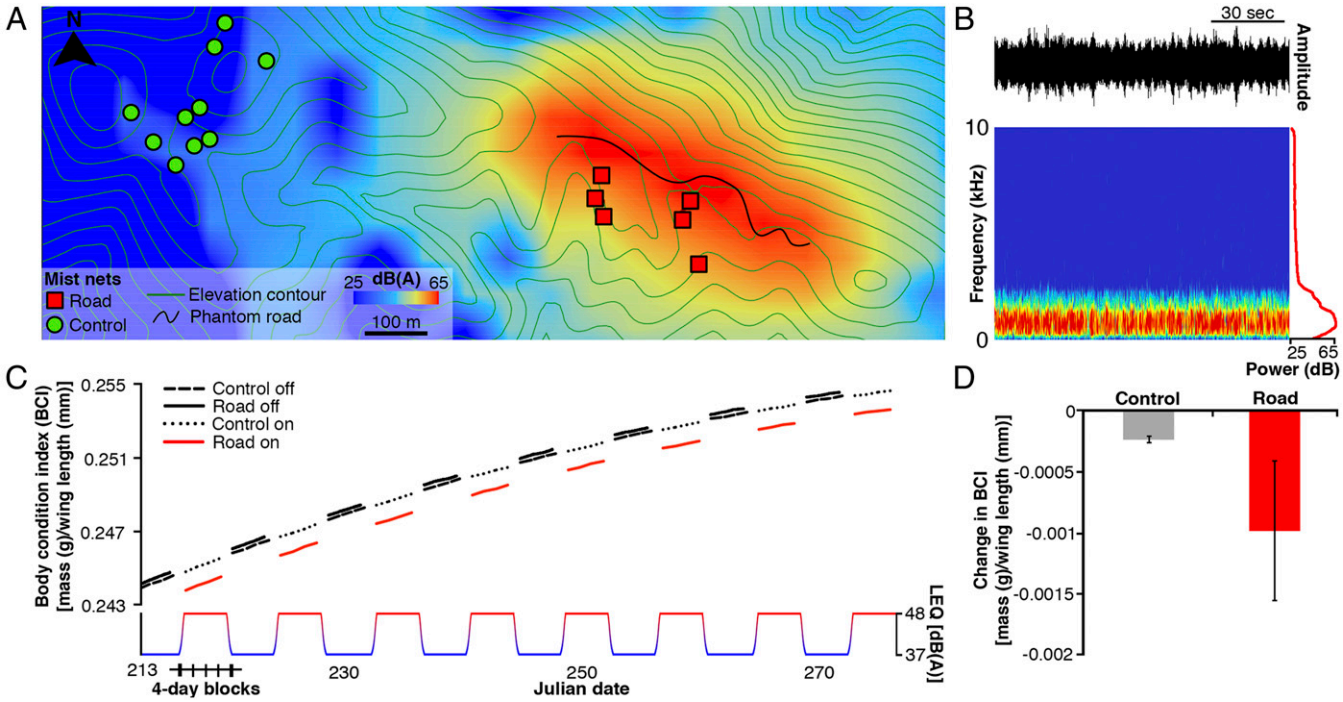

Fig. 1. Phantom road playback causes songbird body condition decline. (*A*) Estimated sound levels [dB(A) 1 h LEQ: The level of a constant sound over a specified time period that has the same energy as the actual (unsteady) sound over the same interval] during periods when speakers were on: from August through October 2012–2013 in the Boise Foothills, Idaho. Sound level was modeled using NMSim (Wyle Laboratories) (20). Circles (control) and squares (road) represent capture sites. With the noise on, mean sound levels at the phantom road capture sites increased by 11 dB(A) to 48 dB(A) (SE = 0.3), whereas the control site averaged 2 dB(A) louder with noise on (mean± SE; 41 dB(A) ± 0.2). With noise off, sound levels averaged 39 dB(A) (SE = 0.2) at the control capture sites and 37 dB(A) (SE = 0.3) at the phantom road. Elevation contours are 50 m. (*B*) A 2-min sample of the phantom road file displayed as an oscillogram, a spectrogram and a power spectrum. (*C*) Predicted values for body condition index (BCI) as birds add fuel throughout fall migration. Estimates are based on the AIC-best model for BCI for all captures combined, with species as a random intercept. A consistent full SD change in BCI is evident during each noise-on block (pattern of noise on blocks displayed along the *x* axis) throughout the migratory period. (*D*) Predicted mean change in BCI at the control and phantom road sites between noise off and noise on periods across the entire study. Error bars represent SE. These differences in BCI (and associated error) are derived from the average of the predictions presented in *C*.

Focusing on birds exposed to a gradient of sound levels, we examined differences in body condition index (BCI) of newly captured birds. BCI is a size-adjusted metric of body mass calculated as mass (g)/natural wing chord (mm). Small changes in BCI represent large differences in condition (21). During migration, high body condition signifies birds with the energy stores needed for long migratory flights (15). The best-fitting model showed that as noise exposure increased, overall BCI of the bird community remaining at the road site decreased (Fig. 1*C*, Table S1, Datasets S1 and S2, and *SI Text*). In fact, BCI in noise declined by a full SD compared with the community mean in control conditions. In the absence of noise, BCI of the songbird community at the phantom road site did not differ from the values at the control site, indicating both were suitable stopover locations (Fig. 1*C*). Models for individual species showed 5 of 21 species significantly decreased BCI in noise. Iterative exposure to noise during the multiple stopovers of saltatory migration may ultimately result in mortality (16) or, in a better case scenario, reduced fitness manifested from slower migration speed (14) which would likely impact fitness and survival in the subsequent life history stage (22).

Because we turned the phantom road off overnight to match typical diel traffic patterns, it is likely that nocturnal migrants (the majority of species in this study; see ref. 23) chose to land at our site when it was quiet, before the phantom road playbacks began in the morning. In effect, diurnally varying traffic noise might function as an ecological trap (24) for migrants. Although staying in traffic noise has a cost, the energetic outlay for individuals to leave a given site might be even greater. Birds with low body condition are less likely to embark on migratory journeys than those in good condition, and depending on the suitability of surrounding habitat, it may not be worth the risk to disperse once landed (25). We cannot differentiate whether the lower BCI we documented in traffic noise is the result of (*i*) higher body condition birds leaving the population or (*ii*) birds losing body condition over the duration of noise exposure. We saw both reduced mean body condition and reduced bird numbers, suggesting that at least some birds with the energetic stores to migrate chose to leave the site and escape the costs of remaining in noise (25).

To examine if the birds that remained in noise were suffering reduced ability to add migratory fuel (i.e., increase BCI), we regressed BCI of new captures against time of day to estimate stopover efficiency. Comparing stopover efficiency of individuals between sites provides an essential metric to compare the relative value of stopover habitat (*SI Text*). The best-fitting model for the entire songbird community included noise intensity level [dB(A)] although the confidence intervals overlapped zero (*SI Text*). For nine individual species, the best-fitting model included a noise variable, however the confidence intervals overlapped zero for all but 3 of these species (Table S1).

For MacGillivray's warblers, the best-fitting model showed that stopover efficiency substantially decreased with increasing decibel levels. MacGillivray's warblers did not show reduced capture rates in noise, and were the species that showed the strongest negative responses for both BCI and stopover efficiency, indicating that individuals stayed but did poorly in noise (Fig. 2*A* and Tables S1 and S2). In contrast, Cassin's finches had significantly increased stopover efficiency in noise and a decreased capture rate (Fig. 2*B* and

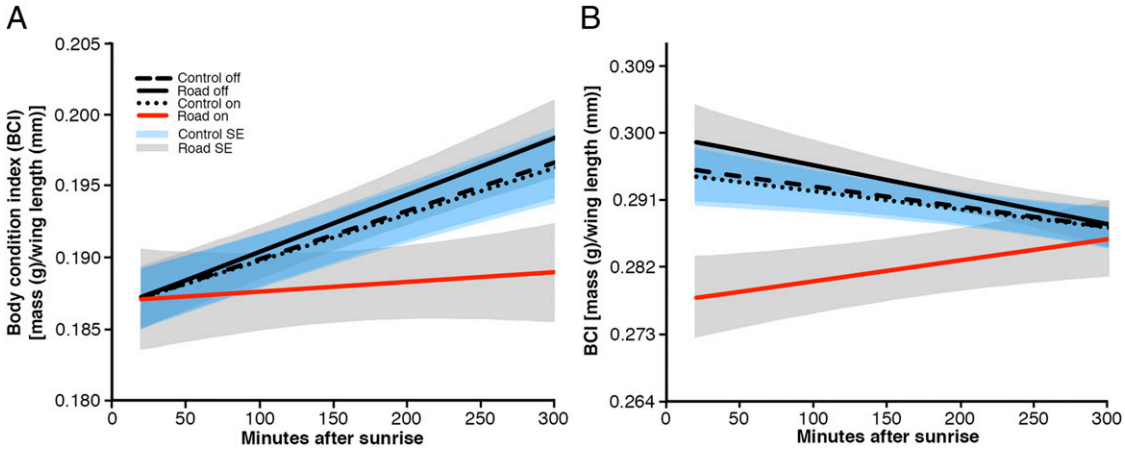

Fig. 2. Stopover efficiency is altered in noise. Predicted values for stopover efficiency for MacGillivray's warblers (*A*) and Cassin's finches (*B*). Estimates were made using average day of season using the AIC-best model for BCI for all captures combined. Values were predicted by inputting average dB(A) levels for each site. Values are shown for the control site noise off [avg. 42 dB(A)], control site noise on [43 dB(A)], phantom site noise off [40 dB(A)], and phantom site noise on [51 dB(A)]. Blue shading represents SE for the control site whereas gray shading represents SE for the phantom road.

Tables S1 and S2). This increase in stopover efficiency might reflect decreased competition for food resources in noise. Although stopover efficiency was increased in noise (Fig. 2*B*), Cassin's finches showed lower initial BCI in traffic noise (Fig. 2*B*), perhaps indicating individuals with higher BCI left the site during noise exposure. The best models for spotted towhees showed a reduced capture rate and also indicated different stopover efficiencies between on-off periods at the control and road sites with efficiency being negatively affected by noise along the phantom road (Fig. S1 and Tables S1 and S2).

It seems that for species impacted by noise, different strategies exist for managing the consequences, which might be based on differences in life history traits such as territoriality during stopover, migratory strategy, or flocking behavior. Our species-specific results show that birds may stay and incur a cost of remaining in noise (e.g., MacGillivray's warblers), or choose to leave (e.g., Cassin's finches). Leaving the noisy area may allow some species to avoid the costs of noise or a species may still experience the impacts of noise despite some individuals leaving (e.g., spotted towhees). Together, our observations of overall changes in the BCI of the entire bird community and of several individual species, as well as the changes in stopover efficiency of spotted towhee and MacGillivray's warbler, demonstrate that addition of traffic noise alone, without the other variables associated with actual roadways, can significantly decrease the value of a stopover site.

In support of our field results, we conducted a controlled laboratory study to test whether traffic noise alters the foraging-vigilance tradeoff in songbirds and could thus mechanistically underpin our field data (*SI Text*). We focused on the second most common species from our field study, white-crowned sparrow (*Zonotrichia leucophrys*), a species that also decreased BCI in noise, to investigate the reduction in foraging and increase in vigilance implied by our community-wide body condition analysis. We quantified head-down duration (i.e., foraging) and head-up rate (i.e., vigilance), because these are known measures of avian visual vigilance that change when auditory surveillance is limited and that correlate with food intake and ability to detect predator attacks (26). We also measured feeding duration (no. seconds per 8-min trial spent feeding) to quantify overall feeding bout duration. Using the same playback file as our field experiment, we played 61 dB(A) and 55 dB(A) traffic noise treatments, plus a silent control track [32 dB(A)] to foraging sparrows (n = 20). White-crowned sparrows decreased foraging by ~8%, increased vigilance levels by ~21%, and decreased feeding duration by ~30% when exposed

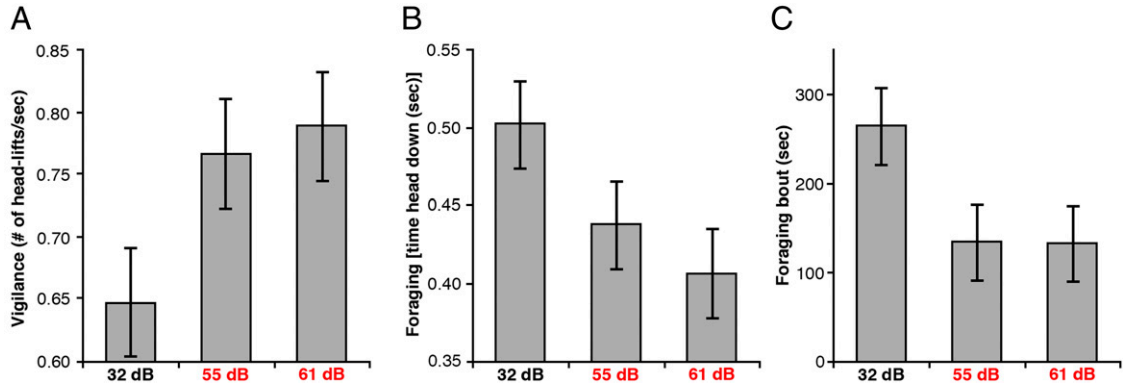

Fig. 3. The foraging/vigilance trade-off is altered in noise. White-crowned sparrows foraging in traffic noise at 61 and 55 dB(A) had reduced foraging rates (*A*), increased vigilance (*B*), and decreased foraging bout duration (*C*) compared with trials in ambient conditions [32 dB(A)]. Data are means ± SE. [Mean head up rate (head lifts/s) for 61 dB(A) = 0.79 ± 0.06, 55 dB(A) = 0.77 ± 0.05, 32 dB(A) = 0.65 ± 0.05. Mean head down duration (s): 61 dB(A) = 0.41 ± 0.03, 55 dB(A) = 0.44 ± 0.04, 32 dB(A) = 0.50 ± 0.04. Mean foraging bout duration (s): 61 dB(A) = 159.25 ± 28.0 55 dB(A) = 147 ± 32.5 32 dB(A) = 228 ± 33.7]. Birds showed more head lifts/s (β = 0.005 ± 0.002), decreased the amount of time spent with their heads down searching for seeds (β = −0.003 ± 0.001), and decreased total feeding duration (β = −4.589 ± 1.944; Movies S1 and S2) during noise playback compared with ambient conditions.

to traffic noise [61 dB(A); Fig. 3, Movies S1 and S2, and Dataset S3]. Vigilance behavior of individuals did not change based on the number of trials experienced, indicating birds did not habituate to the noise (*SI Text* and Table S2). During energetically demanding periods in a bird's life, increasing vigilance can reduce survival because of increased starvation risk (27). In contrast to song masking, which can be partially overcome by frequency shifting (28), release from masking is not possible for auditory cues necessary for aural vigilance (7). With limited auditory information, animals must resort to other methods such as visual scans to compensate for the increase in perceived predation risk, perhaps driven by masking of communication calls and predator-generated sounds (26, 29).

Our behavioral investigations in the laboratory offer compelling evidence that the body condition changes measured in the field were due at least in part to a change in foraging and vigilance behavior, but our field results could be due to a combination of factors that also deserve consideration. For example, noise might also increase physiological stress levels (ref. 30, but see ref. 31) that could cause additional declines in body condition. However, we view it as unlikely that noise can cause a stress response independent of a change in behavior. In addition, noise might indirectly change foraging rates through alterations in prey search time, sleep, or territoriality. For instance, our phantom road might have disrupted foraging behavior by reducing the acoustic detectability of insect prey (32) or reducing insect numbers. We did not test for changes in insect abundance or distribution, but because we found noise impacts on a mixed community of both frugivorous and insectivorous birds (Table S1 and Dataset S1), it seems unlikely that altered insect numbers explain a significant component of the observed patterns. Effects were consistent between the 4-d noise-on blocks throughout migration, despite documented seasonal variation in fruit and arthropod availability at the site (33), so it is more likely that changes in bird behavior drove these responses. Our experimental design was not able to determine whether noise disrupts territoriality or dominance hierarchies during stopover. However, both territorial and nonterritorial species showed negative effects of noise (23) (Table S1 and Datasets S1 and S4). We expect that a subset of these indirect effects plus the behavioral changes quantified in the laboratory contributed to the body condition declines seen in our field experiment. Because provisioning is a constant requirement for birds throughout the year, other effects of noise that occur outside of migration (e.g., refs. 4 and 5) would be in addition to, rather than instead of, the impacts we document here.

Previous work that failed to find a change in animal distributions near roads or other infrastructure has assumed a lack of negative impacts from loud human activities (2, 3). Our results demonstrate that individuals may remain in an area with high levels of noise yet suffer significant costs. We found that different species chose different strategies: to either leave noisy areas, or stay and perhaps incur the costs of noise (Fig. 1, Fig. S2, and Table S1). We exposed the bird community at our phantom road to sound levels similar to some suburban neighborhoods [~55 dB(A) hourly LEQ] (34). Many protected areas and high-value habitats are currently exposed to these levels, and would benefit from noise relief measures (35, 36). The impact of noise reaches far beyond the physical footprint of human infrastructure. Unlike other aspects of roads, noise impacts can be minimized without removing the road itself. Substrate alteration and speed limit reduction on existing roads can significantly lower decibel levels (34).

Our results reveal the need for attention to noise impacts beyond distributional shifts (3). For individuals that remain in areas disturbed by loud human activities, noise pollution represents an invisible source of habitat degradation that has been largely ignored: Traffic noise degrades habitat value but leaves no physical signs of change. Stopover habitat loss and degradation have been identified as major contributing factors to migratory songbird declines worldwide (37, 38). Migrants are exposed to an unknown risk landscape at stopover sites and must therefore rely heavily on increased vigilance to compensate (39–41). Unlike resident species, successful conservation of migratory species requires protection of habitats in breeding, wintering, and stopover locations (41). In addition, reduction in condition or delay in migration could have carry-over effects into the overwintering or breeding seasons (42). Further understanding of anthropogenic noise's impact on body condition is key, as it is an important predictor of fitness across taxa and life stage (22). When managing natural systems, we should ensure that the habitat we protect remains of high quality, including the quality of the acoustic environment.

All birds caught during this project were mist-netted and banded under the Intermountain Bird Observatory's federal permit (22929) and Idaho Department of Fish and Game permit (764–13-000039). All experiments were approved by Boise State University's Institutional Animal Care and Use Committee (006-AC12-007 and 006-AC13-002).

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Why are so many oil trains crashing? Track problems may be to blame

Smoke and flames erupt from the scene of a train derailment March 5, 2015, near Galena, Ill. A BNSF Railway freight train loaded with crude oil derailed in a rural area where the Galena River meets the Mississippi.

(Mike Burley / Associated Press)

By **Ralph Vartabedian . Contact Reporter**

OCTOBER 7, 2015, 3:00 AM

The only sign of trouble aboard a Norfolk Southern train, hauling roughly 9,000 tons of Canadian crude in western Pennsylvania last year, was a moderate sway in the locomotive as it entered a bend on the Kiskiminetas River.

The first 66 cars had passed safely around the curve when the emergency brakes suddenly engaged, slamming the train to a stop. The conductor trudged back nearly a mile through newly fallen snow to see what happened.

Twenty-one cars had derailed, one slamming through the wall of a nearby factory. Four tank cars were punctured, sending 4,300 gallons of crude pouring out of the tangled wreckage.

Cars are seen from a freight train derailment on Feb. 13, 2014, in Vandergrift, Pa.

(Darrell Sapp / Associated Press)

The cause of the accident in North Vandergrift was identified as a failure in the rails — not aging or poorly maintained tracks, but a relatively new section laid less than a year earlier.

The February 2014 crash fits into an alarming pattern across North America that helps explain the significant rise of derailments involving oil-hauling trains over the last three years, even as railroads are investing billions of dollars in improving the safety of their networks. A review of 31 crashes that have occurred on oil trains since 2013 puts track failure at the heart of the growing safety problem.

Track problems were blamed on 59% of the crashes, more than double the overall rate for freight train accidents, according to a Times analysis of accident reports. Investigators and rail safety experts are looking at how the weight and movements of oil trains may be causing higher than expected track failures.

The growing number of trains hauling crude oil from Canada and the Northern Plains are among the heaviest on the rails today, many extending more than 100 cars in length and weighing a cumulative 19,000 tons or more.

Not since the early days of John D. Rockefeller's oil trust have railroads played such a central role in moving oil from wells to refineries. Oil shipments by rail have soared — an 18-fold increase between 2010 and 2014 — as domestic oil production has escalated faster than the construction of new pipelines to carry it to market.

Concerns about the safety of hauling crude began to rise after the horrific Lac-Megantic accident in Quebec in July 2013 that left 47 people dead and the city's downtown in ruins.

The Federal Railroad Administration is preparing in coming weeks to issue a new set of

initiatives to address the track problems, after previously clamping tighter restrictions on tank car designs and railroad operations. But solving the track problems could be a formidable challenge.

l **Infographic**

Oil train crashes since 2013

Sarah Feinberg, chief of the Federal Railroad Administration, said the agency is working hard to improve safety, but preventing accidents that result from defective track involves finding a needle in every haystack along thousands of miles of track.

“We have been incredibly lucky that the accidents have happened mostly in rural areas,” she said. “Some of them have been very close calls.”

The crashes have occurred as the nation’s railroad system is being asked to do more than at any time in history, putting additional wear and tear on the tracks. Since 2001, railroads have seen a modest 12% increase in the number of cars they haul, but a 24% jump in the more comprehensive measurement of cargo that looks at the weight and train mileage the system has to bear, known as ton-miles, according to industry data.

Though railroads have significantly improved safety in general, the oil train accidents are a worrisome trend in the opposite direction and not fully understood.

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Of the 31 crashes involving crude or ethanol since 2013, 17 were related to track problems and 12 a mix of other causes. The cause of the two other crashes remains unclear. The count is based on both final or preliminary government and railroad investigations that were collected by The Times under the Freedom of Information Act or in U.S., Canadian and railroad company filings.

About two-thirds of the accidents resulted in spills, fires or explosions, a record that has already prompted regulators to demand stronger tank cars and other safety measures.

Weight, oil sloshing and cold temperatures are among the issues that might be exacerbating the problem, according to rail safety experts.

Investigators at Safety Transportation Board Canada, which is investigating the eight accidents that have occurred in that country, are beginning to suspect that the oil trains are causing unusual track damage.

“Petroleum crude oil unit trains transporting heavily loaded tank cars will tend to impart higher than usual forces to the track infrastructure during their operation,” the safety board said in a report this year. “These higher forces expose any weaknesses that may be present in the track structure, making the track more susceptible to failure.”

Rick Inclima, safety director at the Brotherhood of Maintenance of Way Employees, also said that oil trains could be creating unique stresses on the track. “You can certainly get some rhythmic forces in ... oil trains that you might not see on a mixed freight train with cars of different sizes, weights and commodities,” he said.

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Crude-oil train wrecks raise questions about safety claims

The nation’s major railroads are investing record amounts of money to upgrade their tracks and improve safety. The seven class-one railroads, which haul the majority of the nation’s freight, are spending $29 billion this year on their systems, nearly double the level of 2001, according to the American Assn. of Railroads. The trade group did not have any response to The Times analysis of oil train accidents, though it said its member companies exceed federal requirements for inspection and safety.

But that has not eliminated the problem. While all types of derailments dropped 17% over the last three years, there are still more than three every day across the nation, involving trains carrying a variety of freight, according to federal safety data. Bad track accounts for about 27% of overall accidents, less than half the rate that track problems are contributing to oil train accidents.

Though railroad technology may seem antiquated in a digital age, it relies on incredible precision to control monstrously heavy loads. The track in North Vandergrift, Pa., where the Norfolk Southern accident occurred, carries about 30 million tons of freight every year.

The relentless pounding plays havoc with any metallurgical flaw. Wooden ties deteriorate as they age. And other track components crack.

Investigators attributed the Pennsylvania derailment to a “wide gauge” failure, in which the rails were pushed too far apart to keep the wheels on the tracks.

The freight tracks in the U.S. and most of the world are supposed to be 56.5 inches apart, a width known as the gauge. Just three inches of movement can cause a derailment. And even if tracks conform to federal standards, they can separate under the force of a heavy train.

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“Wide gauge” is the single largest cause of accidents involving track defects. In the case of the Pennsylvania derailment, it was broken spikes that caused the rail to widen, even though the track had been replaced in 2012, according to Federal Railroad Administration officials.

Private railroad experts have suggested that the sloshing of oil inside the cars may also be involved in the derailments.

Tank cars are only partially filled with oil, allowing for expansion if the temperature

increases. The tanks have internal baffles, but the liquid can still slosh as the cars move, causing higher dynamic loads, said Bill Keppen, an independent rail safety expert. “Sloshing increases the stress on the track,” he said.

Federal safety experts said if sloshing does have an effect, they do not consider it significant.

The Times examination of accident reports also shows the large majority of derailments occurred in below freezing temperatures, ranging down to 23 below zero in a crash this year in Ontario.

As temperatures drop, steel rails progressively shrink, amplifying the potential for any existing defect to cause a failure, FRA safety experts said in interviews. Frozen ballast, the crushed rock that forms the rail bed, also causes rail to undergo greater shocks under the load of heavy trains.

Federal regulators and the industry are trying to improve safety, but opinions are sharply divided about exactly what measures are needed.

The Federal Railroad Administration, for example, has ordered that crude-carrying trains can travel at no more than 40 miles per hour in urban areas. But the North Vandergrift train was going only 36 mph. Nineteen of the trains whose speeds are known were moving 40 mph or slower, and no train was going faster than 50 mph, records show.

The railroad administration has increased its track inspections and railroads have agreed to increase their own inspections, according to Matthew Lehner, the agency’s communications director.

“In the coming weeks, the Federal Railroad Administration plans to announce additional steps to prevent crude oil train derailments,” Lehner said.

Critics say that many of the safety initiatives adopted so far reflect a policy aimed at mitigating the damage caused by derailments rather than preventing them.

“The attention has changed,” said Brigham McCown, former chief of the federal agency that sets tank car standards. “I hear people say, ‘It happens, they derail.’ I think that is an untenable position. As a safety regulator, I don’t think you can ever say, ‘Things blow up,’ or ‘Things crash.’ I believe the Department of Transportation has myopically focused on

incident mitigation. Prevention should be the first question they should address."

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PERMEABILITY OF ROADS AND RAILWAYS TO VERTEBRATES: THE IMPORTANCE OF CULVERTS

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Abstract

The movement of vertebrates through 17 culverts under roads and railways in Central Spain was analysed over the course of an annual cycle. Passage was detected for amphibians, lizards, snakes, small mammals, rats, hedgehogs, rabbits and several species of carnivorous mammals, including Felis sylvestris *and* Genetta genetta. *The intensity of animal movement, which varied considerably among the groups, was influenced by various factors such as the culvert dimensions, road width, height of boundary fence, the complexity of the vegetation along the route, and the presence of detritus pits at the entrance of culverts. It is concluded that adequately designed culverts can aid the conservation of vertebrate populations.*

Keywords: barrier effect, roads, railways, vertebrates, culverts, Spain.

INTRODUCTION

Roads and railway tracks (henceforth generally included under 'roads') are believed to be one of the main obstacles to the movement of land vertebrates. This type of linear infrastructure generates a 'barrier effect', which involves the blockage or restriction of movement by certain species and/or populations across the roads (Velasco *et al.*, in press). There is a number of ensuing negative consequences: reduction of genetic diversity due to the increase of inbreeding, increased risk of local extinction due to population dynamics and catastrophic effects, a decrease in the ability to recolonize, etc. (Van Gelder, 1973; Leedly, 1975; Leedly *et al.*, 1975; Adams & Geis, 1981; Grossenbacher, 1981; Rusch, 1985; Waechter & Schirmer, 1987; Bennett, 1991; Nunney & Campbell, 1993).

Crossings designed specifically to increase the 'permeability' of roads are a basic corrective measure for the barrier effect, and encompass a wide range of types (Erickson *et al.*, 1978; Ryser, 1985; Schultz, 1985; Langton, 1986; Der Bundesminister Für Verkehr, 1987; Van Lierop, 1988; Brehm, 1989; Carsignol, 1991; Velasco *et al.*, in press). However, very little attention has been paid to the use of culverts under roads as wildlife crossings (but see Camby & Maizeret, 1985; Hunt *et al.*, 1987), in spite of the fact that these structures are commonplace and often coincide with preferential crossing points.

The present paper analyses (i) the passage of various groups of vertebrates through several culverts built some time ago and (ii) the characteristics of these culverts and their environment that encourage their use, with a view to improving their utility as crossings for vertebrates.

METHODS

Characteristics of culverts and roads/railways

Seventeen main types and sizes of culverts for temporary streams were chosen to represent the range of types of transport infrastructure. All were located in the Madrid region (Central Iberian Peninsula), under a motorway (n=2), several local roads (10) and a railway line (5).

In order to characterize the crossings, seven continuous and three discrete variables were measured (see Table 1 for range of variation).

Four continuous variables referred to culvert dimensions: length (CL), height (CH), width (CW) and openness (ON), which was calculated from the three former variables according to the formula CW × CH/CL. A further three variables evaluated characteristics of the road or railway: width used by traffic (RW), total highway width including verges, embankments and cuttings (HW), and height of boundary fence (FH).

The three categorical variables were traffic intensity (TI), vegetation complexity (VC), and presence or absence of detritus pits (DP). Three levels of traffic intensity were considered, low (<100 vehicles per hour), medium (100–500 per hour), and high (>500 per hour). As frequency of trains was always less than 10 per hour, all culverts under railways were considered as of low intensity.

Vegetation complexity was indicative of the characteristics of the vegetation landscape intersected by the road; this was classified as (1) pastures, (2) pastures with maquis and/or scattered woodland, and (3) forest or maquis with scattered woodland. When the vegetation structure was different on the two sides of the road it was assigned the value of the less complex class.

Detritus pits are designed to collect debris that may otherwise block the culverts, and are located at the entrance to, and below the level of, the culvert. The detritus pits extend across the full width of the culverts and end dimensions were 50 cm broad by 50 cm deep in all cases (n=3).

Table 1. Range of variation in variables related to culvert, road/railway and environmental characteristics

	CL (m)	CH (m)	CW (m)	ON (m)	RW (m)	HW (m)	FH (m)	TI (1–3)	VC (1–3)
Mean	13·1	1·2	1·2	0·2	7·5	20·8	1·1	2·1	2·2
SD	4·06	1·10	0·74	0·31	1·91	5·66	0·83	0·90	0·90
Maximum	26·0	4·0	3·0	1·0	10·0	30·0	2·0	4·0	4·0
Minimum	10·0	0·4	0·6	0·02	5·0	11·0	0·0	1·0	1·0

CL, Culvert length; CH, Culvert height; CW, Culvert width; ON, Openness; RW, Road width; HW, Total highway width; FH, Fence height; TI, Traffic intensity; VC, Vegetation complexity. These last two variables are considered in three classes (see text).

Animal track recording

Use of the culverts was determined by means of the animal tracks found inside them, using marble dust to facilitate their identification. Marble dust is odourless, permits high-quality impressions, and its density renders it almost unaffected by air currents that often form inside such tunnels and which would impair the clarity of prints in lighter material. The dust was laid in a band 50 cm wide and 1 cm thick across the whole width of the culvert near the centre (Fig. 1). A plastic sheet was laid underneath to avoid capillary moisture penetrating from the soil (Bider, 1968).

Track identification using Bang and Dahlström (1983) and Brown *et al.* (1992) was restricted to vertebrates. Each record included the species, whenever possible, or faunal group, the number of tracks and their direction.

Sampling was carried out at four seasonal periods over a complete annual cycle. Each period consisted of four sampling days, except for culverts in areas with wild ungulates (n=4) where, owing to their low density, the number of visits per period was eight. In two sampling periods (summer and winter), a fuller analysis was made of the relationship between the use of the crossing and the areas near the road by different faunal groups. This was done by means of two 'roadside' bands of marble dust laid near both ends of the culvert and 2–4 m from each side of the road surface, and two 'distant' bands 40–50 m from the culvert (Fig. 1). Their dimensions were 1·0 × 0·5 m, and the animal tracks found were recorded daily.

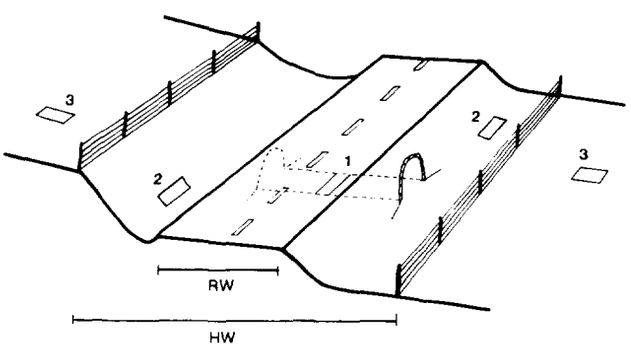

Fig. 1. Location of the marble dust bands (1, culvert; 2, road side; 3, distant) and the boundary fences (not to scale). RW, road width used by traffic; HW, Total highway width.

Data treatment

The total data for animal crossings were corrected for the number of days during which the marble dust trails were laid. Likewise, as the use of the crossing may depend on the abundance of vertebrates in the surrounding area, an index (CI) was calculated to standardize for this factor, according to the formula

$$CI = CTD/(CTD+ETD),$$

where CTD is the number of tracks per day inside the culvert and ETD is the total number of tracks per day on the two distant bands. The value of the index ranged from 0 to 1, with the highest values corresponding to the most used culverts in terms of vertebrate crossings and abundance in the surrounding area. Data concerning the cases where no tracks were recorded in the culvert and in the distant band were regarded as indeterminate, and not included in the analysis.

Spearman's rank correlation coefficient was used to ascertain the relationship between the continuous culvert variables and the use of culverts by fauna. Differences in use of the culverts in relation to the categorical variables (TI, VC and DP) were analysed using Kruskal-Wallis and Mann-Whitney U-tests (Zar, 1984).

Because of the low number of observations for some species, the tracks were grouped into four large classes: (a) reptiles; (b) small mammals up to the size of a hedgehog; (c) rabbits; and (d) carnivorous mammals. Amphibians were excluded from the analyses owing to the low number of tracks recorded (Table 2). Raw data for culvert characteristics and crossings are available upon request.

RESULTS

Crossings: species

In total 1,202 tracks were recorded in the culverts. The average for all vertebrates combined was 3·8 tracks per culvert per observation day (Table 2). The highest frequencies were mice (*Apodemus sylvaticus* in all individuals captured for identification purposes, n=13; 64 % of the total of tracks per day), shrews *Sorex* spp. (13%), and rabbits *Oryctolagus cuniculus* (10%). Cats, mostly wildcats *Felis sylvestris*, comprised the largest number of carnivorous mammals (1·4%), followed by foxes *Vulpes vulpes* (1·1%) and genets *Genetta genetta* (0·6%).

Small mammals were recorded in all the culverts. Only three (18%) were not used by reptiles, two of

Table 2. Movement through culverts expressed in number of tracks per day

	All	Amphibian	Lizard	Snake	Shrew	Rat	Hedgehog	Mouse	Rabbit	Weasel	Genet	Cat	Fox	Dog
Mean	3·78	0·03	0·23	0·02	0·53	0·05	0·01	2·51	0·33	0·01	0·02	0·04	0·03	0·01
SD	2·15	0·06	0·28	0·04	0·49	0·07	0·05	1·49	0·40	0·02	0·09	0·07	0·07	0·03
Maximum	8	0·19	0·88	0·13	1·63	0·19	0·19	5·19	1·25	0·06	0·38	0·22	0·28	0·13
Minimum	0·19	0	0	0	0	0	0	0·09	0	0	0	0	0	0
%	100	0·8	6·1	0·6	12·8	1·4	0·3	64·4	10.0	0·3	0·6	1·4	1·1	0·3

which were the only ones sampled under a motorway. Rabbit and carnivore crossings were verified in 59% and 65% of the culverts, respectively, with the notable fact that none of the three culverts which had detritus pits was used by either of these two faunal groups.

Crossings: seasonal variation

Most vertebrate crossings occurred during spring and summer, with a minimum in autumn (Table 3). Small mammals had the highest percentage of recordings in all periods, and no significant differences were found between seasons (Kruskal-Wallis test, K=3·301; $p>0·05$), although their relative contribution varied between 92% of all tracks in spring and 60% in summer. The passage of carnivores also revealed no significant seasonal differences (K=1·217; $p>0·05$), although records in spring were somewhat lower.

Reptiles and rabbits showed the greatest seasonality in use of culverts, with an increase in relative importance in the summer sample, though only significantly so for the former group (K=34·527; $p<0·01$ and K=5·448; $p>0·05$, respectively).

Table 3. Mean tracks per day for all culverts by seasons and fauna groups

	All	Reptiles	Small mammals	Rabbits	Carnivores
Spring	4·35	0·04	4·02	0·22	0·07
Summer	4·36	0·88	2·61	0·73	0·14
Autumn	2·68	0·04	2·40	0·08	0·15
Winter	3·02	0	2·55	0·32	0·15
CV	24·4	180·0	26·1	82·8	30·3

Seasonal variability of mean values is expressed using the coefficient of variation (CV=100 standard deviation/mean).

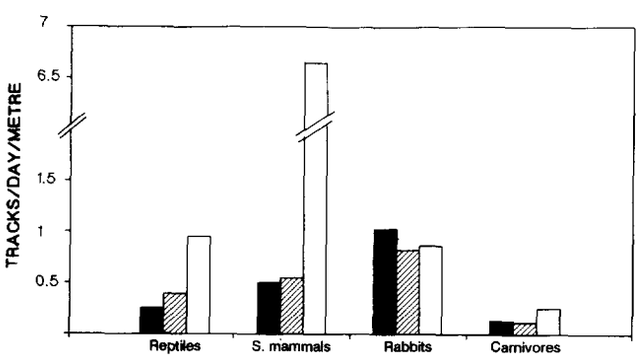

Fig. 2. Mean number of tracks per day per metre of band in distant (■) and roadside (▧) bands, and inside (□) the culverts.

Road environment and culvert usage

The numbers of tracks per day observed for reptiles, small mammals, rabbits and carnivores in the roadside bands (Fig. 2) did not differ significantly from those in the distant bands (Wilcoxon test, z=0·562, 0·315, −1·023 and −0·122, respectively; $p>0·05$).

Neither were there significant differences between abundance of rabbit and carnivore tracks per day per metre of band recorded in the culverts and in the distant bands (z=−0·534 and −0·841, respectively; $p>0·05$). However, the abundance of tracks of reptiles and small mammals was higher inside the culverts than on the distant bands (z=2·830 and 3·575, respectively; $p<0·01$).

No significant correlations were detected among the small mammals between tracks through culverts (n=17) and in the distant bands (r=0·218; $p>0·05$). However, there were positive correlations among rabbits (r=0·647; $p<0·01$), carnivorous mammals and reptiles (r=0·510 and r=0·470, respectively; $p<0·05$).

Crossings: influential factors

Most of the culvert and road variables seemed to influence vertebrate crossing, although there are notable differences between groups. All the continuous variables had significant correlations with the vertebrate crossings. The crossing index (CI) for small mammals (n=17) was correlated negatively with road width and length of the culvert (r=−0·505 and −0·506, respectively; $p<0·05$), and positively with height (r=0·635; $p<0·01$), width (r=0·549; $p<0·05$) and openness (r=0·731; $p<0·01$). The crossing indices for rabbits (n=10) and carnivores (n=12) were negatively correlated with total highway width (r=−0·573 and −0·554, respectively; $p<0·05$) and, for rabbits, with height of boundary fence (r=−0·824; $p<0·01$); for carnivores the last relationship was almost significant (r=−0·497; $p<0·05$).

Passage of reptiles was negatively affected by the presence of detritus pits (U=21·0, n_1=3 and n_2=10; $p<0·05$). In relation to vegetation complexity, significant differences were only found for the crossing index of small mammals (K=7·419; $p<0·05$), which was one-third lower in the roads surrounded by pasture.

DISCUSSION

Faunal differences

The results demonstrate that culverts are used by a wide range of vertebrates. Comparison of abundance of

tracks per metre of band inside the culverts with those in the distant areas suggests that there is no positive avoidance or reluctance to use the culverts exhibited by any faunal group. For reptiles and small mammals the number of tracks per day per metre was higher inside the culverts than on distant bands.

Most crossings were by small mammals (77%) and abundance of this group was similar in the roadside band to that in the surrounding habitat, unlike the findings of Adams and Geis (1983) on other roads. Furthermore, their tracks were much more abundant within the culvert. Considering the small home range of these animals, the culverts were most probably used more as a link between belts of disturbed terrain on the two sides of the road than between distant areas. The ground surface inside the culverts is normally covered in soil and debris deposited by the previous flows of water and presumably provides a less hostile environment for these animals than the open roadway. This may explain the high degree of acceptance.

Reptile crossings through culverts seem to be frequent only in the case of the lizards (6% of all vertebrate tracks). Acceptance of the culverts by reptiles is high and, as in the case of the small mammals, their tracks were more abundant within the culvert than on the distant band. The small home range of many lizards (Stamps, 1977) makes the utilization of culverts unlikely as a channel for movement between distant areas. In contrast, the two tracks of the eyed lizard *Lacerta lepida*, a species with a much larger territory, might reflect a journey between much more distant areas. The important fact is that the culverts allow the passage of reptiles and possibly increase the permeability of roads and railways. Amphibian crossings were probably underestimated in the sample results, as field work was interrupted on rainy days when the marble dust was affected by water. After a rainy day in winter, 75% of the culverts registered anuran crossings.

Rabbits leave a large proportion of all tracks found in culverts; their relatively widespread movements must encourage the acceptance of culverts in their journeys between either side of the road.

As a rule, the response of carnivorous mammals to transport infrastructure varies between the attraction exhibited by the most generalist species, and its avoidance by those most sensitive to human interference (Rusch, 1985). In this analysis, although the differences in the number of tracks per day for all carnivores by the road and the more distant habitats were not significant, they are more frequent in the latter.

Although crossings by medium-sized wild carnivores were a small percentage of the total tracks observed (less than 4%), the high wildlife value and the conservation problems associated with these species make the utilization of culverts as road and railway crossings particularly important. The movement of carnivores through culverts, mentioned previously (Camby & Maizeret, 1985; Hunt *et al.*, 1987), permits mobility among areas that are intersected by the road in the absence of specific tunnels for vertebrates.

Seasonal variability

Seasonality in culvert use varied considerably among faunal groups. Carnivores and small mammals were those that revealed the least seasonality while reptiles had the greatest variability. The largest number of recordings was during summer, when reptiles accounted for over 20% of all vertebrates, between eight and 15 times more than those during the rest of the year. This phenomenon coincides with the increase in lacertid activity during the warmest months of the year in the centre of the Iberian Peninsula (García Paris *et al.*, 1989).

Although the seasonal differences in the number of tracks of rabbits are not significant, it appears that they are more abundant in summer when the population is at its highest in Spain (e.g. Soriguer, 1981).

In general, it appears that the seasonal variations in culvert use are related to the abundance of animals in the surrounding habitat. The positive correlation between the number of tracks in the culvert and in the distant bands in all groups, except small mammals also indicates a dependence of use of culverts on animal abundance.

Culvert characteristics

Vertebrate crossing is related to some of the characteristics of the culverts and their surroundings, and important differences among the faunal groups were revealed.

The dimension of the tunnels is considered as one of the most important variables in the design of passageways for vertebrates (Ulbrich, 1984; Ballon, 1986). In this study, the dimension of the culvert only appeared to affect the crossing index of small mammals, while the other groups were affected to a greater extent by other variables. However, the majority of the culverts studied was sufficiently large to allow the passage of medium-size vertebrates, and it should be pointed out that culverts of smaller dimensions would limit the passage of medium- and large-size mammals.

The crossing index of medium-size mammals (rabbits and carnivores) was affected by the total width of the road and not by the width of road used by the traffic. The change in the complexity of vegetation on the roadside verges appears to impose an additional obstacle to the passage of these vertebrates (SETRA, 1985). However, other factors unrelated to the road must influence the use of culverts by carnivores. Just one of the selected tunnels, located in an area of pasture provided all records of genet crossings, and approximately half of those of wildcats, even when at least eight culverts (47%) coincided with the distribution area of both species (Virgós & Casanovas, 1993).

In these groups the crossing index was also related negatively to the height of boundary fence. While adequate fence design can help to direct fauna towards crossings (Brehm, 1989; Podloucky, 1989; Carsignol, 1991), the fences in the study sample, which are representative of the state of most culverts in the Spanish road network, do not allow access to culverts, and therefore hinder their use. The accidental installation of

a 2 m high fence to enclose two of the selected crossings that were previously used habitually by wild ungulates led to the total absence of recordings of these animals in the 24 sampling days.

Finally, a very important factor in culvert utilization is the presence of detritus pits. Their presence is related negatively with the efficiency of culverts as reptile crossings, and none of the culverts with detritus pits was used by rabbits or carnivores. This type of culvert structure is being installed most frequently in recent years, in detriment to the 'permeability' of the road for vertebrates by culverts.

CONCLUSIONS

The present study shows that culverts can constitute a traffic-free crossing for vertebrates between habitats on the two sides of a road. These may be important for local populations and even for rare species such as wildcats and genets that are capable of using them.

It has been suggested that both tunnels for vertebrates and water culverts should be installed separately (SETRA, 1989). In practice, however, the absence of specific tunnels under most roads, and the reduction in costs of not having to provide special passages when culverts are used by fauna, endow the latter with particular importance for conservation.

When it is intended to encourage vertebrate crossings through culverts, the fences of the roadway should never under any circumstances block the entrance to the culverts and should be constructed so as to funnel animals towards the culverts. It has been suggested by other authors (e.g. Bennet, 1991; Carsignol, 1991), that this funnelling effect can be augmented by artificially increasing the vegetation cover around and towards the entrance of the tunnel. Also detritus pits should be eliminated, or modified using ramps.

The adaptation and improvement of culverts to encourage vertebrate crossings involve minimal outlay in comparison with overall costs and the provision of special tunnels. They are an effective method of increasing the permeability of highways, and thus of lessening the barrier effect. However, owing to the relatively low sample number, further data are needed to check on the value of particular design features for wildlife.

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