Human and Ecological Risk Assessment, 14: 871–897, 2008

ISSN: 1080-7039 print / 1549-7680 online
DOI: 10.1080/10807030802387481

The Apache Longbow–Hellfire Missile Test at Yuma Proving Ground: Ecological Risk Assessment for Helicopter Overflight

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ABSTRACT

A multi-stressor risk assessment was conducted at Yuma Proving Ground, Arizona, as a demonstration of the Military Ecological Risk Assessment Framework. The focus of the assessment was a testing program at Cibola Range, which involved an Apache Longbow helicopter firing Hellfire missiles at moving targets, that is, M60-A1 tanks. This article focuses on the wildlife risk assessment for the helicopter overflight. The primary stressors were sound and the view of the aircraft. Exposure to desert mule deer *(Odocoileus hemionus crooki*) was quantified using Air Force sound contour programs NOISEMAP and MR_NMAP, which gave very different results. Slant distance from helicopters to deer was also used as a measure of exposure that integrated risk from sound and view of the aircraft. Exposure-response models for the characterization of effects consisted of behavioral thresholds in sound exposure level or maximum sound level units or slant distance. Available sound thresholds were limited for desert mule deer, but a distribution of slant-distance thresholds was available for ungulates. The risk characterization used a weight-of-evidence approach and concluded that risk to mule deer behavior from the Apache overflight is uncertain, but that no risk to mule deer abundance and reproduction is expected.

Key Words: ecological risk assessment, aircraft overflight, mule deer, noise, noise contour, sound.

Received 9 February 2007; revised manuscript accepted 1 September 2007.

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INTRODUCTION

Ecological impacts of military training and testing programs involving aircraft are frequently components of environmental impact assessments (USAF 1995; Air National Guard 1997; USAF 1998; Navy 1998). However, until now, impacts of aircraft overflights and other military activities involving physical stressors have not been investigated through the use of a risk assessment framework. The U.S. Environmental Protection Agency's (USEPA's) *Guidelines for Ecological Risk Assessment* (1998) are written to apply broadly to any chemical, physical, or biological stressor. The Military Ecological Risk Assessment Framework (MERAF) was developed as an elaboration of the USEPA guidelines for multiple military activities (Suter *et al.* 2002). Moreover, an ecological risk assessment framework for low-altitude aircraft overflights was developed as part of MERAF to aid in conducting risk assessments for overflights in military training, testing, and other contexts (Efroymson *et al.* 2000, 2001a; Efroymson and Suter 2001).

This article aims (1) to demonstrate the use of MERAF and an activity-specific risk assessment framework for aircraft overflights, (2) to assess the risks associated with the Apache Longbow–Hellfire missile test at Yuma Proving Ground (YPG) to desert mule deer (*Odocoileus hemionus crooki*), and to evaluate the usefulness of an activity-specific risk assessment framework for conducting risk assessments of military programs. This article is one of a series of articles describing an ecological risk assessment for a military activity at YPG (see Efroymson *et al.* 2008, Jones *et al.* 2008, and Peterson *et al.* 2008; all *this issue*). The Apache Longbow–Hellfire missile test is described in Efroymson *et al.* (2001b) and Efroymson *et al.* (2008) in this issue of *Human and Ecological Risk Assessment*, and includes missile firing and tracked vehicle movement as well as helicopter overflight. Sound from missile detonations and explosions is treated in Jones *et al.* (2008, *this issue*).

PROBLEM FORMULATION

Potential Stressors and Modes of Action

Candidate stressors associated with helicopter overflights are presented in Table 1. Stressors are categorized broadly and may arise from several specific sources. For

Table 1. Stressors and modes of action associated with overflights by rotary wing aircraft (modified from Efroymson *et al.* 2000).

Stressor	Potential mode of action
Sound	Behavioral response of wildlife, auditory damage to wildlife, interference with foraging or predation, interference with mating
Sound level at a particular frequency	Interference with signaling among wildlife, interference with echolocation
Visual image or shadow of aircraft	Behavioral response
Air movement (rotor wash)	Erosion and associated effects on plant community, stem breakage

example, noise from helicopters consists of rotor noise, engine noise, gear box noise, and sometimes blade slap (Molino 1982). Although different frequencies of sound could be associated with different effects, sound pressure is treated as a single stressor. Certain stressors were included in the generic risk assessment framework for overflights (Efroymson *et al.* 2000, 2001a) but were eliminated in this implementation because of the test description: physical aircraft (birdstrikes by helicopters are rare and birds are not assessment endpoint entities in this study), vibration (potential modes of action are unknown), and heat (helicopters land on helipads, rather than on soil).

Conceptual Model

The conceptual model for the helicopter overflight is depicted in Figure 1. The model represents the combination of overflight stressors in the Apache Longbow–Hellfire missile test, without making an assessment of importance of each stressor.

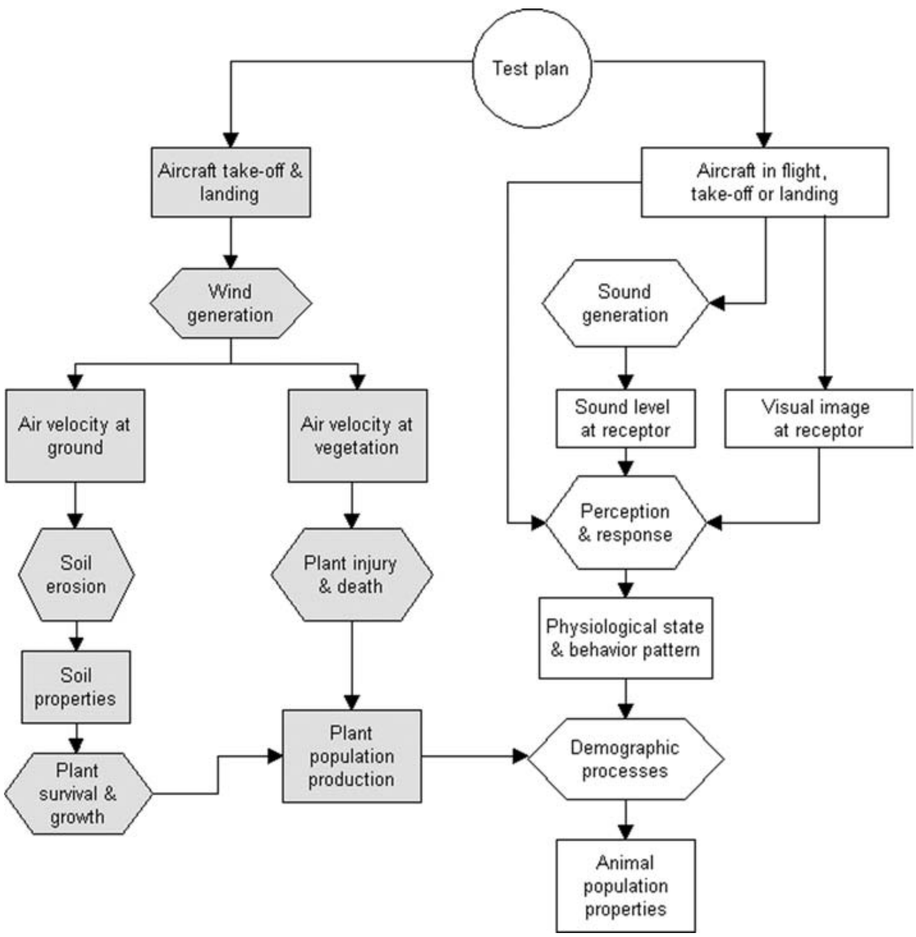

Figure 1. Conceptual model for helicopter overflights in the Apache Longbow–Hellfire test at Yuma Proving Ground. Stressors and pathways that were not considered in this assessment appear in gray.

In this assessment there is no pathway from helicopter rotor wash (air movement) to vegetation in washes (Efroymson *et al.* 2000) because helicopters only land on helipads. In a prospective risk assessment for a new military program, assessors unfamiliar with the location of the Apache Longbow–Hellfire test would have to consider air movement from the helicopter as a potential, direct stressor.

Selection of Activity-Specific Measures of Exposure

Measures of exposure to a stressor include measures of intensity, as well as measures of the spatial distribution and temporal aspects such as frequency and duration.

Intensity measures

Sound. The two principal measures of exposure to sound that provide a description of a single overflight event and are related to responses in wildlife are the sound exposure level (SEL) and maximum or peak sound level (L_{max}). The SEL combines the maximum noise level of an overflight and its duration; all of the acoustic energy of an event is normalized into one second (USAF 1998). No information is available to determine whether the SEL or the maximum sound level is a better predictor of effects on wildlife, and limited effects data are available for each sound metric. Therefore, we use both SEL and L_{max}, as they are both optional output metrics of the MR_NMAP (Military Range NOISEMAP) Air Force noise contour model, and as the former metric can be calculated from the day-night average sound level output of NOISEMAP, another noise contour model. The day-night average sound level (DNL), the primary noise metric used by the Department of Defense (DoD) (especially the Army) (USACHPPM 1998), is not as appropriate for ecological risk assessment. The level is commonly associated with human community effects and often presented as a value that has been adjusted upward by 10 dB for sleeping hours or the "surprise" reaction to some overflights (USAF 1998).[1]

Decibels (except for blast noise, Jones *et al.* 2008, *this issue*) are most often expressed on an A-weighted basis (*i.e.*, adjusted to represent the way the average human ear responds to various frequencies of sound), because sound monitoring devices use this metric and because the appropriate sound frequency weightings for few non-human species are known. A-weighting leads to uncertainty when exposures are extrapolated from species to species or aircraft to aircraft to estimate exposure-response relationships (Efroymson *et al.* 2000). P. R. Krausman of the University of Arizona has developed a weighted sound metric for ungulates and tested the hearing levels for pronghorn (personal communication, Mara Weisenberger, Wildlife Biologist, USFWS San Andres NWR, Las Cruces, NM, May 1, 2001); however, this metric cannot be used to clarify older exposure-response models or thresholds for ungulate behavior or production.

Background sound is not usually a significant contributor to the total sound, as is evident from the logarithmic scale of decibels (Efroymson *et al.* 2000). Thus, in

[1]The U.S. Army is considering changing its noise regulation AR 100-1 to rely on peak sound levels rather than DNLs as predictors of human community annoyance. These peak sound levels would also be useful for estimating wildlife effects (C. Stewart, USACHPPM, personal communication, February 2006).

rural areas such as the study area in Cibola Range, the background contribution to a sound exposure level can be ignored unless noise from natural sources (*e.g.*, insects or wind) or noise from other military tests is high.

Distance

The distance from an aircraft to an animal, sometimes called the "slant distance," as it is the hypotenuse of the right triangle that includes above-ground altitude and lateral distance, is the exposure metric in some exposure–response models for aircraft overflights (Efroymson *et al.* 2000).

Temporal measures

Temporal aspects of exposure include duration, frequency of occurrence, and timing. The duration of an overflight may influence the magnitude of effect, but almost no information is available on effects of this factor. An exception is the SEL metric, which normalizes the sound level based on flight duration. Exposure-response models for overflights do not use frequency of overflight (number per day) as a temporal measure of exposure. However, this frequency may be related qualitatively to the likelihood of habituation by wildlife (see later). The timing of overflights is critical, particularly as it relates to reproductive behavior, home range locations, and the diurnal or noctural activity of candidate assessment endpoint populations.

Spatial measures

Spatial measures of exposure include the spatial extent of overflights; the habitats, home ranges, forage and water locations of mule deer; and the area where mule deer potentially receive a critical level of exposure to sound or to the sound and view of the aircraft combined.

Selection of Measures of Effects

The primary measures of effect are observed behavioral responses of ungulates to aircraft noise, including movement to a new home range and disruption of foraging, rutting, or calving. Changes in heart rate were used as supporting measures of effect. Thus, the measures of effect that are available or that can be simulated in this study are not direct measures of the assessment endpoint entity (mule deer abundance and reproduction).

CHARACTERIZATION OF EXPOSURE

Sound Contours Calculated Using MR-NMAP

Sound levels experienced by mule deer were not measured as a part of this study because of a lack of sufficient funding for acoustic monitors. Therefore, sound levels on the ground were estimated using U.S. Air Force software, MR-NMAP and NOISEMAP. As described later, the use of both programs resulted in estimates of noise contours for the Apache–Hellfire test.

Program structure

MR_NMAP (MOA Range NOISEMAP) v2.1 was obtained from the Air Force Center For Environmental Excellence (AFCEE) website, http://www. afcee.brooks.af.mil/ ec/noise/noisemodels.htm. The program is intended to be run under the DOS operating system but can be run under Microsoft Windows™. This program is designed to simulate noise contours inside Military Operations Areas and Military Training Ranges, but will also simulate noise from bombing tracks. A bombing track is a flight path that is composed of straight segments and turns (Lucas and Calamia 1996). The track algorithms in MR_NMAP are similar to algorithms in the NOISEMAP program. MR_NMAP is not designed for low-level flights by rotary-wing aircraft, even though it is used for that purpose. In Military Training Route (MTR) or bombing track mode, the program can only consider one helicopter overflight at a time, which is a reasonable assumption for this test but not for many large-scale training activities. Training activities can be specified as operations in Military Operations Areas (MOAs), with the number of daily, monthly, or yearly values. MR_NMAP v2.1 was used to generate noise contours for the AH-64 Apache helicopter at YPG.

Within MR_NMAP, the user specifies the percentage of time that the aircraft spends between a series of altitude pairs. A maximum of 10 altitude pairs can be entered for each mission, and the altitude profile must begin at the lowest altitude and be contiguous from one altitude pair to the next.

Thus, instead of MR_NMAP calculating noise contours for different altitudes, it first calculates an Equivalent Acoustical Altitude (EAA), the constant altitude at which the aircraft must fly to produce the same average noise level for a distributed altitude profile. The EAA replaces the altitude distribution in all subsequent calculations. Using the EAA in place of the altitude profile significantly increases the computational speed of MR_NMAP during noise calculations and is intended to emulate the fact that aircraft do not always fly at the exact sequence of altitudes in the flight plans. However, the EAA prevents the user from specifying actual altitude changes within a single track. All noise contours produced by MR_NMAP are symmetrical because of this, regardless of altitude changes made by the aircraft as it moves over the track. The use of EAA in low-level operation may overestimate the noise contours that are produced (personal communication, Kevin Bradley, Wyle Labs, October 2000).

Implementation for Apache–Hellfire test at YPG

Five attack runs for Apache Longbow AH-64 Hellfire testing were simulated. All attack runs begin with a takeoff at the Inverted Range Control Center (IRCC) at YPG, after fitting with Hellfire missiles. The five runs differ in the spatial location where the Hellfire is launched at armored targets traveling along the Moving Target Indicator (MTI) Road. The firing points were provided by Bert Evans of YPG but are not publicly available. Each launch point was 4.0 to 6.4 km from the target.

The MR_NMAP simulations assume that the Apaches fly directly from IRCC to one of the aforementioned firing points, fire, fly to the Pinkrock Impact Point (IP) to assess the success of the mission, then fly directly back to the IRCC. Because the Apaches fly precision attack patterns during the Hellfire tests, we have simulated their paths as bombing tracks within MR_NMAP.

Because there is no provision inside MR_NMAP for changing airspeed along a single track, the noise is simulated by assuming that the Apaches fly at 40 knots airspeed throughout the mission. (An average velocity of 20 knots was recommended by Bert Evans of YPG, but this low value is not an option in the program.) With rotary-wing aircraft in MR_NMAP, the airspeed setting determines the power setting.

In the simulation we assume equal distributions of missions across the five ground tracks and a total of 14 daylight missions each year. We have assumed an altitude profile in which the Apache spends 5% of mission time between 0 and 50 ft above-ground level (AGL), 5% between 50 and 100 ft, 5% between 100 and 150 ft, 5% between 150 and 200 ft AGL, 20% between 200 and 250 ft AGL, 30% between 250 and 300 ft AGL, and 30% between 300 and 350 ft AGL. This altitude profile distribution was recommended by Bert Evans at YPG as closely reflecting the Apache Longbow altitudes during Hellfire testing.

The output sound metrics that were utilized include Sound Exposure Level, or SEL, and Maximum A-weighted Sound Level, or L_{max}. Noise contours were exported as shapefiles to ArcView. The contours, draped on Landsat images, are presented as Figure 2A (SEL) and Figure 2B (L_{max}). These maps depict the extent of above-ambient sound simulated from the Apache–Hellfire test. The highest sound levels are 89 dB SEL and 102 dB L_{max}. The default ambient sound level is 35 dB SEL in MR_NMAP. The default value was not changed because of the insignificance of background sound in most overflight sound exposure estimates (Efroymson *et al.* 2000) and the measurements and programming that would be required to change the default value.

Sound Contours Calculated Using NOISEMAP

Program structure

NOISEMAP 6.5 is another official Air Force noise contour program. A copy was obtained from the Air Force Center For Environmental Excellence (AFCEE) website, http://www.afcee.brooks.af.mil/ec/noise/noisemodels.htm. The program is intended to be run under the DOS operating system but can be run under Windows. NOISEMAP is designed to simulate noise contours at airbase runways or engine power run-up areas and requires the entry of runway locations, take-off directions, and approach and departure patterns (Moulton 1990). Because the YPG Hellfire tests do not involve airports and runways, MR_NMAP was investigated first. However, an advantage of NOISEMAP compared to MR_NMAP is that NOISEMAP allows the input of a flight altitude profile along the aircraft track. NOISEMAP 6.5 includes parameters for the AH-64 and other rotary-wing aircraft. Example files that are generated from NOISEMAP were successfully installed and regenerated.

The "Grid Add constant to data points" option was used to add 49.5 dB to convert the noise metric from day-night average sound level (DNL), a human annoyance metric, to SEL in this test case where there is only one flight per day and no nighttime flights. (The equation for DNL under these specific conditions is: DNL = SEL + 10log(numberflightsperday + 10.0 * numberflightspernight) – 49.37.)

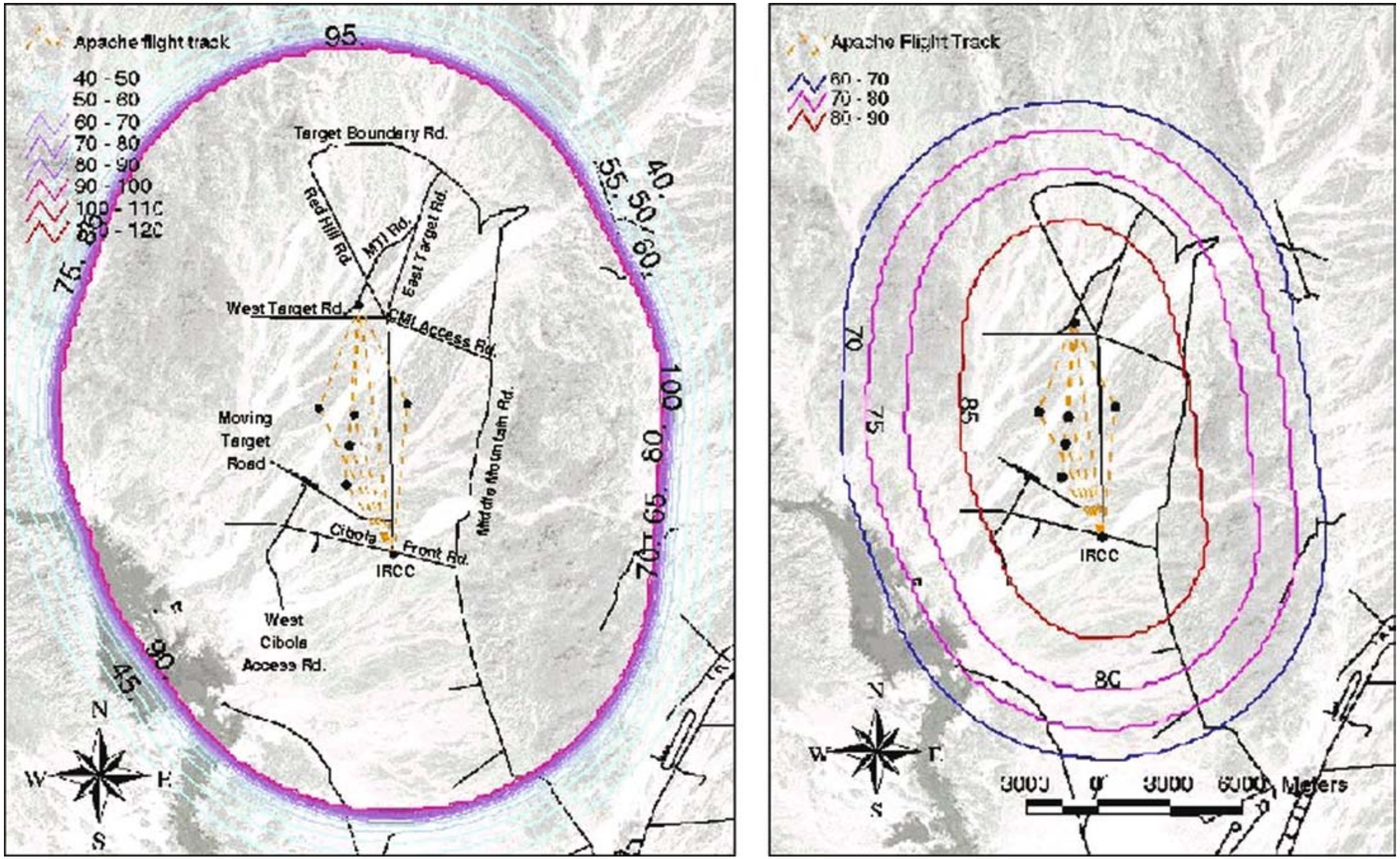

Figure 2. A-weighted decibel sound contours in Sound Exposure Level (SEL) metric (A) and L_{max} metric (B), produced using MR_NMAP software, draped over Landsat 7 image of study site. Waypoints where the aircraft changed course are marked. IRCC = Inverted Range Control Center.

Implementation for Apache–Hellfire test at YPG

Because NOISEMAP is designed for fixed-wing aircraft noise simulation, particularly when operating around airports and bases, it expects operations to be centered on one or more runways. For this reason, it was necessary to create a virtual runway from the Pinkrock Impact Point (IP), to the IRCC (see Figure 1 in Efroymson *et al.* 2008, *this issue*), because this return track was shared by all five practice Hellfire attack patterns.

Each of the five attack patterns was simulated as a closed loop. The common "return" direction was toward the IRCC, but this was the direction of "take off" along the virtual runway. For the purposes of the NOISEMAP noise simulation, the Apaches begin a "take off" over the target at the Pinkrock IP, already at an altitude of 200 feet AGL, fly to the IRCC, land, takeoff, fly to one of the five launch points, and then "end" the closed loop back over the target at the Pinkrock, IP. These simulation tricks were not expected to have any effect on the simulated noise contour outputs. The altitude assumptions were identical to those for the MR_NMAP simulations.

Only the location of the launch point changed for each of the five closed test attack loops. As stated earlier, the coordinates of each launch point (and thus the flight distance for each leg of each attack triangle) were known. However, unlike MR_NMAP, NOISEMAP expects track course inputs in the form of headings and flight distances, as a series of turns. The law of cosines and law of sines for triangles were used to convert the lengths of the sides of each of the five triangles into flight distances and angles, which were then converted into heading changes for input into NOISEMAP. Because a short flight distance is required to make each heading change, exact solutions for the triangular course were adjusted to achieve best track closure.

Humidity was specified as 32%, and temperature was set to 95°F for the noise simulations. All five attack triangles shared the same altitude profiles: 200 ft AGL over Pinkrock IP, 350 ft AGL over IRCC, land at IRCC, takeoff from IRCC, climb to 300 ft AGL, 300 ft AGL over the launch point, fly to Pinkrock IP at 300 ft AGL. The Apaches were simulated as flying at 40 knots LFO (Low Flight Operations) power and speed settings throughout, except for takeoff and landing power where appropriate. These altitudes and power settings were recommended by Bert Evans of YPG, and their percentage distribution matches the altitude distribution profile specified for MR_NMAP simulations.

Sound contours simulated by NOISEMAP are depicted in Figure 3. A maximum SEL of 104.6 dB is reached over the IRCC takeoff/landing zone in the NOISEMAP prediction.

Model uncertainty

The term "model uncertainty" refers to the accuracy of the model used to simulate noise contours. Model uncertainty can be discussed qualitatively by considering the following factors: (1) the extent to which NOISEMAP and MR_NMAP outputs disagree, (2) the extent to which these programs that were designed for fixed-wing overflights may not be appropriate for simulating rotary wing flights, and (3) environmental features that are missing from the simulations.

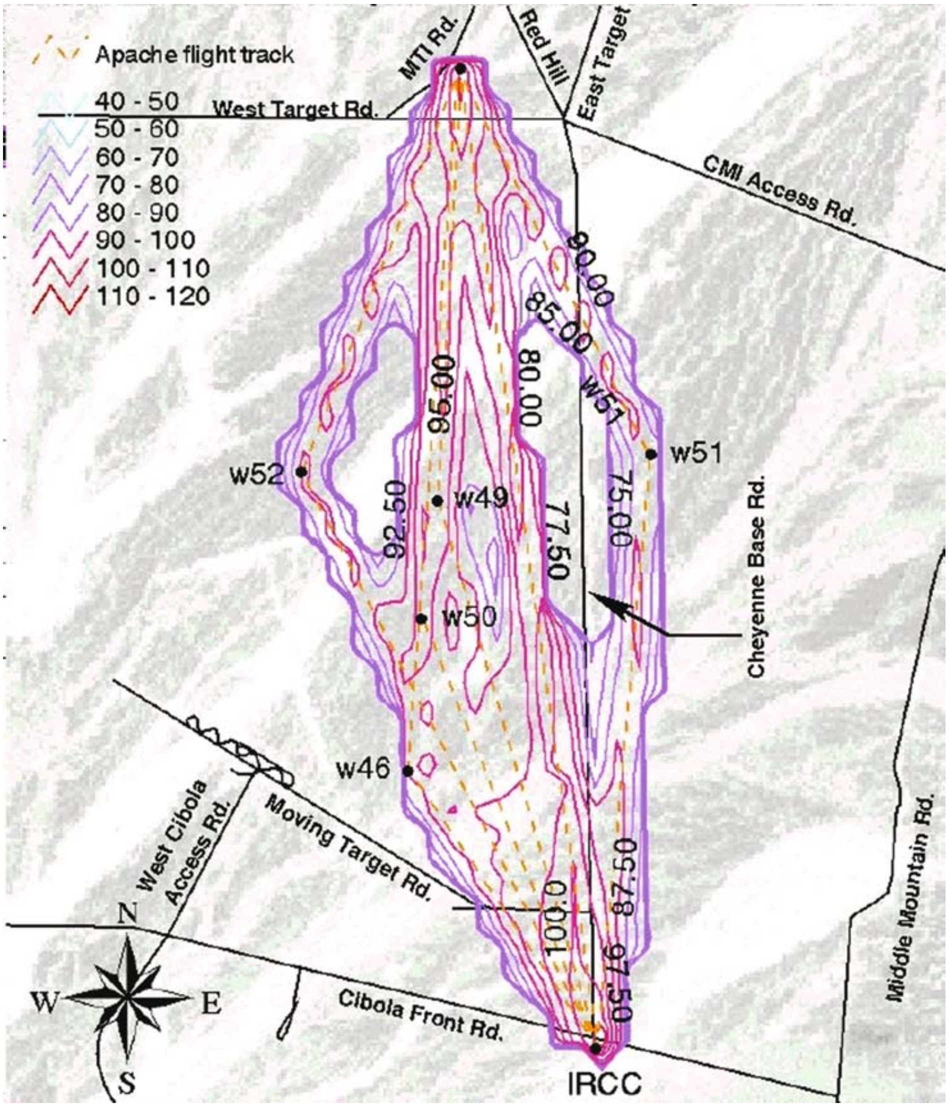

Figure 3. A-weighted decibel sound contours in Sound Exposure Level (SEL) metric, produced using NOISEMAP software, draped over Landsat 7 image of study site. Waypoint designations are marked with "w." See Table 2. IRCC = Inverted Range Control Center.

Despite an attempt to specify as uniformly as possible an identical implementation of the YPG Apache–Hellfire missile training in both NOISEMAP and MR_NMAP, considerable differences exist between the simulated output noise contours that are produced from each tool, even for the same noise metric. The SEL contours predicted from NOISEMAP are much more angular and spatially localized than the oval contours predicted from MR_NMAP. A maximum SEL of 104.6 dB is reached over the IRCC takeoff/landing zone in the NOISEMAP prediction (Figure 2), whereas a maximum SEL of 89 dB is obtained from MR_NMAP (Figure 3). Similarly, whereas the area exceeding 100 dB SEL in MR_NMAP is 0, the area is 0.3 km in NOISEMAP. A maximum L_{max} of 102 dB is predicted within a much larger oval area when using MR_NMAP.

The differences in spatial noise predictions probably relate to the very different ways that the two models treat aircraft altitude. Whereas NOISEMAP allows the specification of starting and ending altitudes along each flight path, MR_NMAP allows only a percentage breakdown of proportion of time spent at each altitude across the entire flight track, specifying altitude in a non-spatial way via EAA, which replaces the altitude distribution in calculations. It is likely that the use of the EAA in MR_NMAP results in the generalization of the projected noise contours into smooth ovals. MR_NMAP loses some of its credibility by depicting noise contours that are unrelated to the location of takeoff or landing, where sound on the ground should be maximized. This uncertainty is considered in the weight of evidence for the risk assessment.

NOISEMAP and related programs "can be and have been used for helicopter operations but are not well suited to this use in their present form" (Lee *et al.* 1996, p. i.). Vertical takeoff and landing is not explicitly considered in NOISEMAP or MR_NMAP. Also, helicopter noise has different directional characteristics, relative to the flight path, on the left, center and right sidelines because of asymmetrical main and tail rotor noise (Lee *et al.* 1996). Levels typically vary 3 to 5 dB in SEL between the left, center, and right sides of the aircraft. Lateral attenuation of sound may differ between fixed-wing and rotary-wing aircraft due to the harmonic content of helicopter noise, the sometimes impulsive nature of helicopter noise, and the open rotors of helicopters (Lee *et al.* 1996). And sharp lateral or vertical maneuvers of helicopters are not simulated in the current programs.

Uncertainties associated with the output of NOISEMAP and MR_NMAP include all of the variables that affect sound propagation that are not included in the model. For example, MR_NMAP does not include wind, ground topography, or day-to-day variations in meteorological conditions (USAF 1998). Some of the errors can be quantified; for example, topographic features can sometimes cause momentary increases in sound levels (reflections) of up to 3 dB for brief periods and can sometimes decrease sound substantially (shielding), often more than 20 dB (USAF 1998). Also, because altitude is calculated relative to the highest local ground elevation, the altitude relative to a canyon bottom is underpredicted. When sound is propagated in the model through distances greater than one or two km, atmospheric absorption and lateral attenuation can lead to large uncertainties (USAF 1998).

Uncertainty in the exposure results could be minimized by a field study using fixed acoustic monitors or radio-collared deer with acoustic monitors as a means of evaluating the two noise models. The latter method might more accurately determine L_{max} and SEL of exposed mule deer.

Estimates of Exposure Based on Slant Distance from Aircraft

The distance from an aircraft to an animal is an exposure metric that may be related to behavioral effects on ungulates (hoofed mammals) (Efroymson and Suter 2001). As stated earlier, this exposure metric typically incorporates two stressors: sound and view of the aircraft.

Table 2. Distances of five helicopter trajectories in the Apache Longbow–Hellfire test.

		Distance (km)			
Trajectory	YPG waypoint[1]	IRCC to waypoint	Waypoint to Pinkrock IP	Pinkrock IP IRCC	Total
1	52	5.91	3.93	8.99	18.83
2	46	3.07	6.39	8.99	18.45
3	50	4.24	4.99	8.99	18.22
4	49	5.20	3.92	8.99	18.11
5	51	5.45	3.87	8.99	18.31

[1]A waypoint represents an intermediate destination along the flight path. These are YPG designations that appear on figures.

The total distance of each of the five trajectories in the military test activity was calculated in Table 2, using segments determined in the geographic information system (GIS). In this exposure analysis, the longest of the five trajectories, trajectory 1, is used because it results in the largest exposed area. The aircraft takes off at IRCC, quickly ascends to 91 m, flies to the waypoint, shoots, descends to 61 m at the Pinkrock IP, ascends to 107 m just before returning to the IRCC and lands. For the purpose of this assessment, it is assumed that the Apache's altitude for each segment corresponds to the average of the lowest altitude at each end of each segment. (Thus, the helicopter's ascent to 107 m immediately before landing is ignored to maximize the assumed, exposed area.) Therefore, the first segment is assumed to be flown at 46 m AGL, the second segment at 76 m AGL, and the third at 31 m AGL.

This activity description serves as the exposure determination for the slant distance–response relationship. It is not possible to calculate the minimum distance to each deer. Affected areas are calculated in the risk characterization using effects thresholds described later.

The principal uncertainty associated with this activity description is the averaging of altitudes along a segment. In addition, aircraft do not always fly to planned altitudes and waypoints.

CHARACTERIZATION OF EFFECTS

Assessment Endpoint Property

Desert mule deer are not threatened or endangered. Thus, the behavior or survival of individuals is not of regulatory interest, and is probably not of broad, societal interest. Therefore, the assessment endpoint property was chosen to be a population-level property, that is, the abundance or production of desert mule deer (Efroymson *et al.* 2008, *this issue*). However, the exposure-response models that relate noise or the view of aircraft to effects on ungulates focus mostly on behavior and occasionally on heart rate. Thus, the extrapolation from behavioral to population-level effects will be qualitative if behavioral effects are expected.

Necessary Extrapolations

As stated earlier, a major extrapolation (and major source of uncertainty) in this assessment is the extrapolation from behavior to population-level effects. Mechanisms by which these extrapolations can occur are depicted in Figure 4. Few studies relate behavior to population-level effects. In one study in which jets flew over captive sheep, the numbers of females bred and young produced were higher than in reference areas (P. R. Krausman, University of Arizona, personal communication, May 15, 2001).

The characterization of effects also involves extrapolations among aircraft and among ungulates; no data on impacts of the Apache Longbow helicopter on desert mule deer exist. Similarly, the characterization of effects must rely on studies carried out at different sites from YPG. Some of these study sites include penned areas with exposure to recorded sound.

As stated earlier, the mechanisms depicted in Figure 4 do not need to be known if behavioral or acoustic effects are zero. Then, population-level effects (abundance and reproduction) are zero also.

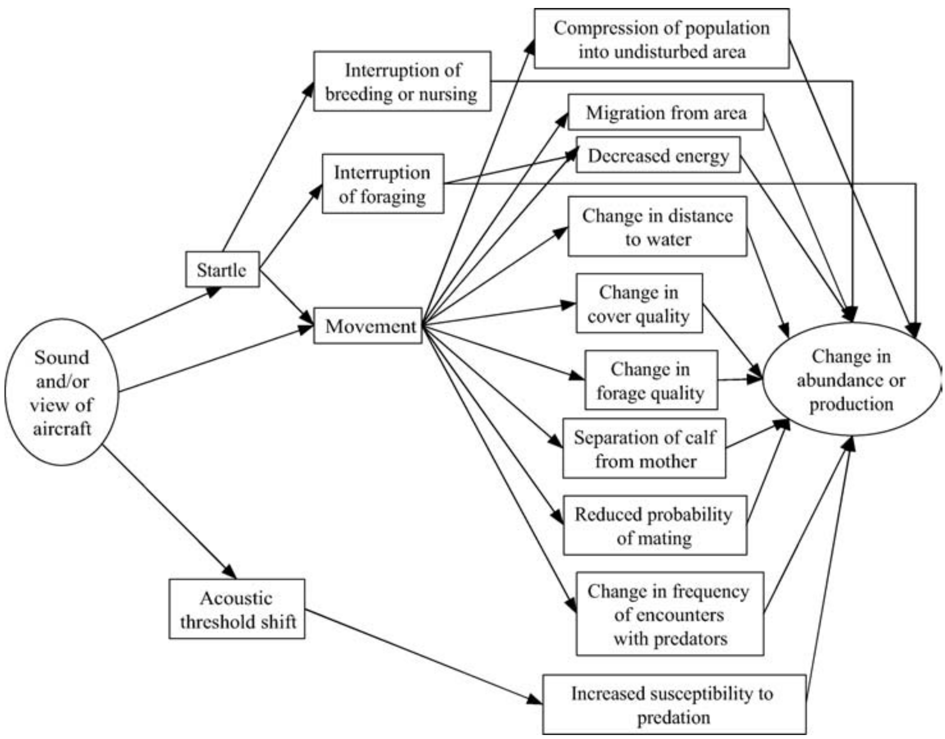

Figure 4. Mechanisms by which sound may affect abundance or production of ungulates. Most involve movement of animals that alter habitat or reproductive activities. Adapted from Efroymson and Suter (2001).

Sound Level Effects Thresholds

Movement and other behavior

Weisenberger *et al.* (1996) observed changes in activities of penned two-to-six-year-old desert mule deer when deer were exposed to simulated low-altitude noise of B1-B and F4-D aircraft. Maximum sound levels for B1-B jets ranged from 101.0 to 112.2 dB and those for F4-D jets ranged from 92.5 to 109.3 dB. During 112 overflight simulations each in the summer (May 12–August 9), late summer (August 13–October 12), and spring (February 4–April 5), deer responded with "alarm" (startle, look toward speaker, and alteration of activity) to 33, 6, and 6 simulations, respectively. (The Apache Longbow–Hellfire missile test occurred in August 2000, so "summer" and "late summer" impacts are most relevant.) The time to return to original behavior averaged 21.6 s in late summer, 114.5 s in summer, and 252.3 s in spring. The researchers did not relate sound exposures to effects; all simulated overflights were treated equally. Thus, a threshold for the effect, if present, is uncertain, and the data cannot be easily reexamined to determine the threshold (M. E. Weisenberger, U.S. Fish and Wildlife Service, personal communication, May 1, 2001). The authors of the study concluded that "the exposures [to] aircraft noise were of such short duration in this study that noise created from low-flying jet aircraft probably could not be considered detrimental (*i.e.*, inhibiting reproductive mechanisms) to desert mule deer. . . . However, there may be additional, or interactive effects from the visual stimulus of actual aircraft" (Weisenberger *et al.* 1996, p. 59). P. R. Krausman of the University of Arizona suggests that deer would be likelier to move in the presence of a helicopter than in the presence of fixed-wing aircraft at the same sound level; the helicopter is overhead longer because of its slower speed (personal communication, May 15, 2001).

LeBlanc *et al.* (1991) simulated noise from F4 aircraft. Pregnant horses were exposed to 4 exposures per day of 113.4 dB (L_{max}) or 112.2 SEL. All non-habituated mares exhibited flight posture (highly elevated head, wide open eye lids, dilated nostrils, quick forward or sideways movement), and movement of the horses was significantly higher in the treatment group than in a control group. Habituated horses did not show this response.

For the purpose of this assessment, the following assumptions are made:

1. 92.5 dB, L_{max}, is a conservative estimate of a behavioral effects threshold for mule deer.
2. 100 dB, L_{max}, is a more reasonable, less conservative estimate of a behavioral effects threshold for mule deer.
3. 112.2 dB, SEL, is probably a nonconservative estimate of a behavioral effects threshold for mule deer, based on responses of horses.

Heart rate changes

Weisenberger *et al.* (1996) observed changes in heart rates of penned desert mule deer under the simulated sound conditions described earlier. The mean heart rates of desert mule deer increased during overflight simulations during two summer and one spring period and remained at a high level for at least 3 minutes in the spring period. The spring response may have been from naive, unhabituated deer. Heart rates did not exceed the maximum values that were observed during the 25- to 30-day period prior to the overflight noise simulation. The increase in heart rates was highest for animals in pens exposed to the loudest overflights.

LeBlanc *et al.* (1991) simulated noise from F4 aircraft. Pregnant horses were exposed to four exposures per day of 113.4 dB (L_{max}) or 112.2 SEL. Thirty-eight percent of non-habituated, exposed mares had mild heart rate increases sustained for 20 s.

Acoustic threshold shift

Temporary or permanent acoustic threshold shift is hearing loss associated with loud sounds. Such hearing loss can make an animal more susceptible to predation and less likely to hear mating signals or a lost calf. No exposure–response relationship is available for the relationship between sound level from low-altitude helicopter or fixed-wing overflights and acoustic threshold shift in ungulates. Therefore, this effect is not considered further.

Slant Distance Effects Thresholds

Most of the exposure–response models for effects of aircraft overflights on ungulates are slant distance thresholds. A distribution of slant distance thresholds for effects of helicopters on ungulates is presented in Figure 5, representing combinations of species (included habituated and unhabituated included), helicopter types,

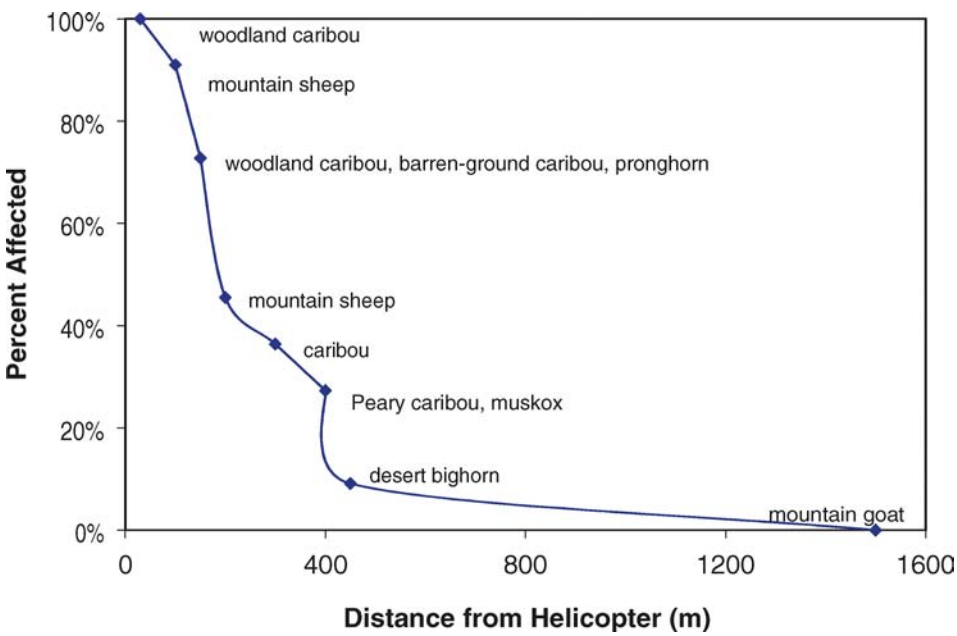

Figure 5. Slant distance thresholds for behavioral effects associated with ungulate exposure to helicopter overflights. Behavioral effects include movement (*e.g.*, escape response), change in habitat, or change in activity (*e.g.*, reduction in foraging).

and environmental conditions. The data are a subset of a distribution of effects thresholds for fixed-wing and rotary wing aircraft from Efroymson *et al.* (2000) and Efroymson and Suter (2001). Thresholds are for behavioral effects, with most indicating movement responses (see Efroymson *et al.* 2000 for detailed descriptions of effects). The distances associated with a 10, 20, and 50% probability of behavioral effects on a randomly drawn combination of ungulates, helicopters, and environmental conditions are 445, 400, and 175 m, respectively (Figure 5). Therefore, at a 400-m slant distance, there is a 20% chance that the mule deer exposed to an Apache helicopter during the Apache–Hellfire test would be affected.

The justification for eliminating response distances for fixed-wing aircraft is that desert ungulates tend to respond differently to helicopters than to fixed-wing aircraft with respect to visual stimuli, regardless of the decibel level (personal communication, Mara Weisenberger, U.S. Fish and Wildlife Service, May 1, 2001). Indeed, if desert mule deer were exposed to two overflights at equivalent distances, one a rotary-wing flight and the other a fixed-wing flight, a mule deer would be likely to run farther in response to a helicopter than a fixed-wing aircraft, because of (1) the greater noise of the former aircraft, (2) the slower speed (and longer exposure to) the former aircraft, and (3) possibly a visual image of the former aircraft that creates a greater response (personal communication, P. R. Krausman, University of Arizona, May 15, 2001). For example, mule deer exposed to fixed-wing aircraft at 91-m or greater lateral distance do not usually exhibit a behavioral response, whereas deer exposed to helicopters at smaller distances often do (personal communication, P. R. Krausman, University of Arizona, May 15, 2001).

Picacho Mountains in South-Central Arizona

One study is not included in the slant distance threshold distribution because it relates to fixed-wing rather than rotary-wing aircraft. However, it is somewhat relevant to the case study because it directly concerns desert mule deer.

Light, fixed-wing aircraft were flown over desert mule deer in the Picacho Mountains to determine whether or not the deer shift their home ranges in the presence of survey aircraft (Krausman *et al.* 1986). Seven female and nine male deer were observed from the ground and were also radio-collared. Seventy responses of deer to aircraft (*i.e.*, multiple responses of deer to different overflights) were recorded in 17 days. Interestingly, whether a deer changed habitats was independent of the above-ground height of the aircraft, although this lack of a relationship could have been due to the small number of animals or the large number of variables. Three of 16 radio-collared deer moved to adjacent habitats during one overflight each, out of 70 possible positive responses. If all exposures are considered, the positive response rate is 4%. If only non-habituated deer are included, the positive response rate is 19%. For the purpose of this demonstration, a "threshold" response may be assumed to have a 20% probability of occurrence. Thus, if altitude is related to effects, the No-Observed-Adverse-Effects Level is below a 50-m altitude, and the Lowest-Observed-Adverse-Effects Level (LOAEL) would be expected to be substantially below a 50-m altitude, as none of the flights below 50 m had a behavioral effect on the deer.

Magnitude of Movement Effects

No information is available regarding the distances that mule deer that react to helicopter overflights (sound or distance) move. Limited data on movement distances are available for other ungulates, including mountain goats (*Oreamnos americanus*) (Côté 1996) and mountain sheep (*Ovis canadensis*) (Bleich *et al.* 1994; Bleich *et al.* 1990). Movement distances of barren-ground caribou (*Rangifer tarandus*) in response to military jets are described in Harrington and Veitch (1991) and Maier *et al.* (1998). None of these studies estimate home range shifts, based on movement distances. Because of the difference in these species and habitats from mule deer, movement distances and potential home range changes associated with helicopter overflights are not estimated. To determine a home range shift, an assessor would probably have to utilize species-specific and habitat-relevant data (as in the aforementioned Picacho Mountains study) or perform a site-specific field study.

Factors That Modify Magnitude of Effects

Habituation

Krausman *et al.* (1986) observed that desert mule deer in south-central Arizona seemed to habituate to low-altitude, fixed-wing overflights. Of the three deer that changed habitats during overflights, the two adults only did so during the first overflight (a yearling male moved during the eighth overflight). In a study of heart rate changes in desert mule deer exposed to simulated noise from fixed-wing, jet aircraft overflights, Weisenberger *et al.* (1996) observed that mule deer habituated to the sound with each season of exposure (mid-summer, late summer, and the following spring). Habituation meant fewer alarmed responses and decreased response times with increased exposure. This study did not include the visual stressor (view of the aircraft) that is present in the Apache–Hellfire test.

In Krausman *et al.* (1986), mule deer only infrequently responded to overflights by light, fixed-wing aircraft by changing habitat. The authors speculate that desert mule deer in south-central Arizona have already habituated to low-flying aircraft.

Desert mule deer would be expected to acclimate to daily helicopter overflights during the Apache Longbow–Hellfire missile test (P. R. Krausman, personal communication, May 15, 2001). In the absence of other helicopter overflights, it is unlikely that they would still be habituated to the activity in the three years between similar tests. However, helicopter overflights are associated with numerous test programs in the area. Thus, the time period without helicopters probably determines whether deer would move sufficient distances to change their home ranges during the Apache Longbow–Hellfire missile test. No studies have been undertaken to determine the frequency or duration of exposure that would be required for habituation (P. R. Krausman, personal communication, May 15, 2001). If deer move, they may not return for a period of time, and habituation of those deer would not be relevant (P. R. Krausman, personal communication, May 15, 2001).

Several other ungulate species have been observed to habituate to overflight exposure. Bighorn sheep (Weisenberger *et al.* 1996) and barren-ground caribou of the Delta herd in interior Alaska have habituated to aircraft overflights (Valkenburg and Davis 1985). Horses have habituated to simulated aircraft sound (LeBlanc *et al.* 1991).

Previous activity

The response of ungulates to overflights is dependent on the activity that the animals are engaged in at the time, although data are not available for desert mule deer, specifically. Barren-ground caribou at river crossings were most reactive to overflights, followed by traveling and feeding animals, and followed by resting animals (Calef *et al.* 1976). Woodland caribou ran farther and for longer periods of time if they were initially walking, compared to animals that were resting, standing, or feeding (Harrington and Veitch 1991). Similarly, responses of muskoxen were dependent on the previous activity of the animals (Miller and Gunn 1979). Insufficient information is available to modify exposure–response relationships for mule deer, based on activities at the time of overflight.

Season

Season is also an important determinant of effects of overflights on ungulates. Behavioral responses of female barren-ground caribou to military jets were strongest during postcalving, intermediate during the insect season, and lowest in the late winter (Maier *et al.* 1998). Mountain sheep move greater distances following helicopter disturbances in the spring than in other seasons (Bleich *et al.* 1994). During spring and fall migration periods, barren-ground caribou responses are greater than during calving (Calef *et al.* 1976). These varied responses do not suggest how mule deer might respond to helicopter overflight on a seasonal basis. However, it is reasonable to assume that reproductive behavior would be potentially more sensitive to overflights during critical reproductive periods than during other times.

Habitat

Vegetation type did not affect response of barren-ground caribou (Calef *et al.* 1976) but did determine distances that mountain sheep moved following overflights (Bleich *et al.* 1994). If data on deer movements associated with the test at YPG were available, an assessor could consider whether the habitat (*i.e.*, cover, forage, water availability) to which deer are being chased is equivalent to or worse than that from which they are being chased (see Gerlach *et al.* 1986). Reproductive effects would probably not result if habitat were equivalent and unoccupied, and if substantial energy resources had not been used in movement.

Biological survey

An ideal study of desert mule deer that would support this risk assessment or a larger scale assessment for a training program would be conducted with helicopters (noise and visual stressor) and free-ranging desert mule deer and would examine behavioral effects on all age and sex classes, especially during reproductively sensitive times, and more direct measures of reproduction (*e.g.*, calving success).

RISK CHARACTERIZATION

Expected Behavioral Impact Area, Based on Sound

In a previous empirical study, desert mule deer behavior was impacted by simulations of fixed-wing overflight noise at sound levels somewhere between 92.5 and 112.2 dB, L_{max} (Weisenberger *et al.* 1996), with thresholds estimated to be between 92.5 dB (conservative) and 100 dB (less conservative). Horses were impacted at sound levels of 112.2 SEL (LeBlanc *et al.* 1991). The areas of land and number of deer exposed to these sound levels are presented in Table 3. The core assessment area is 126 km^2, and the approximate number of deer in that area is 70 (Efroymson *et al.* 2008). The range of deer that are expected to be behaviorally impacted range from 0 to all 70 deer in the core assessment area, plus about 190 additional deer in the influence area (up to 263 deer total, Table 3).

Expected Behavioral Impact Area, Based on Distance

As stated previously, the slant distances associated with a 10, 20, and 50% probability of effects on an individual or group of ungulates are 445, 400, and 175 m, respectively. For the longest helicopter trajectory, these slant distances correspond to areas of 8.3, 7.5, and 3.2 km^2, which are associated with 5, 4, and 2 deer, respectively, if distributed uniformly.

These area estimates and deer density estimates are rather uncertain, as the variability in sensitivity among species is uncertain. Also, the areas only approximately correspond to the slant distances, given that the exact locations of altitude shifts (and the altitudes themselves) are unknown.

If an altitude effects threshold is present, the Picacho Mountain LOAEL for behavioral effects on mule deer exposed to overflights by light, fixed-wing aircraft (described earlier) is likely well below 50 m. Only the takeoff and landing occur below 50 m, and slant distances based on these altitudes were ignored in the characterization of exposure because the Apache quickly ascends after taking off (Efroymson *et al.* 2008). The IRCC is essentially a parking lot for helicopters and other vehicles. Therefore, the number of deer that would be exposed to altitude below 50 m would be expected to be negligible. In addition, deer inhabiting nearby areas would be expected to be habituated to the sound from helicopter takeoffs for other tests and training activities.

Potential Change in Heart Rate, Based on Sound

A conservative threshold estimate for changes in heart rates of deer is 92.5 dB, L_{max}. Assuming the same deer are exposed throughout the test, the number of deer that would be expected to be affected in the study area would be 70 (all of the deer), with an additional 193 deer outside of that area (Table 3). At the more reasonable threshold estimate of 100 dB, L_{max}, the estimate is not very different (Table 3). There is less confidence in the threshold heart rate effects value for horses, 112.2 dB SEL. At this threshold, the number of deer affected would be expected to be zero (Table 3).

Table 3. Number of deer and areas exposed to sound levels of potential concern for behavior.

Simulation	Sound level	Reference	Area,[1] km^2	Number of deer
MR_NMAP	92.5 dB, L_{max}	Conservative threshold estimate, Weisenberger *et al.* (1996)	470	263
	100 dB, L_{max}	Reasonable threshold estimate, Weisenberger *et al.* (1996)	460	258
	113.4 dB, L^{2}_{max}	Threshold estimate, LeBlanc *et al.* (1991)	0	0
	112.2 dB, SEL	Threshold estimate, LeBlanc *et al.* (1991)	0	0
NOISEMAP	92.5 dB, SEL	Conservative threshold estimate based on Weisenberger *et al.* (1996); inappropriate noise metric but improved altitude profile over MR_NMAP	10	6
	100 dB, SEL	Reasonable threshold estimate based on Weisenberger *et al.* (1996); inappropriate noise metric but improved altitude profile over MR_NMAP	0.3	0
	112.2 dB, SEL	Threshold estimate, LeBlanc *et al.* (1991)	0	0

[1]Core area and influence area, combined.
[2]Low confidence in MR_NMAP L_{max} (based on response of horses) compared to other L_{max} values (based on response of mule deer).

Acoustic Threshold Shift

No evidence of hearing loss by ungulates due to these overflights or others has been obtained.

Population Issues

To our knowledge, the reduction of reproduction and abundance of ungulates due to aircraft overflights has not been reported. Most of the exposure–response relationships signified by arrows in Figure 4 cannot be quantified with data from YPG, data from other sites, or existing mechanistic models. Factors such as home range for desert mule deer, watering point locations, timing and prevalence of migration, and timing of key reproductive activities were included in the problem formulation to support the development of a mechanistic model of effects, but the development of that model is beyond the scope of this risk assessment.

If we were confident that there were no behavioral effects on mule deer, we could be confident that there would be no population-level effects. Given that the likelihood of movement, the average distance of movement, the direction of movement, the time of displacement, and the habituation period are all unknown, then one cannot quantitatively assess risks to abundance or reproduction unless behavioral effects are estimated to be low or negligible.

The population of mule deer would not be expected to be affected appreciably by short-term changes in heart rate. Herbivores such as mule deer would be expected to have evolved tolerance for frightening stimuli, such as predators that were once present in the area. Similarly, it is unlikely that frightened movements of mule deer would lead to the physiological inhibition of reproduction or death. Therefore, risks to mule deer populations are inferred from overt behaviors rather than from heart rates or other evidence of transient stress.

Weight of Evidence

Multiple defensible methods are available to derive the sound exposure estimates and different behavioral effects thresholds associated with the different exposure metrics. Therefore, risks should be estimated by each method and the relative merits of the results should be weighed.

Several criteria may be used to weigh evidence: (1) data relevance (whether or not the estimated effect is a direct estimate of the assessment endpoint); (2) credibility of exposure–response relationship; (3) relevance of temporal scope of effect; (4) relevance of spatial scope of effect; (5) quality of exposure and effects data; (6) quantity of observations, especially related to variance and biases in sampling; and (7) relevance to a requirement to integrate risks from multiple activities (Suter *et al.* 2000; Suter *et al.* 2002). In addition, the importance of multiple modes of action are considered.

The weight of evidence for risks to mule deer that are associated with Apache overflights is presented in Table 4. The predictions of exposure, and therefore the predictions of behavioral and potential reproductive effects on mule deer, are inconsistent.

Outputs of NOISEMAP (suggesting no behavioral risk) may be slightly more reliable than outputs of MR_NMAP (suggesting some behavioral risk), because

Table 4. Summary of the risk characterization for the desert mule deer population exposed to Apache Longbow helicopter overflight in the 126-km study area in Cibola Range, Yuma Proving Ground.

Evidence	Behavioral Effect Result[1]	Population-level Effect[2] Result	Explanation
Slant-distance/ungulate behavior relationship	–	–	Approximately 4 deer in a 7.48 km^2 area are exposed to a distance from the helicopter that has been associated with behavioral effects in 20% of ungulate groups exposed to helicopter overflights. This quantity represents about 6% of the 70 deer presumed to inhabit the valley between the Chocolate and Middle Mountains.
Altitude/deer behavior relationship	–	–	No deer are expected to be exposed to an altitude of well under 50 m, the possible LOAEL for mule deer exposed to light, fixed-wing aircraft (if there is a relationship between behavior and altitude, which is uncertain).
Sound level/ungulate behavior relationship	+	±	The maximum sound levels at ground level that are predicted by MR NMAP software are higher than the threshold sound level from overflights that is associated with behavioral effects on mule deer. All deer (70) in the 126 km^2 area are exposed, and about 2.7 times as many deer (190) in outlying areas are predicted to be exposed.
	–	–	The sound exposure levels at ground level that are predicted by NOISEMAP software are lower than the minimum threshold sound level from overflights that is associated with behavioral effects on horses. Therefore, no behavioral effects on mule deer are expected.
Weight of evidence	±	–	The weight of evidence suggests that the helicopter overflight component of the Apache Longbow test program may affect behavior of mule deer, but effects on abundance or reproduction of the population are unlikely.

[1]An effect is presumed to be negative if fewer than 20% of the mule deer are affected.
[2]Population-level effects may occur (±) if behavioral effects are significant, but would be predicted to occur (+) only if effects were large scale.

NOISEMAP does not do any altitude-averaging for overflight missions. However, the output of MR-NMAP feeds more reliably into a credible exposure–response relationship for mule deer (L_{max} sound threshold). Distance exposure estimates are highly reliable, and both the slant distance metric (combined with a distribution of response thresholds for ungulates and helicopters) and the altitude metric (combined with a threshold for effects on mule deer) lead to a conclusion of no or low risk to mule deer behavior. The weight-of-evidence result is an uncertain risk to mule deer behavior.

However, the conclusion is that there is no risk to mule deer abundance or reproduction for the following reasons:

1. Most lines of evidence point to no behavioral effects.
2. If a threshold of 103 dB L_{max} instead of 100 dB L_{max} were chosen as the likely LOAEL, the conclusion would be that no deer are behaviorally affected by the sound. 102 dB L_{max} is the highest sound contour produced by MR-NMAP (Figure 2).
3. Critical reproductive time periods for mule deer are May–June (fawning) and November–December (rutting). If behavioral effects were to influence reproduction, they would likely occur in these months. The test did not occur in these months.
4. Most of the effects data are for unhabituated deer. Most deer in the test area would be expected to be habituated to helicopter noise following the first day of the test if not from previous tests involving helicopters.
5. Helicopter movement would not be expected to cause deer to move away from water sources. In fact, deer running from a north-oriented flight might be expected to move toward a tank located northeast of the study area.
6. Frightening a fraction of a population of deer would not be expected to lead to population-level effects, because deer would be expected to have evolved tolerance for moderately frightening stimuli.

An investigation completed by Krausman *et al.* (2004) since this risk assessment was undertaken provides evidence that ungulates might be behaviorally affected by aircraft overflights, but the duration of the behavioral change was not recorded and many flights occurred during training events with multiple activities and stressors present. Sonoran pronghorn (*Antilocapra americana sonoriensis*) exposed to military aircraft flying close to overhead (within 100 m of side of animal) at Barry M. Goldwater Range in Arizona often (41% of the time) changed behavior from bedded to standing, walking to bedded, and foraging to bedded. These were "likely similar to normal changes in pronghorn behavior" (Krausman *et al.* 2004, p. 22). The vast majority of aircraft flew at an altitude above 300 m, significantly higher than altitudes flown in this test program. However, pronghorn did not respond with altered movement (>10 m), compared with those at a reference site (Krausman *et al.* 2004).

Uncertainty and Variability

We concluded during the development of the risk assessment framework for aircraft overflights that: "It is evident from the exposure analysis component of the framework for military overflights that good, quantitative measures and models are available for estimating exposure of endpoint species to sound and other stressors" and that "the accuracy and precision of ecological risk assessments for aircraft overflights will probably not be very limited by the exposure analysis" (Efroymson and Suter 2001, p. 264). In contrast, during this study we have found that the magnitude of the uncertainty associated with estimating noise contours may be as large as that associated with exposure–response thresholds. It is evident from the inconsistent outputs of MR_NMAP and NOISEMAP that noise contours and associated exposure estimates to mule deer are highly uncertain. The lack of consideration of topography, weather, and the flight and noise behavior of helicopters contribute to the uncertainty.

Effects thresholds are estimated based on data that are not completely relevant to the Apache Longbow–Hellfire missile test. That is, behavioral effects thresholds for sound are based on a variety of responses of a variety of ungulates to a variety of helicopter types in a variety of environments. This is a significant source of uncertainty. Moreover, these thresholds are derived from opportunistic studies or studies with captive animals that may be quite different from conditions at YPG or during this test. One study that could not be used to estimate effects of the isolated overflights in the Apache Longbow–Hellfire missile test is the home range tracking of mule deer during a large-scale training activity at Piñon Canyon Maneuver Site in southeastern Colorado (Stephenson *et al.* 1996). The training activity, which was conducted for a 2- to 3-week period for 3 years in August, involved 2624 to 6619 troops per 2- to 3-week exercise, 30 to 50 helicopters on site at one time, and 584 to 2397 vehicles on site at one time (Stephenson *et al.*1996). Battlefield simulations included machine gun fire and cannon fire (without live ammunition). Traffic included jeeps, trucks, armored personnel carriers, tanks, helicopters, and jet fighter overflights.

The extrapolation of behavioral effects (or acoustic damage) to make predictions about population-level effects is also highly uncertain, unless behavioral effects are not observed or predicted, in which case no population-level effect can occur.

RESEARCH GAPS

Several research and development topics related to aircraft overflights and desert mule deer would improve future risk assessments of testing programs at YPG and training and testing programs at other military installations. These recommended topics are based on the uncertainties mentioned earlier.

Clearly, some of the improvements in NOISEMAP and MR_NMAP that are expected in the near future (or that have been added since this study) are needed, such as the consideration of topography, weather, and the flight and noise behavior of helicopters. However, others (such as eliminating the altitude averaging algorithms of MR_NMAP and adding L_{max} to NOISEMAP) are also recommended.

Research is needed to validate or verify results of MR_NMAP and NOISEMAP, particularly at locations below and near the flight tracks. A study using radio-collared deer equipped with acoustic monitors could serve this purpose, as well as providing information about movements of deer in the presence of aircraft overflights. For the Apache Longbow–Hellfire test, additional research on specific responses of desert mule deer to overflights of Apache Longbow would be recommended over the use of limited data on a variety of ungulates and a variety of helicopter models in a variety of environments. More information is needed concerning the effects of aircraft overflights on vertebrate behavior and especially on direct measures of reproduction and abundance.

Research is needed concerning the relative sound frequencies that vertebrates other than humans hear. A-weighted decibels do not necessarily reflect ungulate or mule deer hearing. Similarly, thresholds for hearing damage could be investigated.

Mechanistic models that predict population-level effects from changes in home range, watering point locations, forage locations, timing and prevalence of migration, and timing of key reproductive activities would be useful. Such models could be demographic models or energetic models. These models would be particularly pertinent to integrating effects of multiple military activities, as mechanistic models are recommended for integration where metrics of exposure and effects are disparate (Suter 1999). Studies are also needed that provide data for potential use in validation of these models. The aforementioned Krausman *et al.* (2004) study would be such a study; however, the presence of multiple military activities can detract from accuracy of wildlife exposure–response relationships for aircraft overflights.

ACKNOWLEDGMENTS

This research was funded by a contract from the U.S. Department of Defense Strategic Environmental Research and Development Program (SERDP) project CS-1054, *A Risk Assessment Framework for Natural Resources on Military Training and Testing Lands,* to Oak Ridge National Laboratory, which is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725. We thank Bob Holst and John Hall for serving as project sponsors and Winifred Hodge Rose and Keturah Reinbold of the U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) for serving as project Co-Principal Investigators. We also acknowledge the contributions of the following people for data, guidance, manuals, programming advice, text reviews, activity descriptions, and other assistance: Valerie Morrill, Chuck Botdorf, and Junior Kerns from the Yuma Proving Ground Environmental Sciences Division; Sergio Obregon, David McIntyre, and Bruce Goff from Jason & Associates, Yuma Proving Ground Office; Rick Douglas and Bert Evans from Yuma Proving Ground Aviation and Airdrop Systems; Dick Gebhart and Kim Majerus from CERL; Todd Kuiken, Paul Hanson, and Robert Washington-Allen from Oak Ridge National Laboratory; Bob McKinley from Wright-Patterson Air Force Base; Bob Lester and Nancy Mabie from the U.S. Air Force Center for Environmental Excellence; Kevin Bradley from Wyle Labs; Catherine Stewart from the U.S. Army Center for Health Promotion and Preventive Medicine; Mara Weisenberg from the USFWS San Andres NWR; and Paul R. Krausman from the University of Arizona.

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