# Noise Mapping: Modeling Chronic Natural Gas Compressor Noise across Pennsylvania State Forests in the Marcellus Shale Formation

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## INTRODUCTION

Anthropogenic noise is becoming more common across the terrestrial landscape, including the increase in noise from oil and gas development. Natural gas extraction from unconventional sources, such as shale formations, has become more economically viable due to new drilling techniques and hydraulic fracturing methods (EPA 2012; Kargbo et al. 2010), resulting in growing interest in natural gas extraction across the United States (EPA 2012). The Marcellus Shale formation is one of the most expansive shale basins in the nation, covering 240,000 square kilometers (km$^2$) (60 million acres) and underlying three-quarters of Pennsylvania and portions of the surrounding northeastern states (Kargbo et al. 2010).

Unconventional gas extraction from Pennsylvania’s Marcellus Shale formation began in 2007 with fewer than 100 wells, but rapidly increased to nearly 9,000 by September 2015 (PA DEP 2015). The majority of natural gas extraction occurred on Pennsylvania’s private lands, but in 2008, shale gas development was authorized on Pennsylvania state forest land when the Pennsylvania Department of Conservation and Natural Resources (DCNR) issued a drilling lease on 74,000 acres (DCNR 2013a). Two additional leases were issued, one in January 2010 for 32,000 acres and another in May 2010 for 33,000 acres (DCNR 2013a). These three leases total about nine percent (139,000 acres) of the 1.5 million acres of state forest land underlain by the Marcellus Shale formation. In late 2010, the DCNR halted lease issuance and began an impact analysis evaluating potential environmental effects of additional leases on state forest land, with the report released in 2014 (DCNR 2014a).

Pennsylvania’s state forest lands underlain by the Marcellus Shale formation contain some of the largest contiguous forests in the Eastern United States and are considered by the DCNR to be a “priceless public asset” (DCNR 2007a; DCNR 2013b). These large tracts of interior forest in north central Pennsylvania, otherwise known as ‘core forest’, support the greatest diversity of forest interior bird species in the state (Thomas et al. 2014). Core forest obligate bird species rely on contiguous forest tracts for effective breeding, and have greater nest success in large versus small forest patches (DCNR 2007b). Additionally, these contiguous forests provide opportunities for human outdoor recreation for those seeking solitude and a wilderness experience (DCNR 2014a).

The Shale-Gas Monitoring Report states that core forest fragmentation increased due to shale-gas development activities, resulting in increased edge forest habitat of more than 4,000 acres and a loss of around 9,000 acres of core forest greater than 500 acres (DCNR 2014a). The DCNR concluded that changes due to shale-gas infrastructure will occur primarily in interior forest (DCNR 2014a). This loss of core forest would greatly impact available remote areas for human recreation and affect forest-interior-obligate wildlife species.

DCNR uses an inventory and planning tool—the Recreation Opportunity Spectrum (ROS)—adapted from the U.S. Forest Service (Clark and Stankey 1979), to manage state forest lands. The ROS system classifies forest lands along a continuum, from primitive to developed, representing the degree of the area's wild character and its restricted land use activities (DCNR 2014a). Currently, natural gas development activities are excluded from the state forest's primitive and semi-primitive non-motorized land classes (DCNR 2013b).

Noise level monitoring of the operational compressor stations for the Shale-Gas Monitoring Report indicated that 86 percent (six of the seven monitored) were louder than thresholds recommended under the Guidelines for Administering Oil and Gas Activity on State Forest Lands— exceeding the established decibel level (55 decibel A-weighted [dBA]) at any distance greater than 300 feet from the compressor building (DCNR 2014a). Many of the compressor stations were approved prior to the noise guidelines and are not currently required to comply with these requirements (DCNR 2014a). However, the DNCR anticipates an additional 100 to 200 new compressor stations will be built on state forest lands that would be subject to any new noise guidelines (DCNR 2014b).

The natural gas compressor stations pressurize the extracted gas from surrounding wells and direct it into the distribution pipelines. Each compressor station is usually equipped with one to three motors and several cooling fans, all of which run continuously (Habib et al. 2007). The compressor stations are considered loud, and can emit noise levels between 75-90 dBA (Bolstad Engineering 1978 in Habib et al. 2007), and sometimes reach 105 dBA (MacDonald et al. 1996 in Habib et al. 2007) at close proximity. Exposure to noise above 85 dBA for prolonged periods can cause human hearing loss (NIH 2015).

Gabrielson (2014) conducted a pilot study evaluating gas compressor station noise at one site in the Tiadaghton State Forest, Lycoming County, Pennsylvania (compressor station 289) and recorded its spectral signature. The research objective was to help develop better noise guidelines that will minimize the human impact of gas compressor noise and improve the recreational experience on Pennsylvania's state forest land. Gabrielson (2014) evaluated the noise produced by normal operation from a distance of 300 feet (ft). The findings indicated that the compressor station's spectral signature had strong low frequency tonal noise characteristics, which are far more noticeable and "annoying" to the human ear than broadband noise (which is more similar to "white noise"). Additionally, the spectral signature showed that the lower frequency sound intensity levels (dB) were sustained at greater distances than higher frequencies (Gabrielson 2014), supporting the concept that the low frequency noise (<200Hz) generated by the compressor stations attenuates (degrades) more slowly than higher frequency sounds and can thus travel further distances. Despite Gabrielson's research (2014), it remains unclear how far low frequency noise produced by gas compressor stations can travel. This makes it difficult to calculate the potential areas impacted by compressor noise within Pennsylvania's state forests. Considering the anticipated increase in the number of gas compressor stations on state forest land in the near future (DCNR 2014b), it is critical to model the spatial extent of the existing station noise in relation to remote wilderness areas to aid future siting of new compressor station locations.

There are several noise mapping software programs available, but many are expensive commercial products that are intended for urban planning applications. SPreAD-GIS is the only open-source noise model developed for evaluating environmental effects. SPreAD-GIS is an ArcGIS toolbox add-in created in the Python scripting language. It is based on the System for the Prediction of Acoustic Detectability (SPreAD) developed jointly by the Environmental Protection Agency and the U.S. Forest Service (Harrison et al. 1980, Reed et al. 2012). The original SPreAD model was used to determine potential noise propagation from anthropogenic activities and to aid in forest planning, but was calculated manually (Reed et al. 2012). SPreAD-GIS includes the six modifiers that influence sound propagation from the original SPreAD model: topography, land cover, air temperature, relative humidity, wind speed and direction, and seasonal conditions. However, unlike the original model, SPreAD-GIS automates the calculations and outputs the results in GIS format (Reed et al. 2012).

The goal of this research was to construct acoustic propagation models of the distribution of natural gas compressor station noise across Pennsylvania's state forest land. I used the SPreAD-GIS model to understand potential noise impacts on human recreation areas and how it can inform future compressor station siting locations. To achieve this goal, I addressed the following three research questions:

1. What is the spatial extent of gas compressor noise in the core forests in the Marcellus shale region of north-central Pennsylvania? I will consider specific biotic and abiotic aspects of this region including seasonal conditions, wind gradients, vegetation, terrain profiles and other site-specific characteristics.

2. Would gas-compressor noise propagation modeling modify the interpretation of U.S. Forest Service's Recreational Opportunities Spectrum maps created for Pennsylvania state forest lands? In other words, are current recreation guidelines adequate or will noise propagate into 'pristine' areas, requiring revised maps or noise limiting infrastructure.

3. What topographic features of the landscape minimize compressor station noise propagation and could aid in future station siting?

## METHODS

### *Data Acquisition*

Geospatial data was collected from a variety of sources (Table 1). The compressor station locations were available through the Pennsylvania Spatial Data Access (PASDA) Geospatial Data Clearinghouse (PASDA 2013) and the DCNR Interactive Map (DCNR 2016). There were 14 compressor stations from these data sources that met the three criteria for analysis: 1) located within the State Forest Lands boundary, 2) within the Marcellus Shale basin, and 3) contains a constructed facility (verified by visual inspection using 2015 National Agriculture Imagery Program [NAIP] imagery). The compressor stations of interest are located within seven north-central Pennsylvania counties and seven state forests (Table 2, Figures 1 and 2). All data and models were processed using ArcGIS Desktop Software v.10.3.0 (ESRI 2014).

*Table 1. Project data layer, source, type and details.*

| Data Layer | Source | Data Type |
|---|---|---|
| Digital Elevation Model | PASDA (US Geological Survey County Mosaics) | Raster 30m |
| Land Cover | National Land Cover Dataset (2011) | Raster 30m |
| Compressor Stations | PASDA and DCNR Map Viewer | Point |
| Compressor Station Extent | Created (20km) | Polygon |
| State Forest Lands | PASDA (2015) | Polygon |
| Recreation Opportunity Spectrum | PASDA (2012) | Polygon |
| Marcellus Shale | US Geological Survey (Energy Data Finder) | Polygon |
| County Lines | PASDA (2016) | Polygon |
| NAIP | PASDA (2015) | Raster 1m |

*Table 2. Compressor stations meeting criteria for analysis.*

| Compressor Station | Name (if known) | County | State Forest |
|---|---|---|---|
| CS001 | Clermont West Compressor | McKean | Elk |
| CS002 | Unknown | Elk | Elk |
| CS100B | Bodine Mountain Compressor | Lycoming | Loyalsock |
| CS100H | Hagerman Compressor | Lycoming | Loyalsock |
| CS285 | Unknown | Clinton | Sproul |
| CS289 | Unknown | Lycoming | Tiadaghton |
| CS293 | Unknown | Lycoming | Tiadaghton |
| CS324 | ECA Compressor | Clearfield | Moshannon |
| CS587 | State Lands Corp | Tioga | Tioga |
| CS595 | Unknown | Tioga | Tioga |
| CS685 | Unknown | Lycoming | Tiadaghton |
| CS729 | Unknown | Lycoming | Tiadaghton |
| CS839 | Pad H | Tioga | Tioga |
| CS997 | PGE Pine Hill Compressor | Potter | Susquehannock |

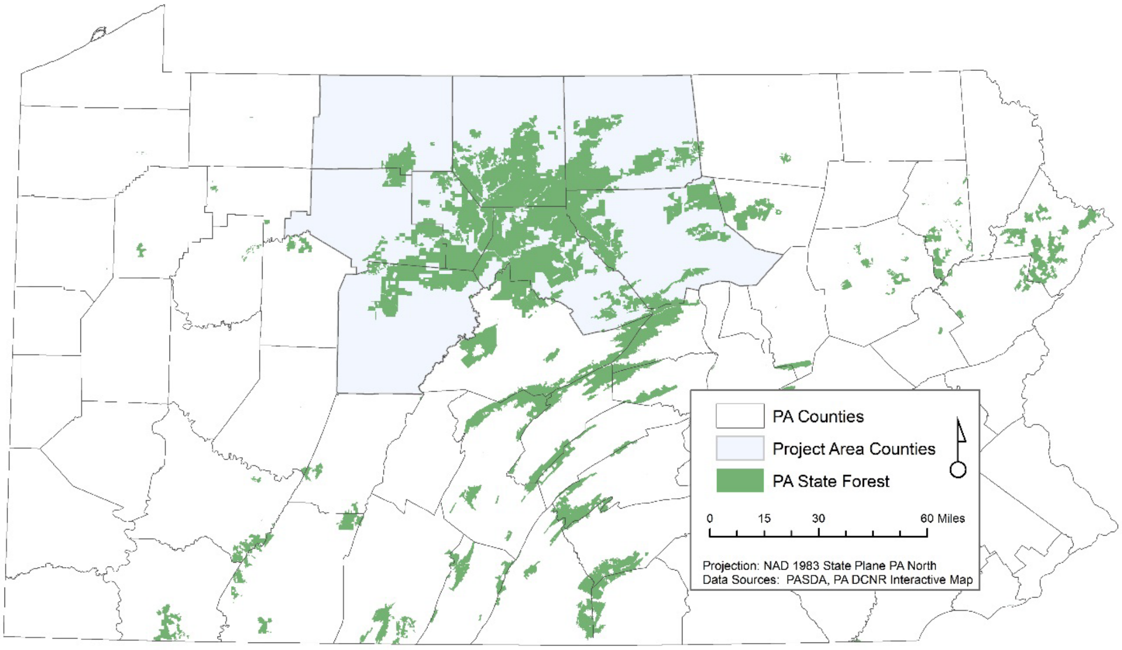


*Figure 1. Distribution of PA state forest lands and the project area (counties in blue).*

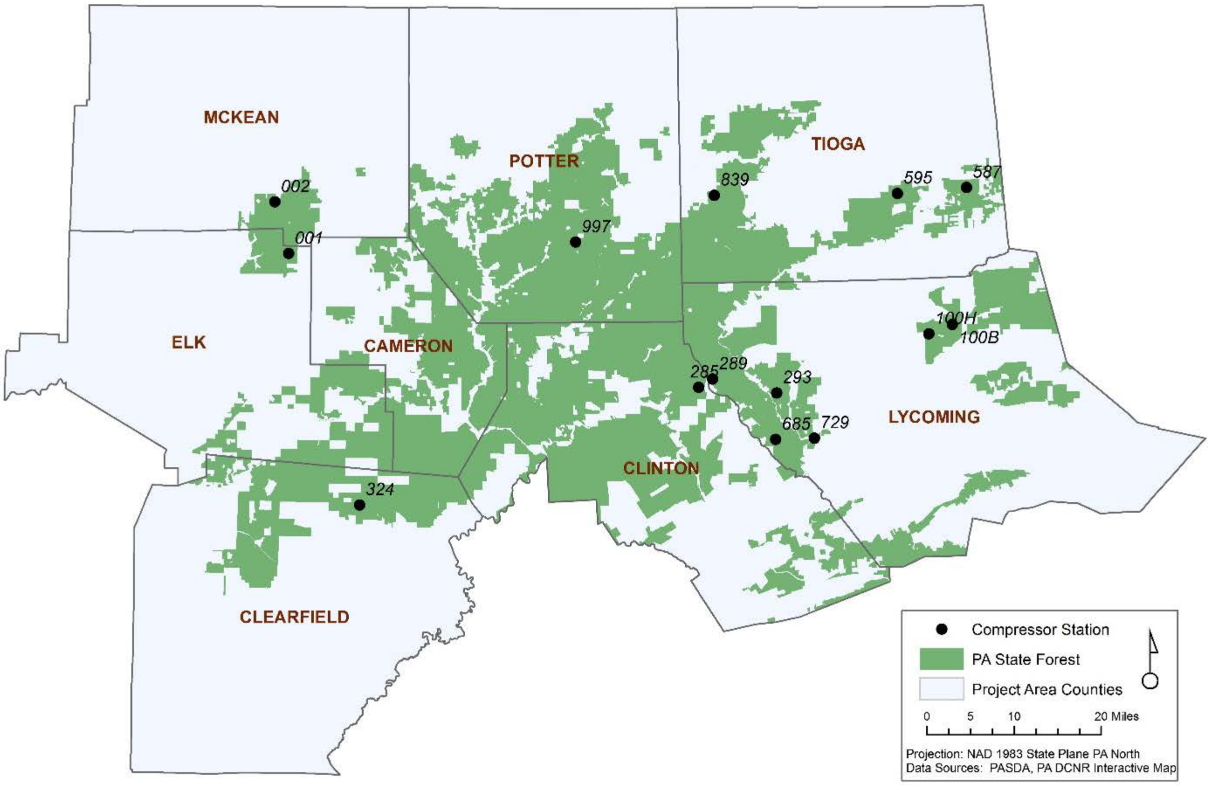


*Figure 2. Distribution of compressor stations and state forest land in north-central Pennsylvania.*

### *Data Preparation*

Spatial datasets were formatted to meet the specifications of the SPreAD-GIS model. A model extent with a 20 kilometer (km) radius was created for each compressor station (source point). The elevation dataset (Digital Elevation Model, DEM) and land cover dataset (National Land Cover Dataset, NLCD) were set to a resolution (cell size) of 30.48 meters (100 feet) and clipped to the model extent for each compressor station analyzed. The land cover dataset was reclassified into seven cover types (from 15 types) to meet the requirements for the SPreAD-GIS model (Table 3).

*Table 3. List of NLCD land cover classification values and descriptions within the analysis area and the reclassification categories for the SPreAD-GIS model.*

| NLCD Value | NLCD Class Description | SPreAD-GIS Model Classification |
|---|---|---|
| 11 | Open Water | Water |
| 21 | Developed, Open Space | Herbaceous or grassland |
| 22 | Developed, Low Intensity | Urban or developed |
| 23 | Developed, Medium Intensity | Urban or developed |
| 24 | Developed High Intensity | Urban or developed |
| 31 | Barren Land (Rock/Sand/Clay) | Barren land |
| 41 | Deciduous Forest | Hardwood or deciduous |
| 42 | Evergreen Forest | Coniferous forest |
| 43 | Mixed Forest | Hardwood or deciduous |
| 52 | Shrub/Scrub | Shrub |
| 71 | Grassland/Herbaceous | Herbaceous or grassland |
| 81 | Pasture/Hay | Herbaceous or grassland |
| 82 | Cultivated Crops | Herbaceous or grassland |
| 90 | Woody Wetlands | Water |
| 95 | Emergent Herbaceous Wetlands | Water |

### *SPreAD-GIS Model*

The SPreAD-GIS model toolbox consists of five individual tools:

Tool 1: Create Ambient Sound Conditions Dataset
Tool 2: Calculate Noise Propagation for One Point
Tool 3: Calculate Noise Propagation for Multiple Points
Tool 4: Sum Noise Propagation for Multiple Points
Tool 5: Calculate Noise Propagation for Multiple Frequencies

The compressor station noise analysis for this study required the use of the first two tools (ambient noise dataset and noise propagation for one point, respectively). The other tools run the same analyses but for multiple points or frequencies simultaneously, and were not necessary for the study.

The first tool (ambient noise tool) creates an ambient noise dataset for each compressor station location for a user-defined frequency (in 1/3 octave bands, 125Hz – 2000Hz). The second tool (noise propagation tool) uses the ambient noise layer created by the ambient noise tool, in combination with other inputs, to calculate the spatial extent of the noise from the source point. There are two output rasters from the noise propagation tool, which include a full propagation noise model that does not include the ambient dataset, and a second output, an exceedance model that subtracts the ambient noise dataset from the full propagation model. Both output rasters were used in the study.

*Ambient Noise Tool*

The ambient noise tool requires the following inputs to run: a user-selected frequency, reclassified land cover classification dataset, and ambient sound level values for each land cover type (Figure 3).

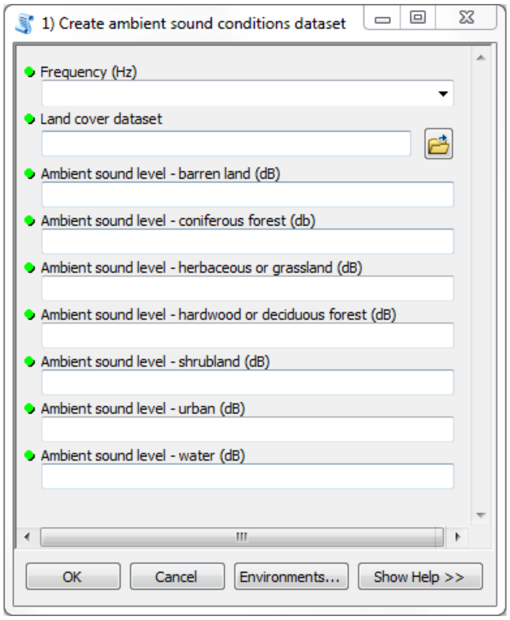


*Figure 3. SPreAD-GIS model input Graphical User Interface for Tool 1 (ambient noise tool).*

The ambient noise tool requires ambient noise values (in decibels) for each of the seven land cover types at each 1/3 octave band frequency, because ambient noise differs by land cover class and by frequency; for example, a barren land cover class has a different background noise level than a hardwood forest, and the difference among these land classes also differs across frequencies. The SPreAD-GIS guidance (Reed et al. 2012) recommends using a chart of values adapted from Harrison et al. (1980) for each land cover type. However, the chart only includes background decibel levels from 400Hz to 2000Hz and does not provide recommendations below 400Hz (i.e., 125, 200, 250, and 315Hz) (Reed et al. 2012). Therefore, the lower frequencies were interpolated using values from the recommended chart for winter (i.e., snow) and spring weather conditions (i.e., no snow) using trendline equations for each land cover type (Table 4, Figure 4). Linear regression $R^2$ values ranged from 0.96 - 0.99 across the land cover types, supporting the use of a linear equation for interpolation.

*Table 4. Ambient sound levels by frequency and land cover type for spring and winter season conditions. Values ≥ 400Hz are sourced directly from the chart provided in Reed et al. 2012, the values 125-315Hz were interpolated using Figure 4.*

| Season | Spectrum Level (Hz) | Land cover type | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Conifer CON | Hardwood HWD | Herbaceous HEB | Shrub SHB | Barren BAR | Urban URB | Water WAT |
| Spring | 125 | 33 | 25 | 26 | 29 | 26 | 44 | 26 |
| | 160 | 32 | 24 | 25 | 28 | 24 | 42 | 24 |
| | 200 | 30 | 23 | 25 | 27 | 22 | 40 | 22 |
| | 250 | 29 | 22 | 24 | 26 | 20 | 38 | 20 |
| | 315 | 27 | 22 | 23 | 26 | 18 | 37 | 18 |
| | 400 | 26 | 21 | 23 | 25 | 16 | 35 | 16 |
| | 500 | 24 | 20 | 22 | 24 | 14 | 33 | 14 |
| | 630 | 22 | 20 | 21 | 23 | 12 | 31 | 12 |
| | 800 | 21 | 19 | 21 | 23 | 10 | 30 | 10 |
| | 1000 | 19 | 18 | 20 | 22 | 8 | 28 | 8 |
| | 1250 | 18 | 17 | 20 | 21 | 6 | 26 | 6 |
| | 1600 | 16 | 17 | 19 | 20 | 4 | 24 | 4 |
| | 2000 | 15 | 16 | 18 | 20 | 2 | 23 | 2 |
| Winter | 125 | 19 | 20 | 25 | 26 | 21 | 36 | 21 |
| | 160 | 18 | 19 | 24 | 25 | 19 | 35 | 19 |
| | 200 | 18 | 19 | 23 | 25 | 17 | 33 | 17 |
| | 250 | 17 | 18 | 22 | 24 | 15 | 32 | 15 |
| | 315 | 16 | 17 | 22 | 23 | 14 | 31 | 14 |
| | 400 | 15 | 17 | 21 | 23 | 12 | 30 | 12 |
| | 500 | 14 | 16 | 20 | 22 | 10 | 28 | 10 |
| | 630 | 13 | 15 | 20 | 21 | 8 | 27 | 8 |
| | 800 | 12 | 15 | 19 | 21 | 6 | 26 | 6 |
| | 1000 | 11 | 14 | 18 | 20 | 4 | 24 | 4 |
| | 1250 | 10 | 14 | 17 | 20 | 2 | 23 | 2 |
| | 1600 | 9 | 13 | 17 | 19 | 0 | 22 | 0 |
| | 2000 | 9 | 12 | 16 | 18 | 0 | 21 | 0 |

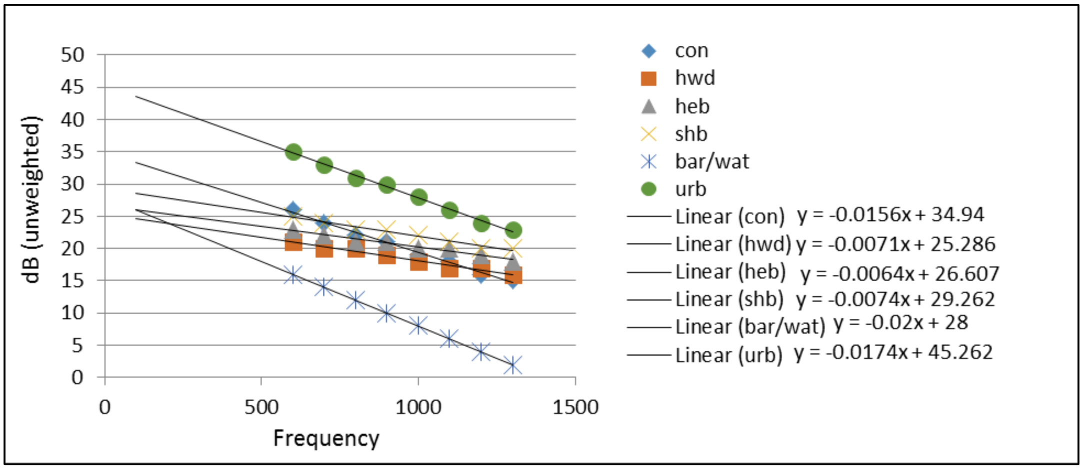
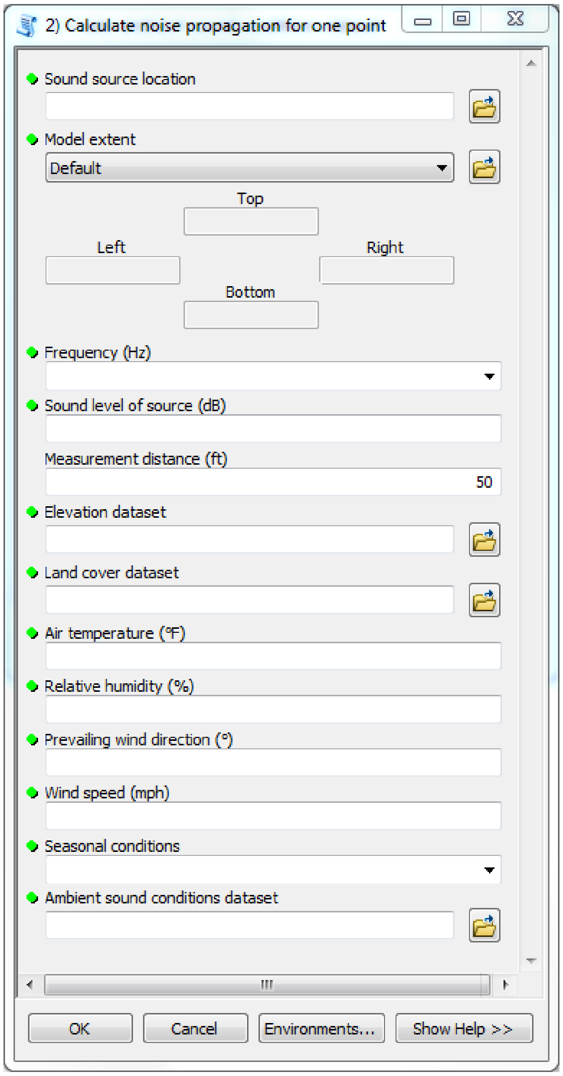


*Figure 4. Ambient sound levels by land cover type and frequency. The 13 frequencies were assigned values in increments of 100 (i.e., 100-1300) to ensure equal spread of values on x-axis and minimize bias from greater spread among higher frequencies. Equations for trendlines were used to interpolate values for frequencies less than 400Hz.*

The outputs from this tool are 13 raster datasets representing the land cover class ambient noise values for each of the 13 1/3-octave frequency bands (125-2000Hz) at each compressor station evaluated. These outputs serve as inputs for the noise propagation tool at each given frequency and station location.

### *Noise Propagation Tool*

Similar to the ambient noise tool, the noise propagation tool requires a user-selected frequency and a reclassified land cover dataset, but also includes 10 additional inputs. These additional inputs include: the site location, model extent (area evaluated around the source point), sound level (decibel value) at a specific distance, elevation dataset, air temperature, relative humidity, wind speed and direction, seasonal conditions setting, and the ambient noise dataset output from the ambient noise tool (for the given frequency being evaluated) (Figure 5).


2) Calculate noise propagation for one point

Sound source location

Model extent: Default

Top

Left

Right

Bottom

Frequency (Hz)

Sound level of source (dB)

Measurement distance (ft): 50

Elevation dataset

Land cover dataset

Air temperature (°F)

Relative humidity (%)

Prevailing wind direction (°)

Wind speed (mph)

Seasonal conditions

Ambient sound conditions dataset

Figure 5. SPreAD-GIS model input Graphical User Interface for Tool 2 (noise propagation tool).

The 14 compressor site locations and their associated extents (20 km area around each site) were uniquely named and used as model inputs for each model run (by frequency and site). The sound levels (decibel value) at a specified distance from the compressor station were also included as model inputs.

Empirical measurements for compressor station (CS) 289 were collected in 2014 and made available for this study by Gabrielson (2014) (Table 5). The empirical data represented the frequency (in 1/3 octave bands) and the unweighted decibel level. These data were only available for CS 289, but were used as inputs for the model runs for other CS locations, since no other empirical data were available for those sites. The SPreAD-GIS model guidelines provide recommended decibel level inputs, but the empirical data are believed to be a better representation of the CS noise output across all stations than the generic values given by Reed et al. (2012). However, it is noted that the decibel levels could be higher or lower than the empirical data at other sites. Therefore, the model results are analyzed for CS 289 first, followed by other stations. The empirical data were collected at 300ft from the site, and this measure (300 ft) is used as the input for the "measurement distance" required in the tool.

*Table 5. The empirical decibel values (unweighted) and associated SPreAD-GIS model frequencies at 300ft.*

| Frequency (Hz) | dB (unweighted) at 300 ft |
|---|---|
| 125 | 47.8 |
| 160 | 52.0 |
| 200 | 42.7 |
| 250 | 46.8 |
| 315 | 48.2 |
| 400 | 45.5 |
| 500 | 43.9 |
| 630 | 41.2 |
| 800 | 43.0 |
| 1000 | 40.5 |
| 1250 | 38.2 |
| 1600 | 38.6 |
| 2000 | 36.6 |

The elevation and land cover datasets discussed in the *Data Preparation* Section were used as the next model inputs for the tool, followed by wind speed and wind direction, air temperature, and relative humidity.

A wind direction of 270° was used as a model input due to prevailing westerly winds common across the state of Pennsylvania (PA Climatologist, n.d.). Wind speed was set to two miles per hour (mph) to represent calm winds within the model extent. The 14 compressor stations are located across four climate regions in Pennsylvania (PA Climatologist, n.d.), so the average temperatures for winter and spring across all four regions were used as model inputs—25° and 50°F, respectively (PA Climatologist, n.d.). The average relative humidity for the same months were 60 and 50 percent, respectively for Williamsport, PA, the recording location nearest the project area (Horstmeyer 2008). However, for ease of comparison among model runs, 60 percent relative humidity was used for all sites and seasonal conditions.

Lastly, the SPreAD-GIS model provides 10 preconfigured seasonal condition selection options, and include permutations of the weather (clear, calm and clear, windy), season (summer and winter), and time of day (day and night), with two additional generic conditions, “cloudy, calm” and “cloudy, windy.” The differences among each seasonal condition are the Φ (phi) value, or angle of the sound trajectory; with $\Phi = 180$ for all conditions except for clear, calm summer night, any clear, windy condition, and the generic conditions, which have values less than 180.

### *Model Analysis*

#### *Seasonal and Day-Night Differences*

CS 289 in the Tiadaghton State Forest (Lycoming County) was the focus of the SPreAD-GIS noise propagation model analysis since empirical data was available for the station location (Gabrielson 2014). The spatial extent of the noise propagation model for CS 289 was measured under two daily (day and night) and two seasonal (spring and winter) conditions using the air temperature values of 25° and 50°F for winter and spring, respectively. The seasonal conditions were set to “clear, calm” for both seasons and time of day (day and night).

The full propagation model output areas were converted to an integer from a floating point decimal (*Int* tool), values less than one excluded from the model (*Set Null* tool), and model area measured using *Zonal Statistics to Table* tool. The resulting calculation was converted from pixel count to hectares (pixel size 30.48m x 30.48m * 0.0001 square meter to hectare ratio).

#### *Noise Propagation Area and Distance*

Based on the maximal noise propagation area of the spring-night condition for CS 289, these conditions were used for further analysis for the station. The maximal distance extent of the model for each frequency was measured in km from the compressor station point using the *Measure* toolbar feature. Linear and exponential regression lines were fit to the area and distance measurements graphs across frequencies to evaluate the relationships of area and distance to increasing frequency. Additionally, the spectral signature of the sound recording for CS 289 was used to compare the spikes and dips in propagation for selected frequencies to the peaks and troughs in the sound recording.

#### *Compressor Station Comparisons at 160Hz*

The propagation areas and distances for the remaining 13 compressor stations were evaluated at 160Hz under spring-night condition. The relationship between propagation area and distance across the sites was evaluated using visual analysis and point distribution in a scatterplot and box-and-whisker plot. The distance and area calculations for each model run followed the same methodology described above.

#### *Empirical Data Comparison*

The SPreAD-GIS model created two final raster outputs for each site at each frequency; the full noise propagation model and the noise exceedance model. The first output represents the distance and area of the noise spread across the landscape by factoring in elevation, land cover and weather conditions. The second output is the full noise propagation model minus the ambient noise condition dataset, which displays areas with source noise that exceed background sound levels. The empirical data used to calibrate the model recorded the noise levels at 300ft from CS 289 in 1/3 octave band frequencies for all noise at the recording location. It is assumed that the dB values include ambient noise and any additive or sound masking effects for each frequency. However, to ensure that the full noise propagation model is an appropriate output to use in the analyses, the dB value for both modeled full propagation and exceedance outputs were measured at the recording location, using the *Extract Multi Values to Points* tool.

### *Recreation Opportunity Spectrum*

The DCNR uses a GIS tool to classify their state forest lands into the ROS land-use classes using two metrics—degree of remoteness and size (DCNR 2014a). There are four main categories (in decreasing remoteness): primitive, semi-primitive non-motorized, semi-primitive, and developed. The primitive category requires that the area be greater than one mile from a motorized road, trail or railroad, and larger than 1,000 acres. Semi-primitive non-motorized category areas are greater than ½ mile from a motorized road, trail or railroad and 500 acres or larger in size. Semi-primitive classified lands must be greater than ¼ mile from a motorized road, trail or railroad and greater than 250 acres. There are no requirements for the developed land classification.

Although not explicitly stated, the remoteness metric is supposed to account for the noise associated with roads, trails and railroads, and concludes that one mile is a sufficient distance from a linear noise source to maintain a primitive area and its “wild character”. Currently, the ROS for state forest lands excludes natural gas development in primitive and semi-primitive non-motorized land classes (DCNR 2013b), but it is possible that gas compressor stations built within the approved semi-primitive and developed lands produce noise that could travel further than one mile, which could reach primitive areas. Additionally, the compressor noise could also reach regions classified as unique areas on the state forest land, such as state designated Natural Areas and Wild Areas.

To evaluate the potential for gas compressor noise reaching state forest lands classified as primitive, or a Natural Area or Wild Area, the SPreAD-GIS model for each compressor station was visually evaluated for overlap and the total overlapping area calculated, following the methodology previously discussed.

### *Topographical Effects*

A hypothetical point with very different topography near CS 289 was used to better visualize how topography affects sound propagation. The point was located in a river basin at an elevation approximately 800ft less than the surrounding area. This visual analysis helped to compare the maximum distance noise can travel across a natural barrier compared to CS 289 which was situated at higher elevation with fewer barriers in the form of higher elevation ridges. Additionally, the 3-Dimensional viewing capabilities of ArcScene were used to visually analyze the noise propagation models across the topography for the two sites with the greatest propagation area, CS 587 and CS 595.

# RESULTS

### *Seasonal and Day-Night Differences*

The spatial extent of the noise propagation model for CS 289 was measured under two daily (day and night) and two seasonal (spring and winter) conditions (Table 6, Figure 6). Winter conditions for both day and night had the same noise propagation area when temperature and humidity values are equivalent (only daily condition differed). Spring-night conditions for CS 289 resulted in a greater spatial distribution and noise propagation area when compared to the other conditions for the same site across all frequencies. Spring-night, on average, had a 31 percent greater propagation area than the winter conditions evaluated (Range: 3 – 72 percent) and a 19 percent greater propagation area than spring-day (Range: 14 – 25 percent) when measured across frequencies (Table 6). The increase in the spatial extent of spring-night over spring-day increased from 125Hz to 800Hz, where it peaked and then declined at higher frequencies, whereas the spring-night noise extent continued to increase above 250Hz over winter propagation. Interestingly, winter conditions had a greater noise propagation area, compared to spring-day, in the lower frequencies (from 125 – 400Hz), but the trend reversed at higher frequencies, where spring-day exhibited increased spatial extent. Based upon these findings the spring-night conditions were used to represent maximal noise propagation for subsequent models.

| Frequency (Hz) | spring PM: spring AM | spring AM: winter | spring PM: winter |
|---|---|---|---|
| 125 | 14% | -3% | 11% |
| 160 | 14% | -3% | 11% |
| 200 | 17% | -6% | 12% |
| 250 | 18% | -18% | 3% |
| 315 | 19% | -10% | 11% |
| 400 | 22% | -2% | 20% |
| 500 | 24% | 3% | 26% |
| 630 | 22% | 14% | 33% |
| 800 | 25% | 26% | 44% |
| 1000 | 24% | 29% | 46% |
| 1250 | 21% | 31% | 45% |
| 1600 | 17% | 54% | 62% |
| 2000 | 16% | 67% | 72% |

*Table 6. The difference among the temporal and seasonal conditions in total propagation area for each frequency (e.g., Spring PM has a 14% greater propagation area than Spring AM at 125Hz).*

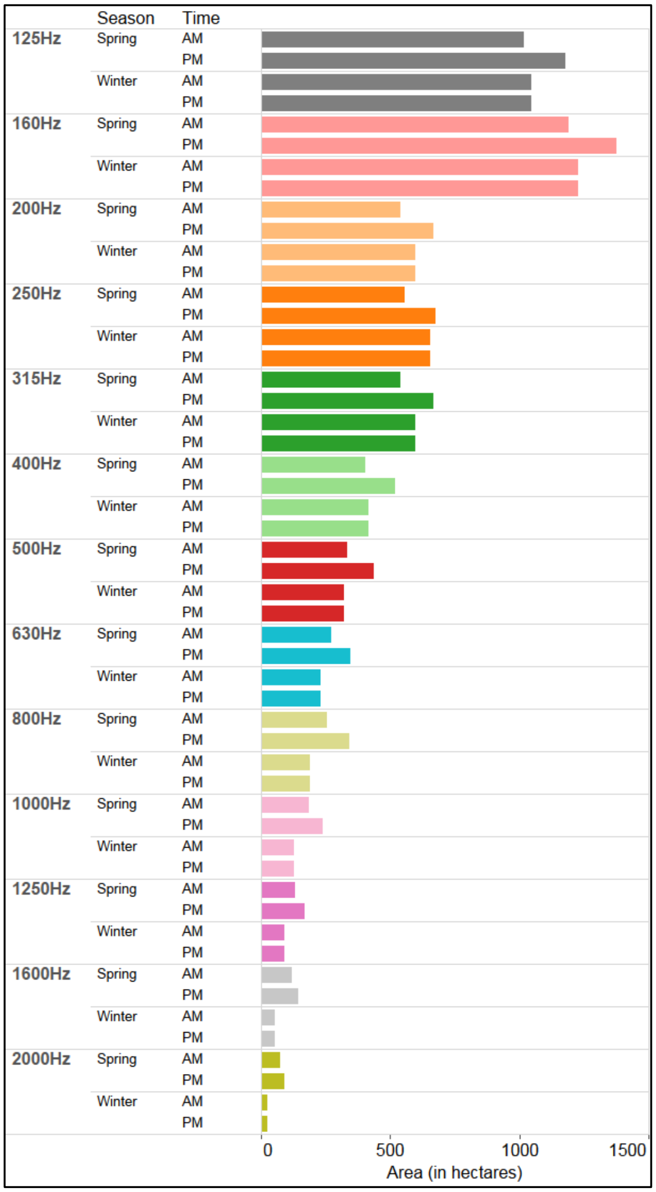


*Figure 6. Differences in propagation area for daily (AM and PM) and seasonal (spring and winter) conditions across all frequencies.*

### *Noise Propagation Area and Distance*

The noise propagation models for 1/3 octave band frequencies 125 – 2000Hz for CS 289 showed a maximum propagation area of 1,421 hectares (around 3,500 acres) at 160Hz and minimum area of 92 hectares (around 230 acres) at 2000Hz when run under a spring-night scenario (see *Seasonal and Day-Night Differences* Section for scenario differences) (Table 7, Figure 7). The minimum and maximum extent of the noise propagation distance was 1.3km (at 2000Hz) and 11.2km (at both 125 and 160Hz) (Table 7). The noise propagation area was inversely related to frequency (exponential regression, $R^2 = 0.92$; linear regression, $R^2 = 0.82$) (Figure 7A), mirroring the pattern seen in the noise propagation distance (exponential regression, $R^2 = 0.96$; linear regression, $R^2 = 0.94$) (Figure 7B) and decibel levels collected empirically (linear regression, $R^2 = 0.78$; Table 5). The spatial extent differences of the noise propagation areas across frequencies can be seen in Figure 8.

*Table 7. Noise propagation area for CS 289 under spring-night conditions (unweighted) for each SPreAD-GIS model frequency.*

| Frequency (Hz) | Propagation Area (Hectares) | Propagation Distance (Km) |
|---|---|---|
| 125 | 1,215 | 11.2 |
| 160 | 1,421 | 11.2 |
| 200 | 584 | 6.9 |
| 250 | 698 | 8.2 |
| 315 | 691 | 7.9 |
| 400 | 536 | 6.1 |
| 500 | 449 | 5.1 |
| 630 | 357 | 3.9 |
| 800 | 352 | 3.8 |
| 1000 | 248 | 2.8 |
| 1250 | 173 | 2.1 |
| 1600 | 148 | 1.7 |
| 2000 | 92 | 1.3 |

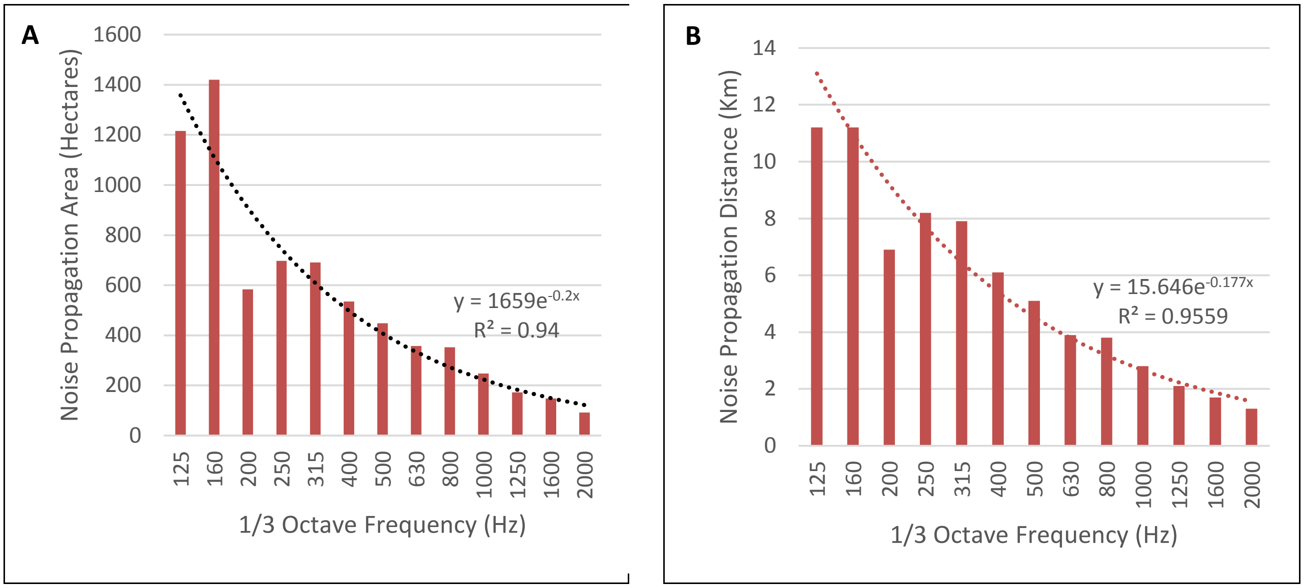
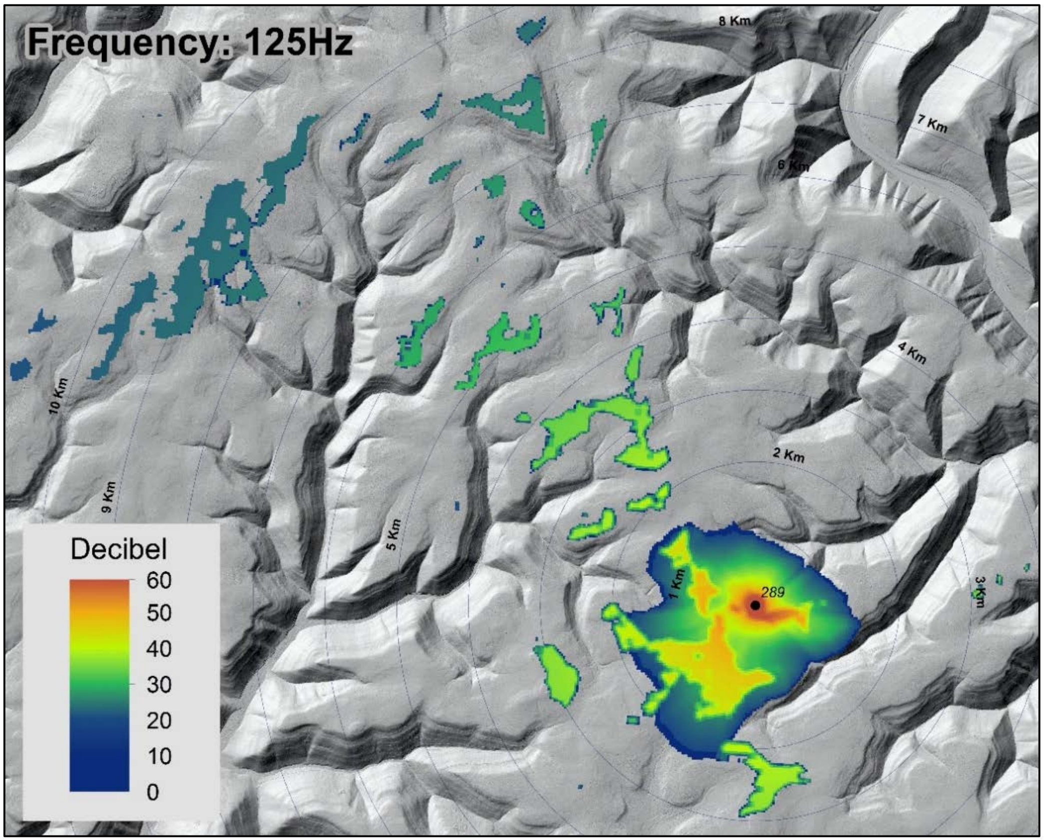


*Figure 7. Noise propagation area(left) and distance (right) for CS 289 under spring-night conditions for each SPreAD-GIS model frequency, fitted with regression lines.*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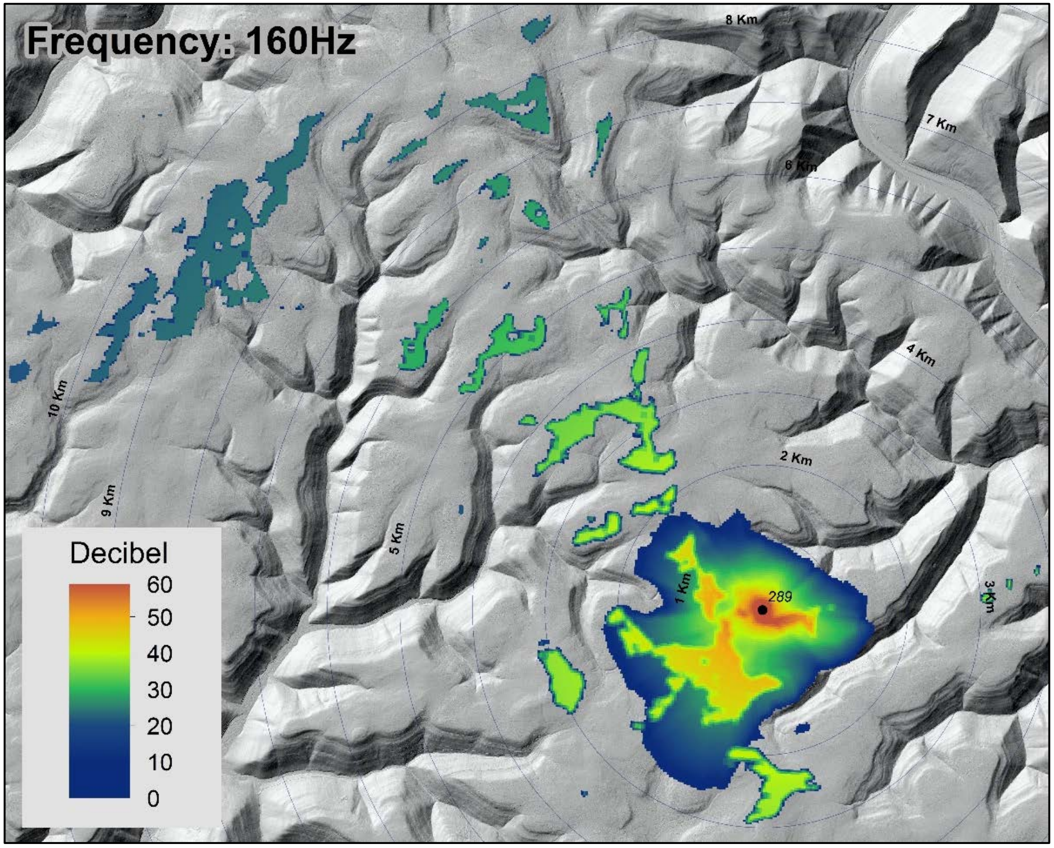
7 Km
6 Km
4 Km
2 Km
3 Km
1 Km
5 Km
9 Km
10 Km
289
Decibel
60
50
40
30
20
10
0


Frequency: 160Hz
8 Km
7 Km
6 Km
4 Km
2 Km
3 Km
1 Km
5 Km
9 Km
10 Km
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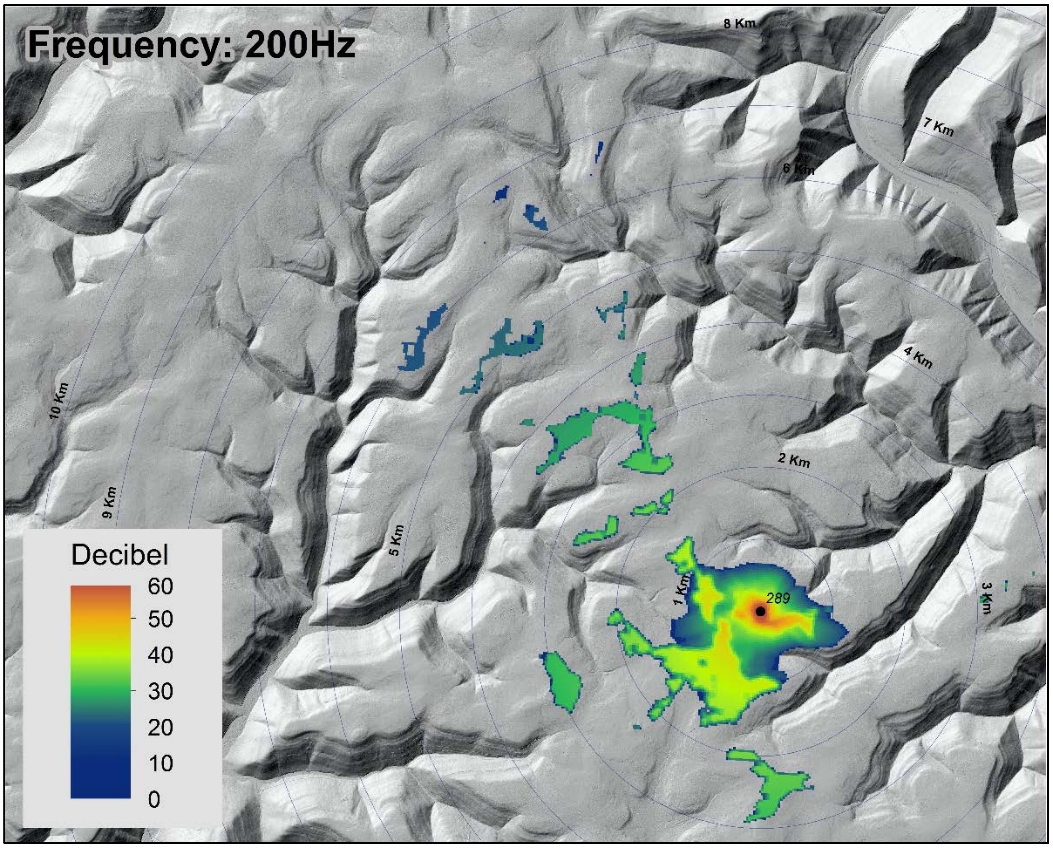
Decibel
60
50
40
30
20
10
0


Frequency: 200Hz
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4 Km
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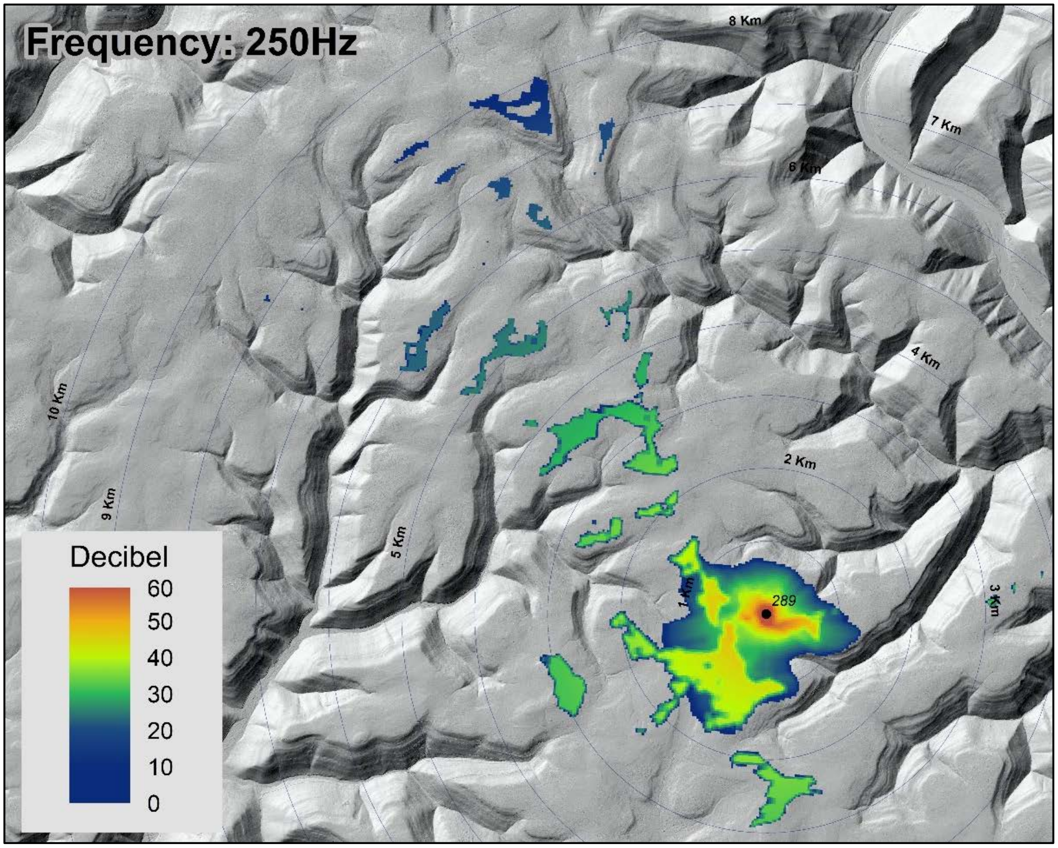
9 Km
5 Km
1 Km
3 Km
289
Decibel
60
50
40
30
20
10
0


Frequency: 250Hz
8 Km
7 Km
6 Km
4 Km
2 Km
10 Km
9 Km
5 Km
1 Km
3 Km
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Decibel
60
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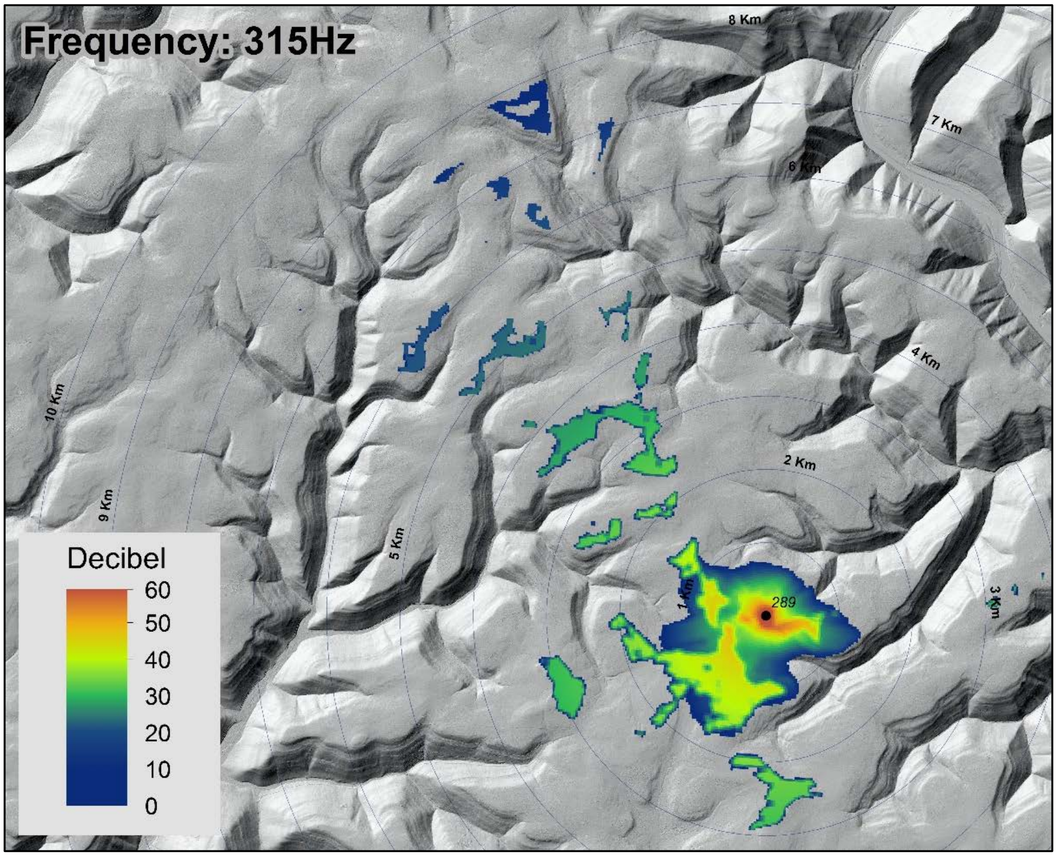
40
30
20
10
0


Frequency: 315Hz
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7 Km
6 Km
4 Km
2 Km
1 Km
289
3 Km
5 Km
9 Km
10 Km
Decibel
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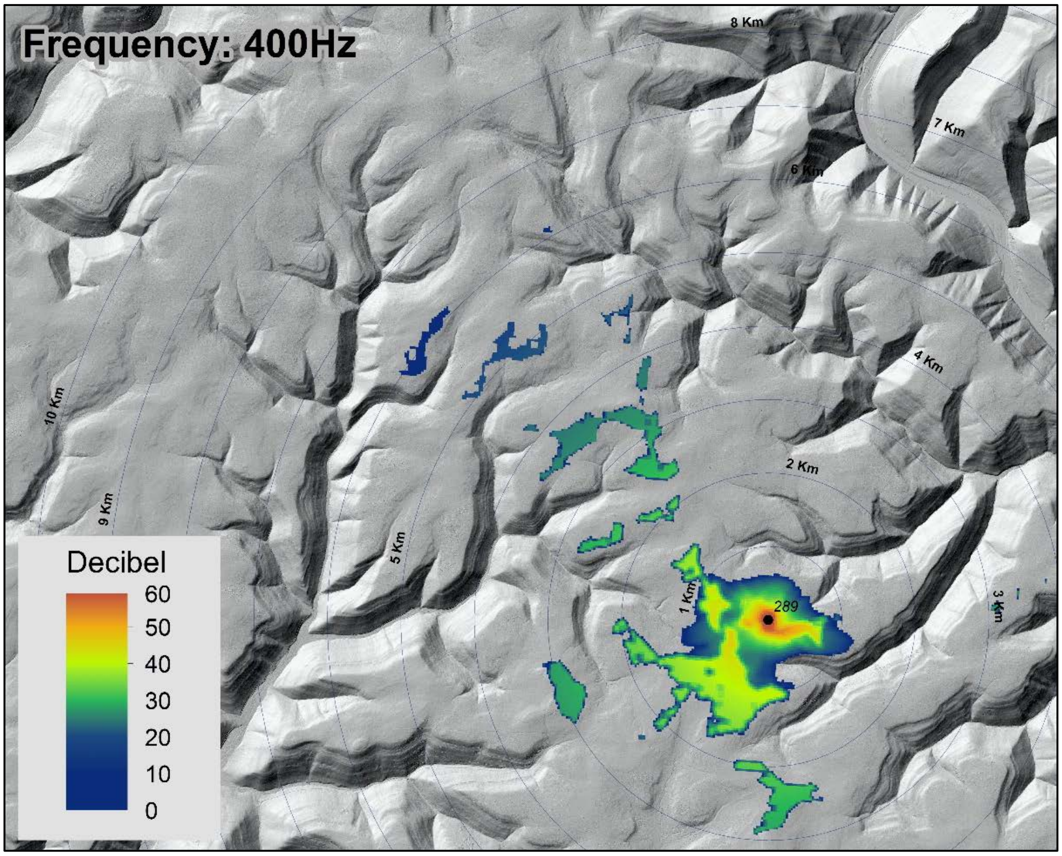
50
40
30
20
10
0


Frequency: 400Hz
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7 Km
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1 Km
289
3 Km
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Decibel
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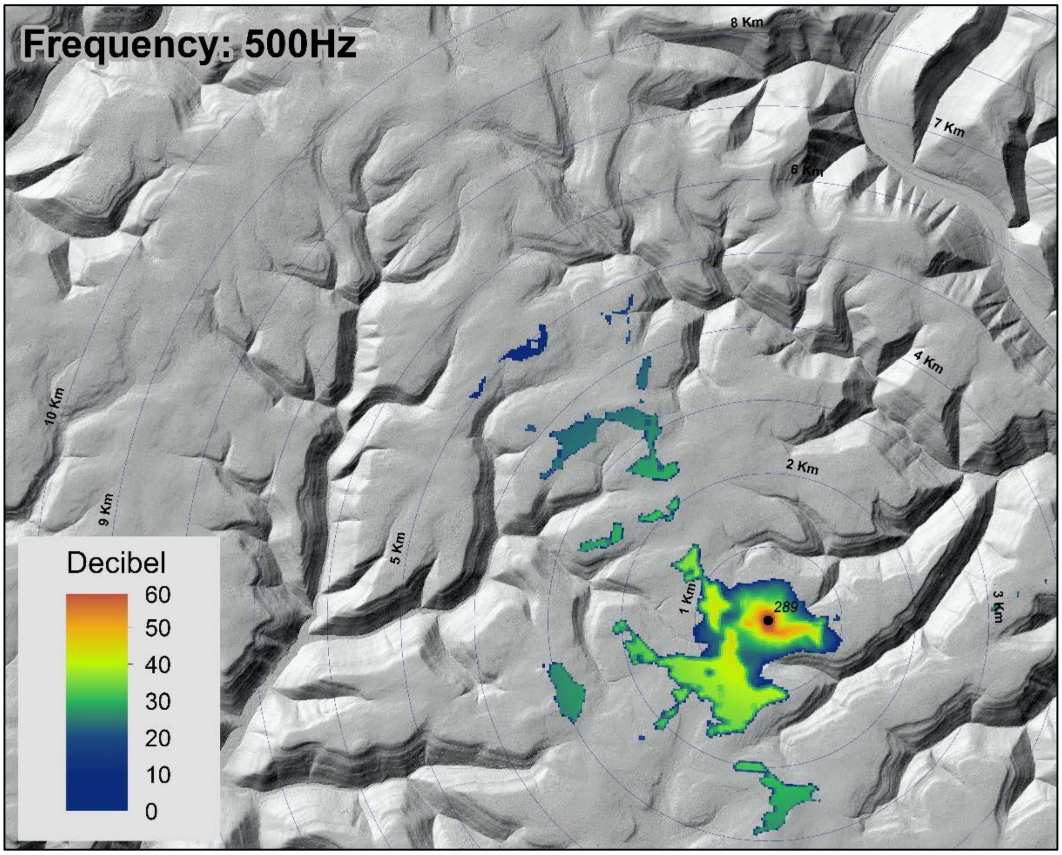
50
40
30
20
10
0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6 Km
4 Km
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1 Km
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5 Km
9 Km
10 Km
289
Decibel
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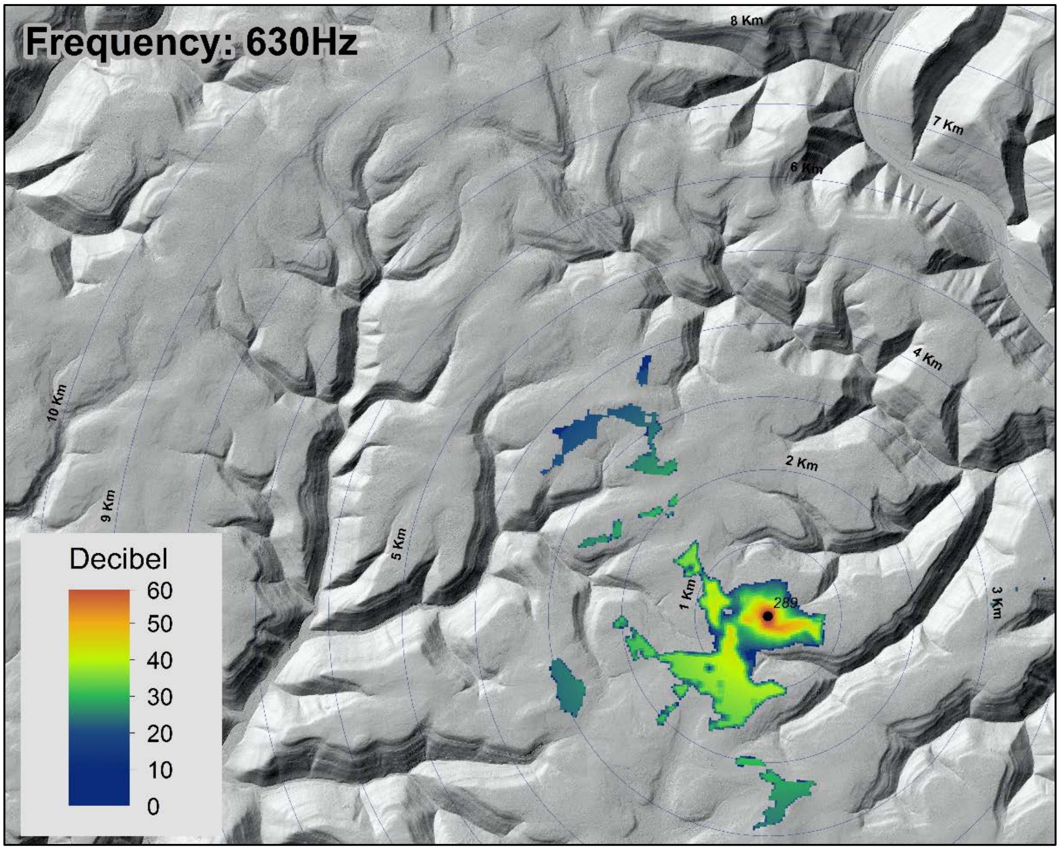
50
40
30
20
10
0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4 Km
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1 Km
3 Km
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9 Km
10 Km
289
Decibel
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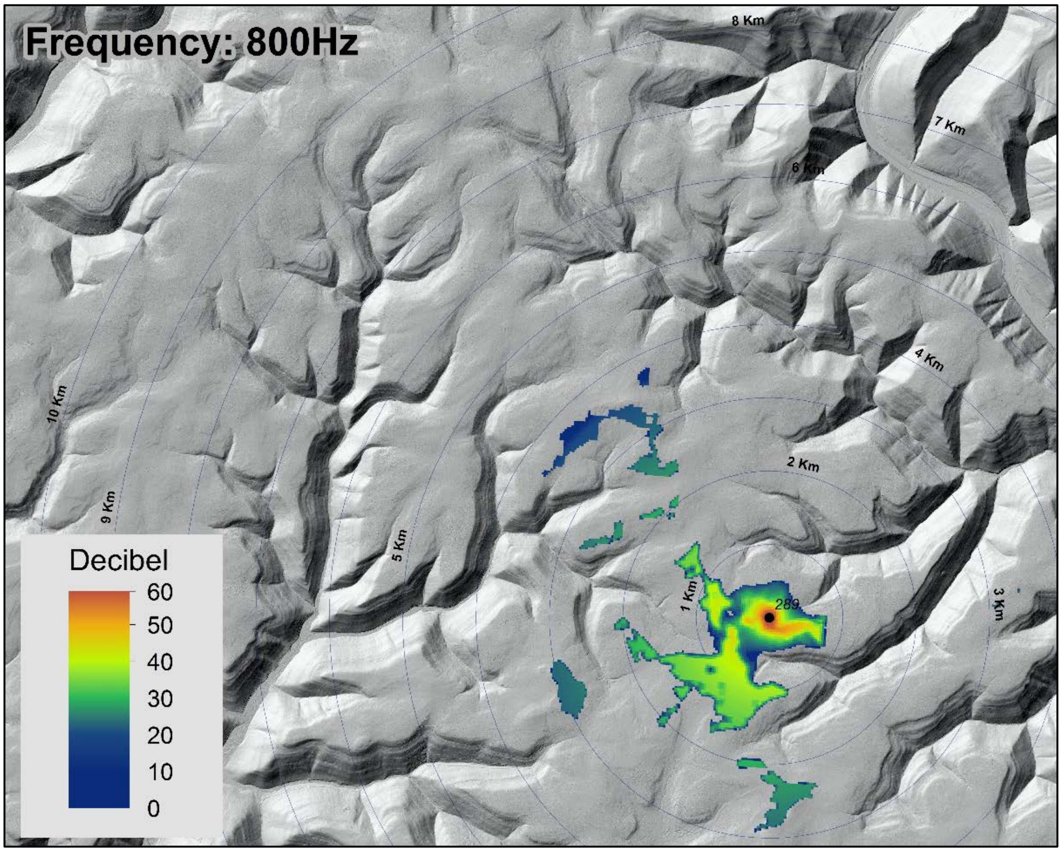
50
40
30
20
10
0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9 Km
5 Km
1 Km
3 Km
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Decibel
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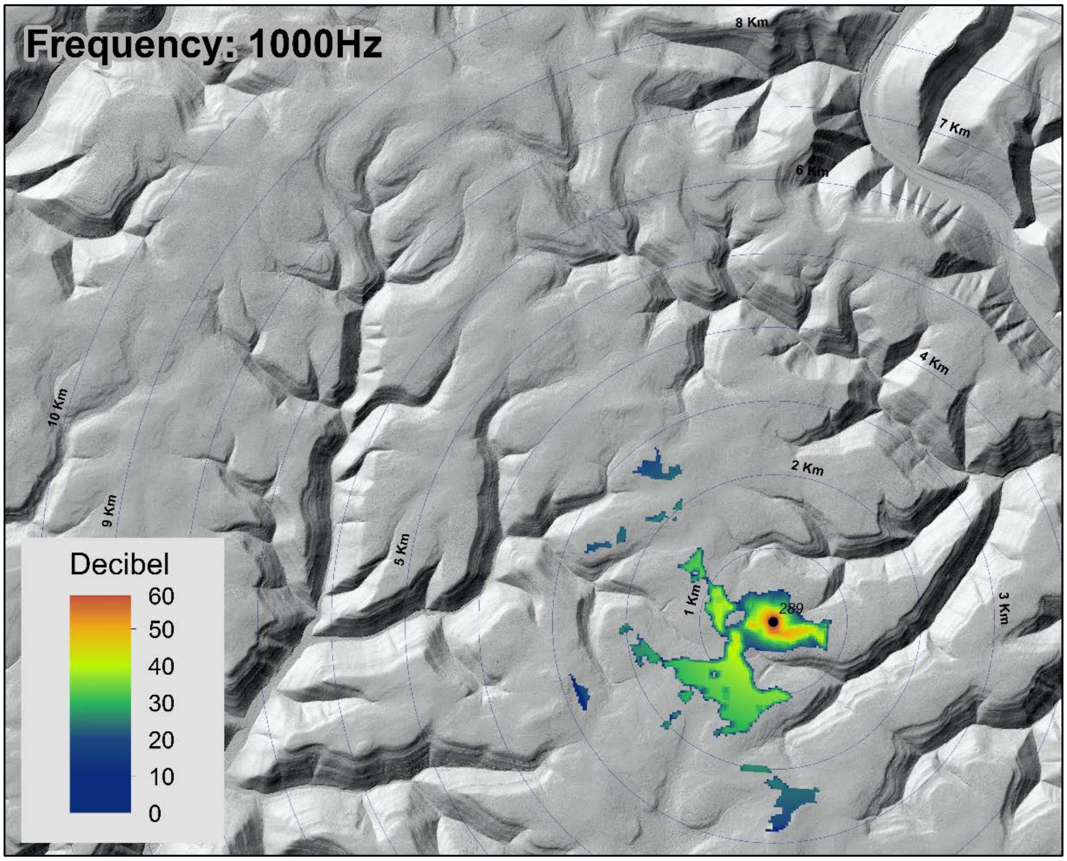
50
40
30
20
10
0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8 Km
7 Km
6 Km
4 Km
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9 Km
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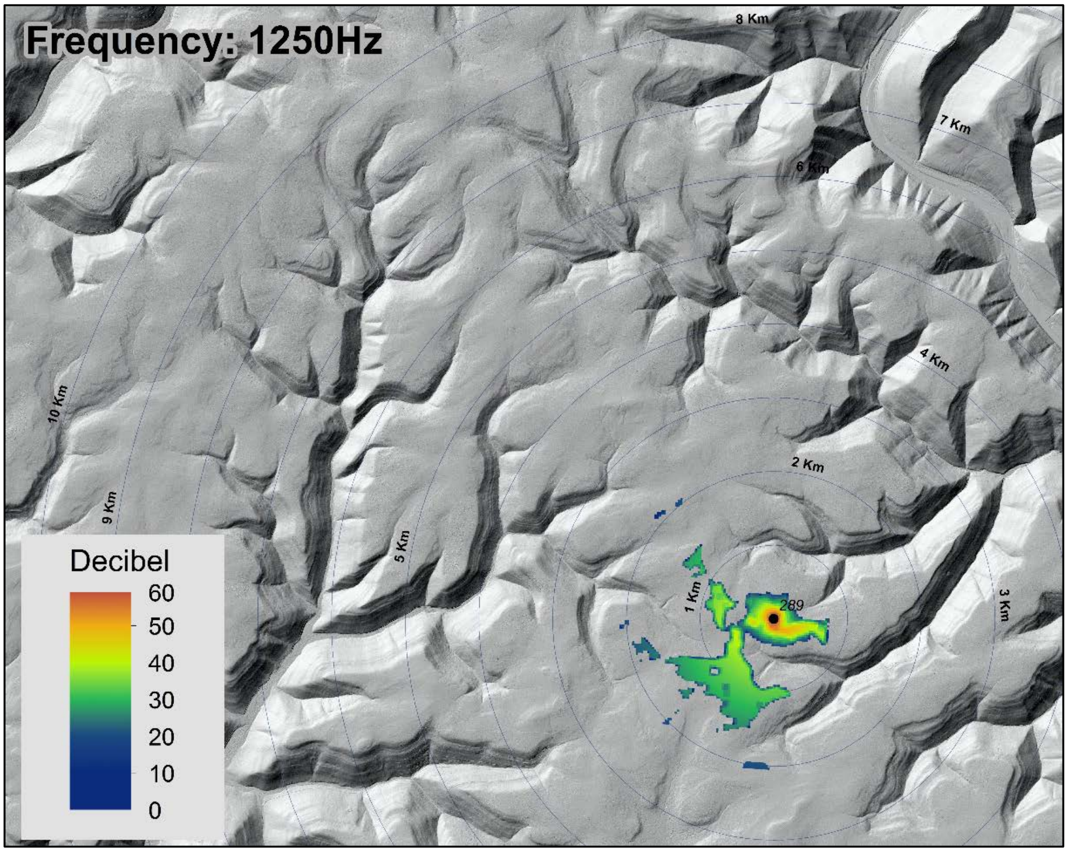
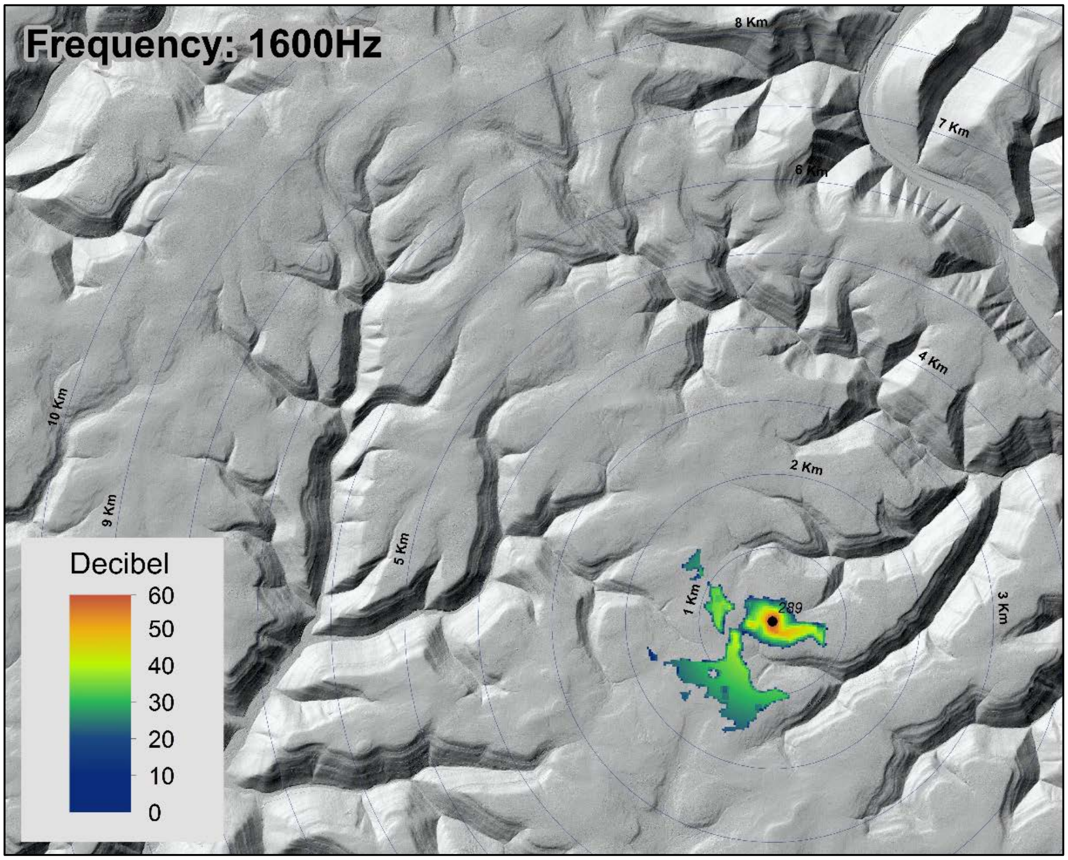
1 Km
3 Km
289
Decibel
60
50
40
30
20
10
0


Frequency: 1250Hz
8 Km
7 Km
6 Km
4 Km
2 Km
3 Km
1 Km
5 Km
9 Km
10 Km
289
Decibel
60
50
40
30
20
10
0


Frequency: 1600Hz
8 Km
7 Km
6 Km
4 Km
2 Km
3 Km
1 Km
5 Km
9 Km
10 Km
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50
40
30
20
10
0

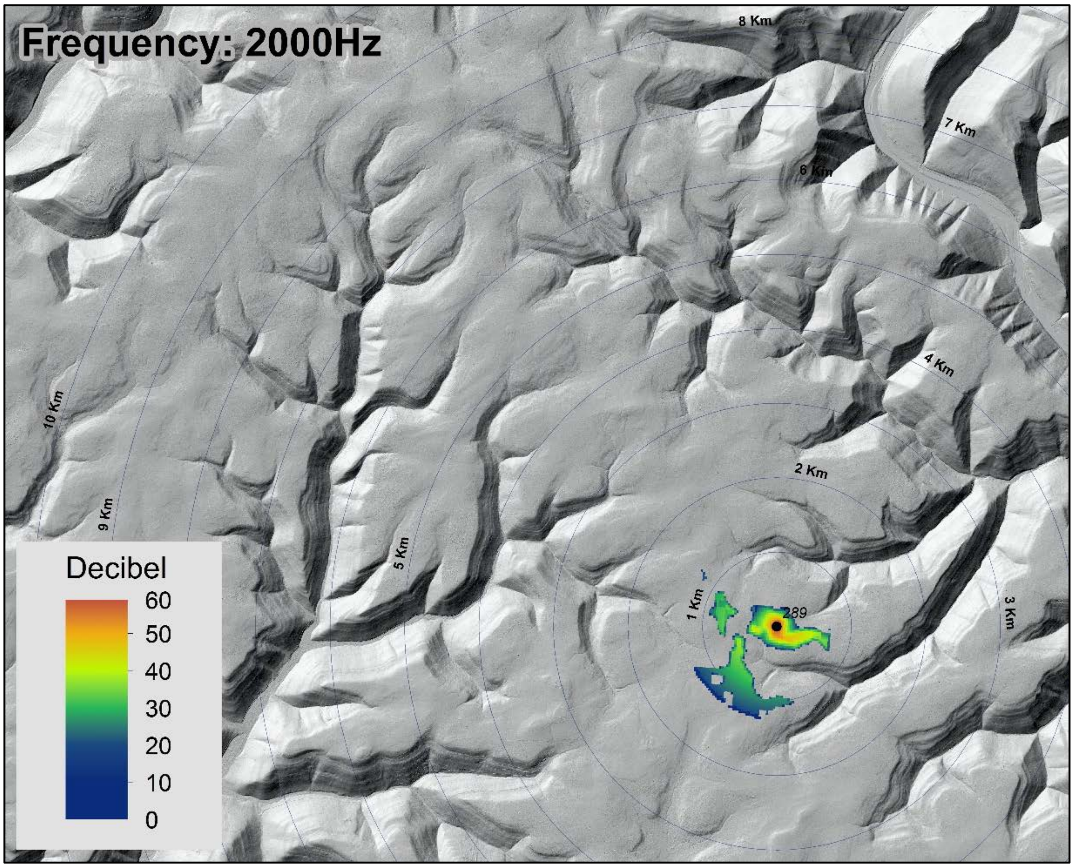

*Figure 8. Noise propagation models for all frequencies (125 – 2000 Hz) and associated decibel levels for CS 289. Propagation distance can be measured using 1km concentric circles (blue lines) from the source point (black point).*

Interestingly, the noise propagation areas for 160Hz and 315Hz were higher, and 200Hz was lower, than expected based on the inverse relationship of frequency to propagation area (Table 7, Figure 7). However, these findings correspond to the peaks and troughs in the spectral signature of the sound recording from CS 289 that shows the increased acoustic power (higher dB values) at 160Hz and 315Hz, and a decrease in power at 200Hz (Gabrielson 2014) (Figure 9). These peaks are associated with the unique tonal components of the compressor station sound signature, specifically the engine-exhaust tone at 160Hz (Gabrielson 2014).

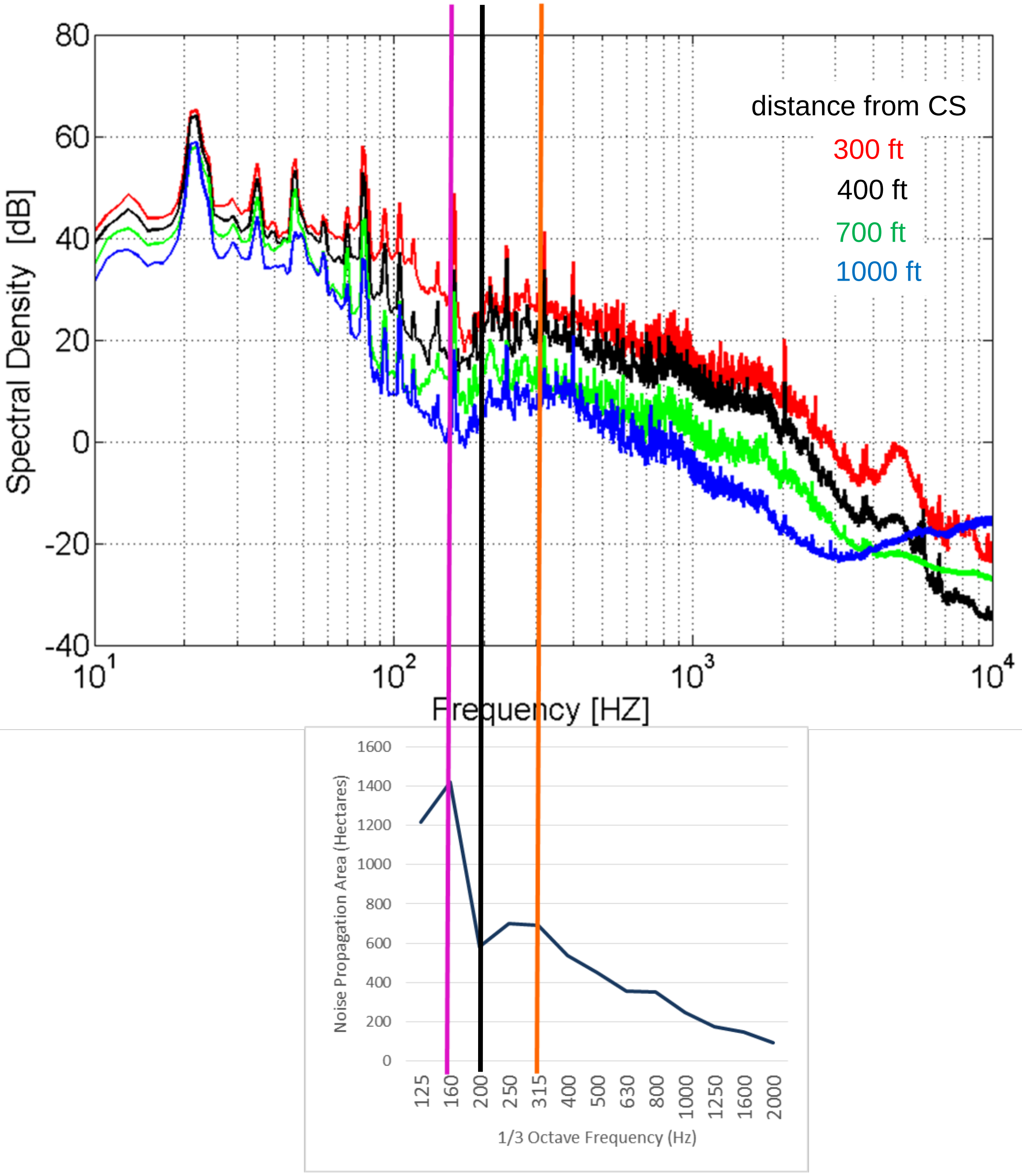

*Figure 9. Spectral signature of the sound recording for CS 289 (top), displaying peaks and troughs across frequencies (at varying distances), but highlighting the peaks at 160Hz (pink line) and 315Hz (orange line), and trough at 200Hz (black line). The lines correspond to the calculated noise propagation area from the SPreAD-GIS model frequencies (bottom).*

### *Compressor Station Comparisons at 160Hz*

The results of the noise propagation models for CS 289 showed a maximum spatial extent at 160Hz, therefore, the propagation areas and distances for the remaining 13 compressor stations were evaluated at the same frequency and conditions (spring-night). The average propagation area and distance were 1,632 hectares and 12.5 km (range: 590 - 3,840 hectares; 3.9 – 14.4 km), respectively, which are slightly higher than those for CS 289 (Table 8). The visual display of the spatial extent of each compressor station can be seen in the *Recreation Opportunity Spectrum Analysis* Section.

No clear relationship between propagation area and distance across sites could be determined, as sites with expansive spreading area were not always associated with an increased distance, for example, CS 285 or CS 997 versus CS 587 (Figure 10). The scatterplot shows some clustering of sites when distance and area are compared, but there are several outliers in the data (beyond the 95 percent confidence intervals), as shown in the box-and-whisker plot (outliers: distance—CS 839; area—CS 587 and CS 595) (Figure 11). The effects of topography are evaluated as a potential explanation for the differences (see *Topographic Effects* Section).

*Table 8. Noise propagation areas and distances for compressor stations at 160Hz, under spring-night conditions.*

| Compressor Station | Area (Hectares) | Distance (Km) |
|---|---:|---:|
| CS 001 | 2,431 | 14.4 |
| CS 002 | 1,562 | 12.5 |
| CS 100B | 1,388 | 14.3 |
| CS 100H | 1,205 | 11.5 |
| CS 285 | 1,258 | 14.2 |
| CS 289 | 1,421 | 11.2 |
| CS 293 | 764 | 8.2 |
| CS 324 | 590 | 12.2 |
| CS 587 | 3,840 | 14.2 |
| CS 595 | 3,525 | 14.2 |
| CS 685 | 975 | 13.9 |
| CS 729 | 1,320 | 14.2 |
| CS 839 | 731 | 3.9 |
| CS 997 | 1,624 | 14.2 |

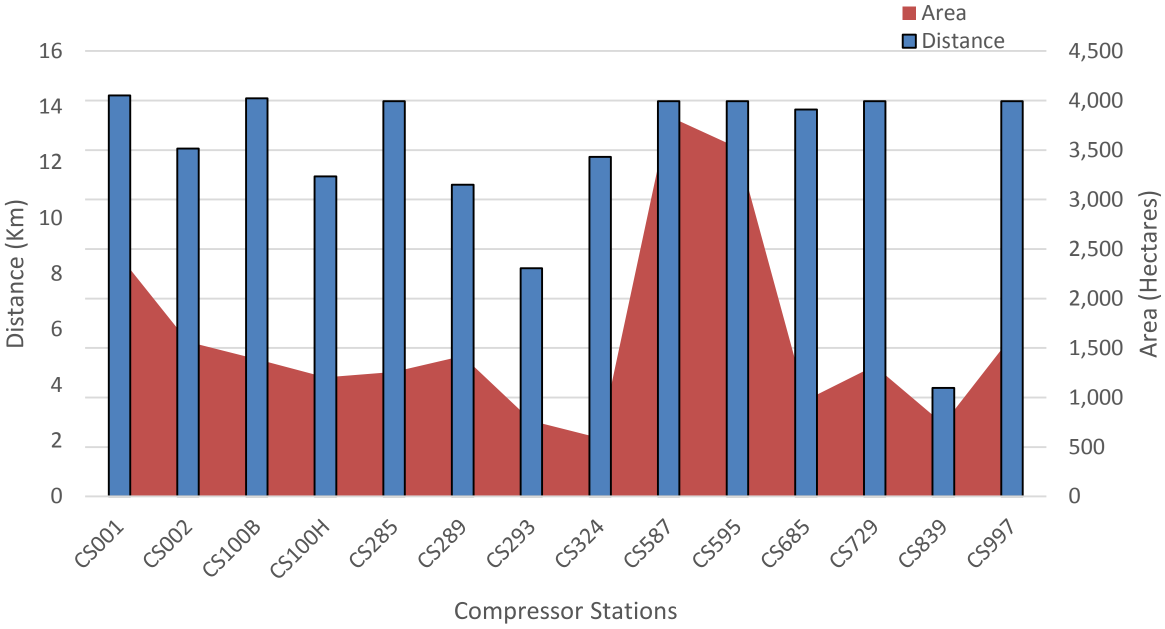

*Figure 10. Noise propagation distances (blue bars, primary y-axis) and areas (red area, secondary axis) for compressor stations at 160Hz, under spring-night conditions.*

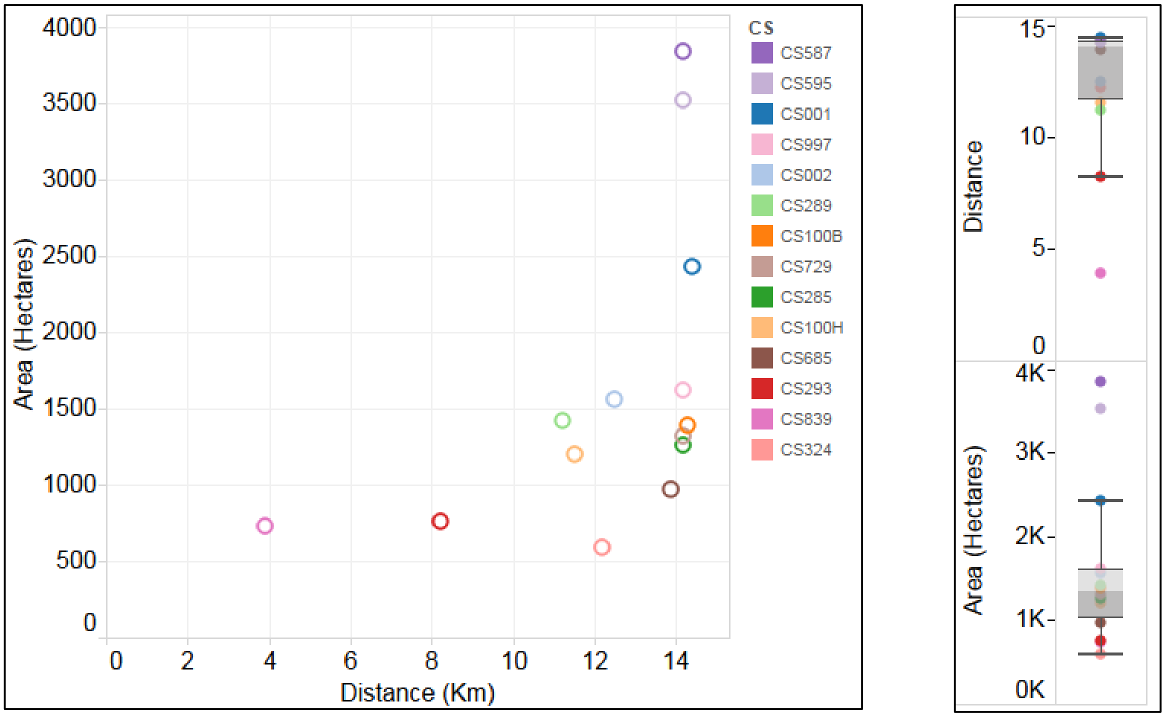

*Figure 11. Scatterplot (left) and box-and-whisker plot (right) for noise propagation distances and areas for compressor stations at 160Hz, under spring-night conditions.*

### *Empirical Data Evaluation*

The full propagation model and exceedance model output decibel values were measured at the sound recording location 300ft from CS 289 for all 1/3 octave frequencies in SPreAD-GIS. The full noise propagation model more closely matched the values from the empirical data collected at the site than the exceedance model (Table 9). However, the full propagation model, on average, underestimates the value by 5.5 dB from the empirical data measurement (range: 4.6 – 8.5 dB). Since the full propagation model values more closely represent the field recordings, this model was used to explore the overlap of the model's spatial extent with the Recreation Opportunity Spectrum.

*Table 9. Empirical measurements, full model and exceedance model values, and ambient noise level at the recording site for each frequency in SPreAD-GIS.*

| | dB at 300 Ft | | | |
|---|---|---|---|---|
| Freq (Hz) | Empirical Data | Full Model | Exceedance Model | Ambient Noise Level (dB) |
| 125 | 47.8 | 43.2 | 18.2 | 25 |
| 160 | 52.0 | 47.4 | 23.4 | 24 |
| 200 | 42.7 | 38.0 | 15.0 | 23 |
| 250 | 46.8 | 42.0 | 20.0 | 22 |
| 315 | 48.2 | 43.4 | 21.4 | 22 |
| 400 | 45.5 | 40.6 | 19.6 | 21 |
| 500 | 43.9 | 39.0 | 19.0 | 20 |
| 630 | 41.2 | 36.1 | 16.1 | 20 |
| 800 | 43.0 | 37.6 | 18.6 | 19 |
| 1000 | 40.5 | 34.6 | 16.6 | 18 |
| 1250 | 38.2 | 31.7 | 14.7 | 17 |
| 1600 | 38.6 | 31.2 | 14.2 | 17 |
| 2000 | 36.6 | 28.1 | 12.1 | 16 |

### *Recreation Opportunity Spectrum (ROS)*

The full noise propagation models for three compressor stations showed overlap with primitive ROS classified areas: CS 997, CS 285, and CS 595, overlapping by about 50, 100, and 200 hectares, respectively (Table 10). Additionally, three compressor station noise models overlapped with Natural and Wild Areas across state forest land: CS 729, CS 285 and CS 100B (Table 11). The spatial extent of the models at 160Hz across the ROS classified areas are displayed in Figures 12-25.

*Table 10. Measurement of the overlap between the full propagation model and the Recreation Opportunity Spectrum dataset for each compressor station at 160Hz.*

| Compressor Station | Overlap Area (Hectares)<br>Semi-Primitive | <br>Semi-Primitive Non-Motorized | <br>Primitive |
|---|---|---|---|
| CS 001 | 242 | 20 | 0 |
| CS 002 | 0 | 0 | 0 |
| CS 100B | 329 | 267 | 0 |
| CS 100H | 261 | 0 | 0 |
| CS 285 | 245 | 40 | 99 |
| CS 289 | 285 | 2 | 0 |
| CS 293 | 233 | 0 | 0 |
| CS 324 | 43 | 0 | 0 |
| CS 587 | 701 | 35 | 0 |
| CS 595 | 567 | 497 | 197 |
| CS 685 | 173 | 20 | 0 |
| CS 729 | 132 | 17 | 0 |
| CS 839 | 123 | 0 | 0 |
| CS 997 | 411 | 376 | 47 |

*Table 11. The compressor stations whose full propagation models overlap PA state forest Wild and Natural Areas, with the number of hectares of overlap, designation type, and site name.*

| Compressor Station | Area (Hectares) | Type | Name |
|---|---|---|---|
| CS 100B | 453 | Wild Area | McIntyre Wild Area |
| CS 285 | 129 | Wild Area | Wolf Run Wild Area |
| CS 729 | 63 | Natural Area | Miller Run Natural Area |

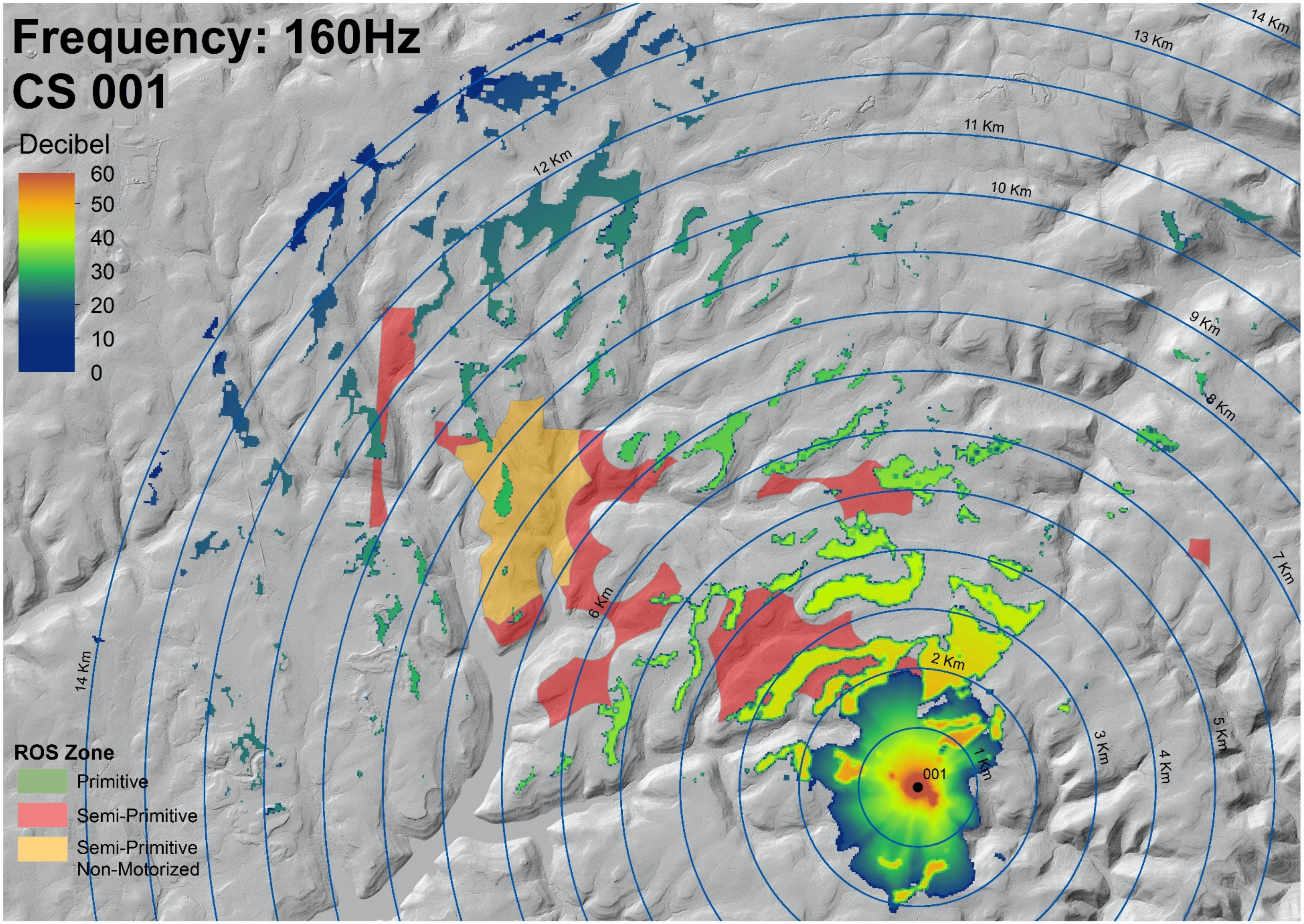

*Figure 12. Noise propagation model of CS 001 displaying overlap with ROS area classifications.*

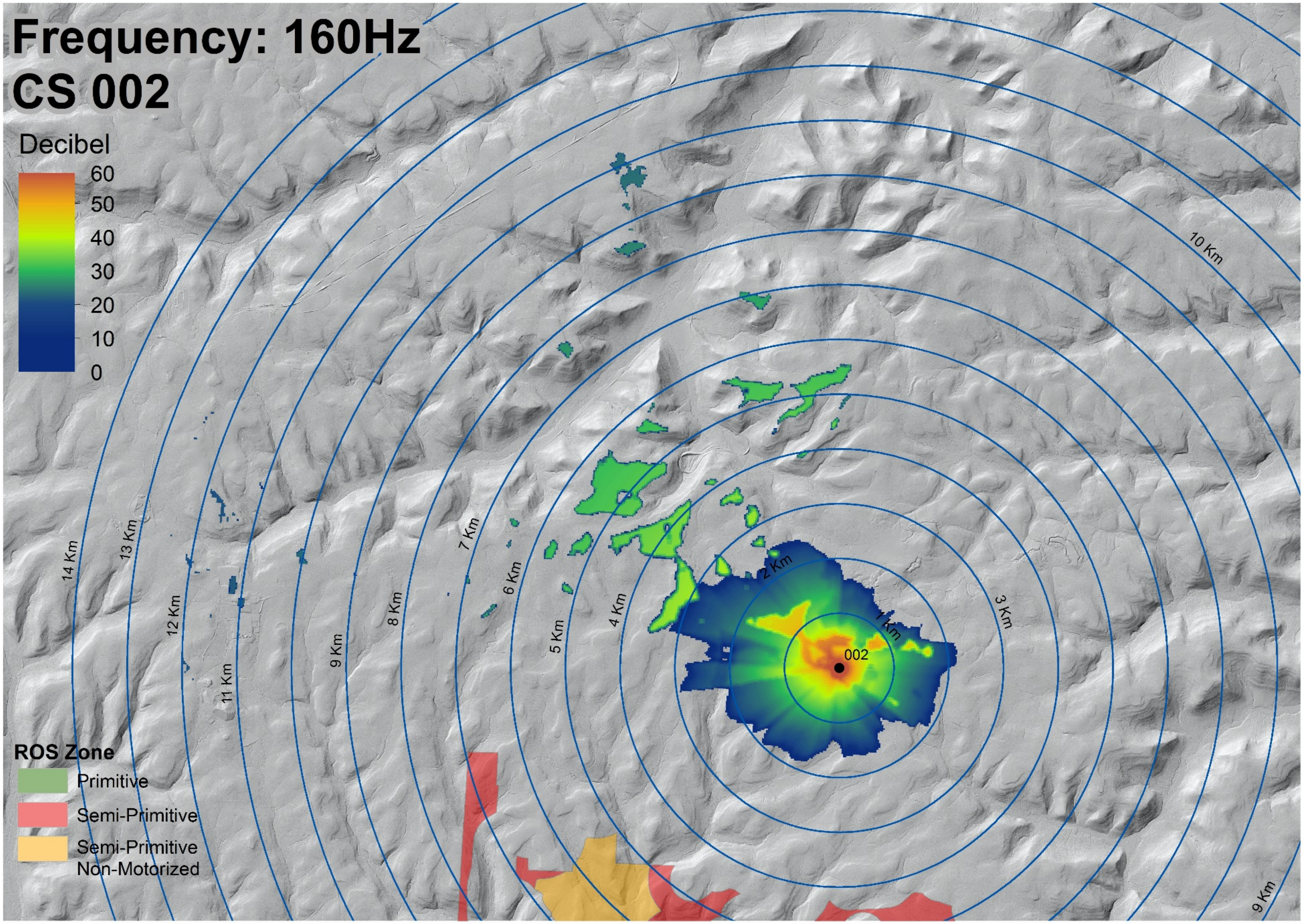

*Figure 13. Noise propagation model of CS 002 displaying no overlap with ROS area classifications.*

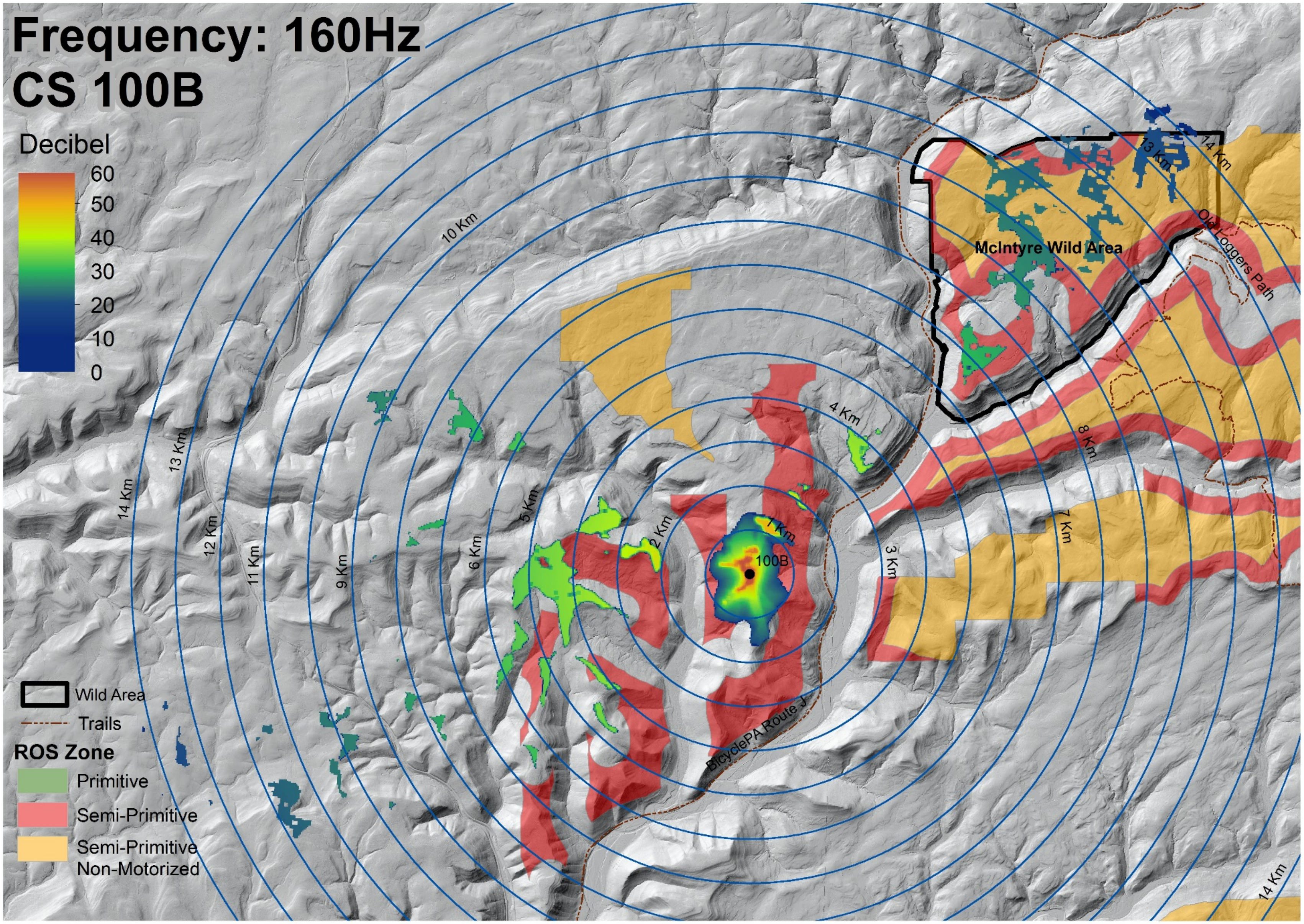

*Figure 14. Noise propagation model of CS 100B displaying overlap with ROS area classifications and McIntyre Wild Area.*

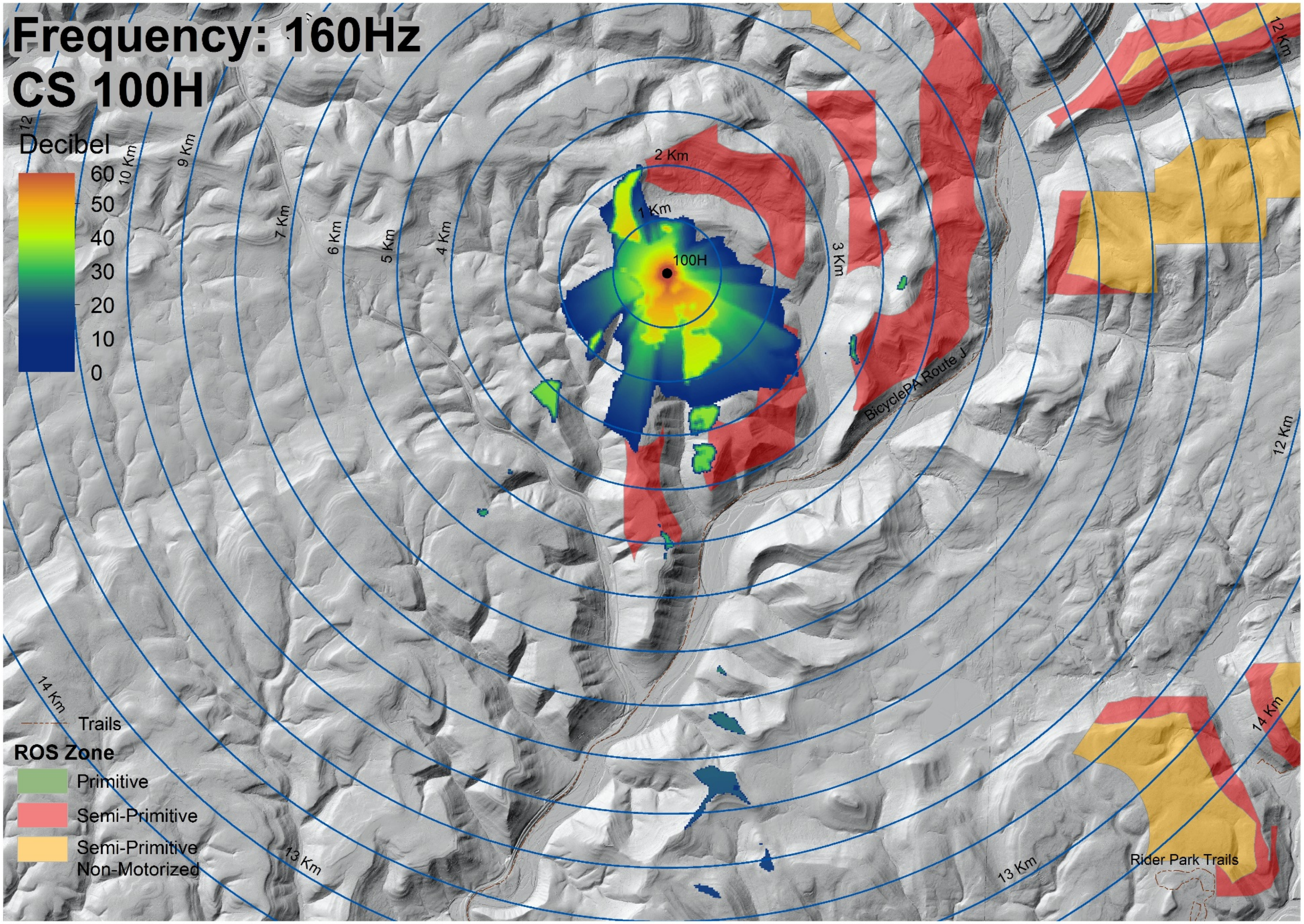

*Figure 15. Noise propagation model of CS 100H displaying overlap with ROS area classifications.*

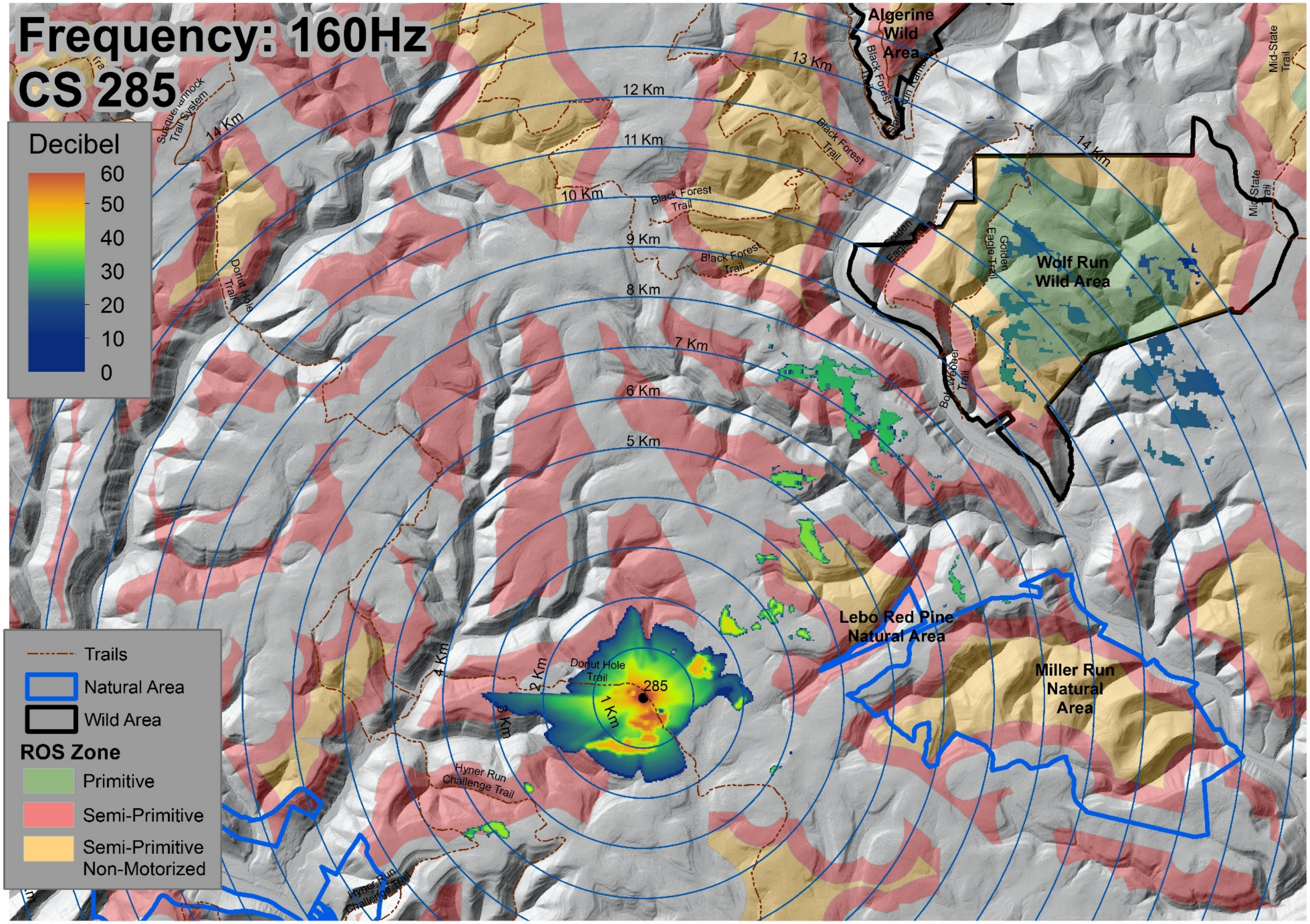

*Figure 16. Noise propagation model of CS 285 displaying overlap with ROS area classifications and Wolf Run Wild Area.*

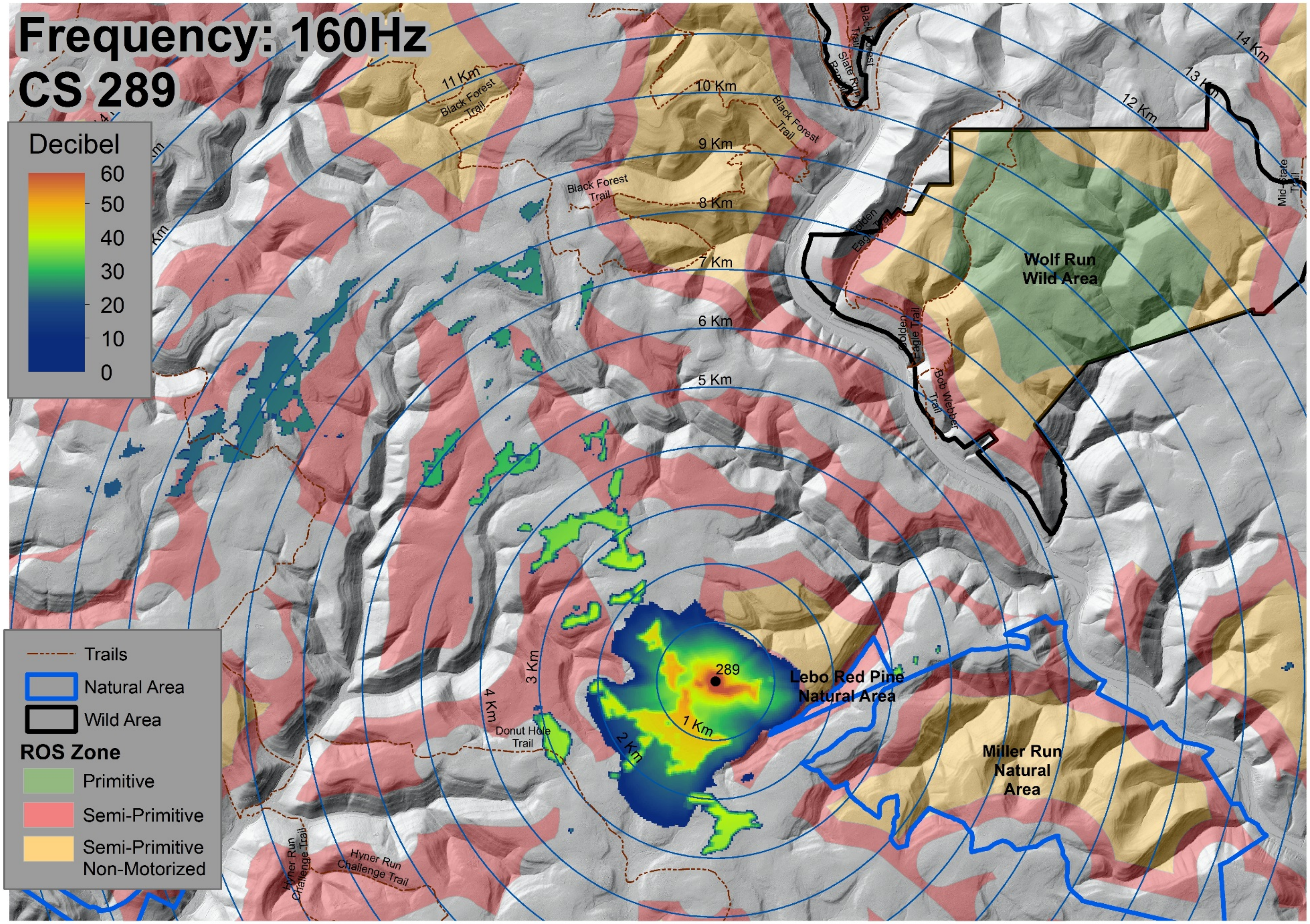

*Figure 17.  Noise propagation model of CS 289 displaying overlap with ROS area classifications.*

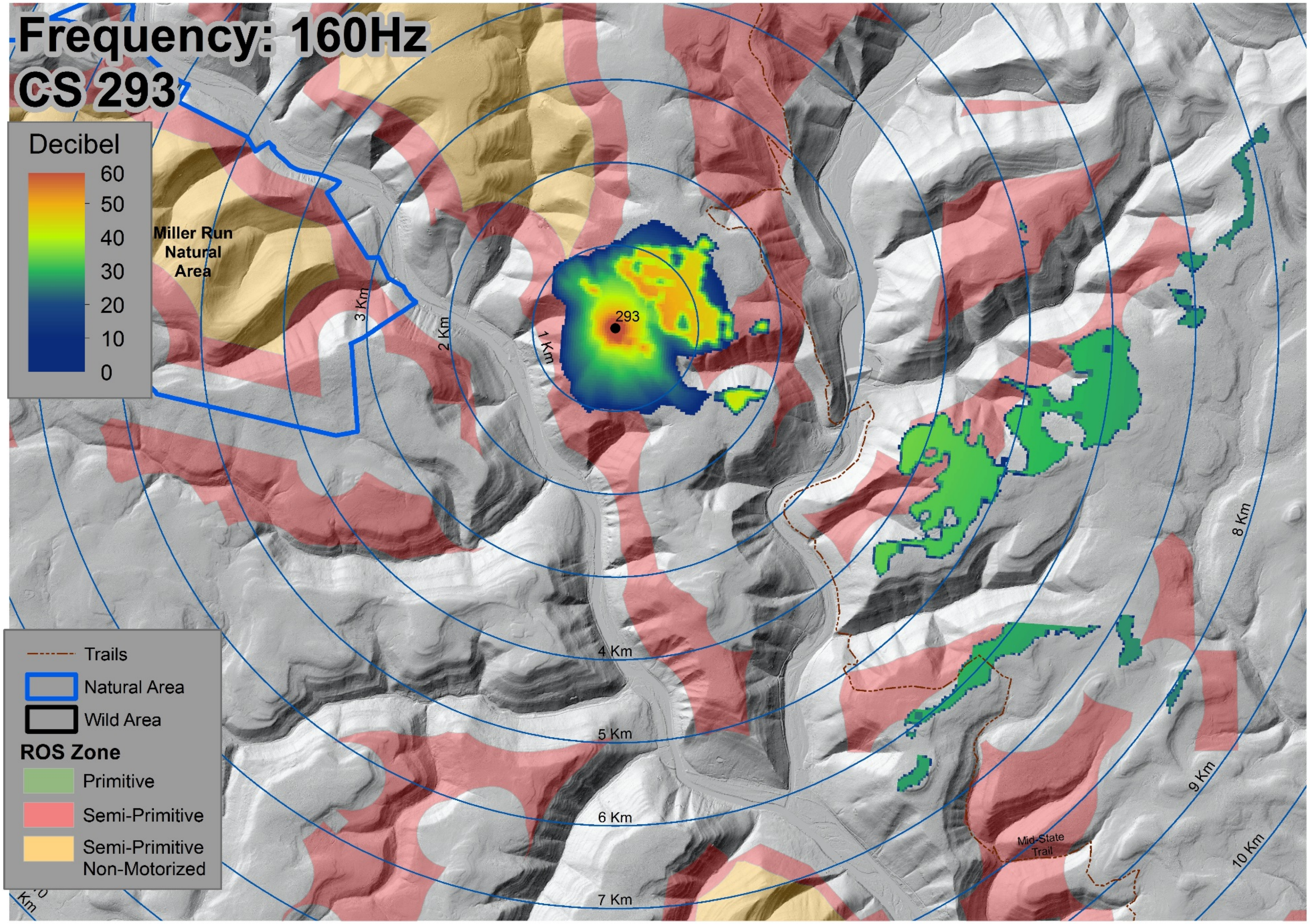

*Figure 18. Noise propagation model of CS 293 displaying overlap with ROS area classifications.*

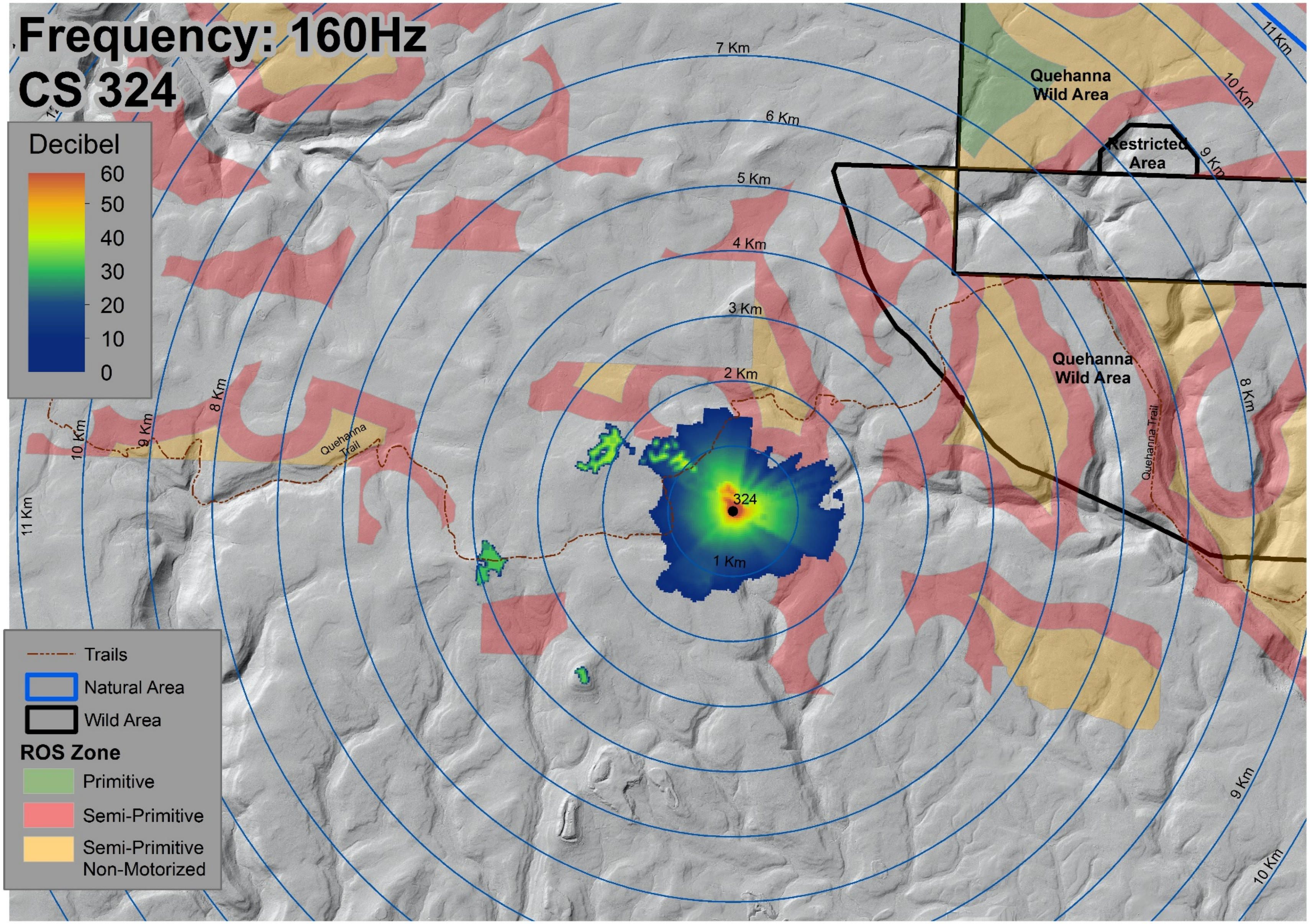

*Figure 19. Noise propagation model of CS 234 displaying overlap with ROS area classifications.*

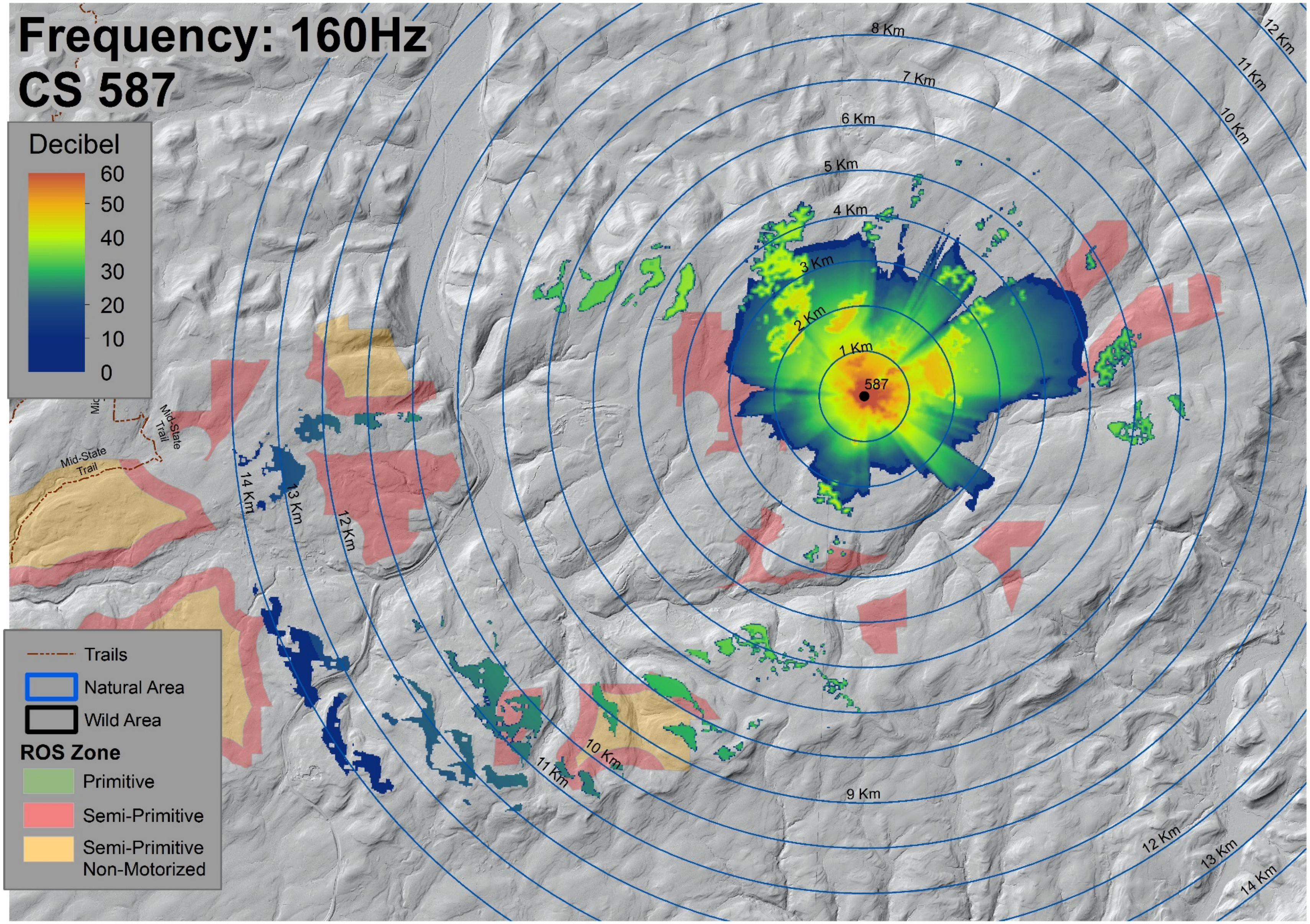

*Figure 20. Noise propagation model of CS 587 displaying overlap with ROS area classifications.*

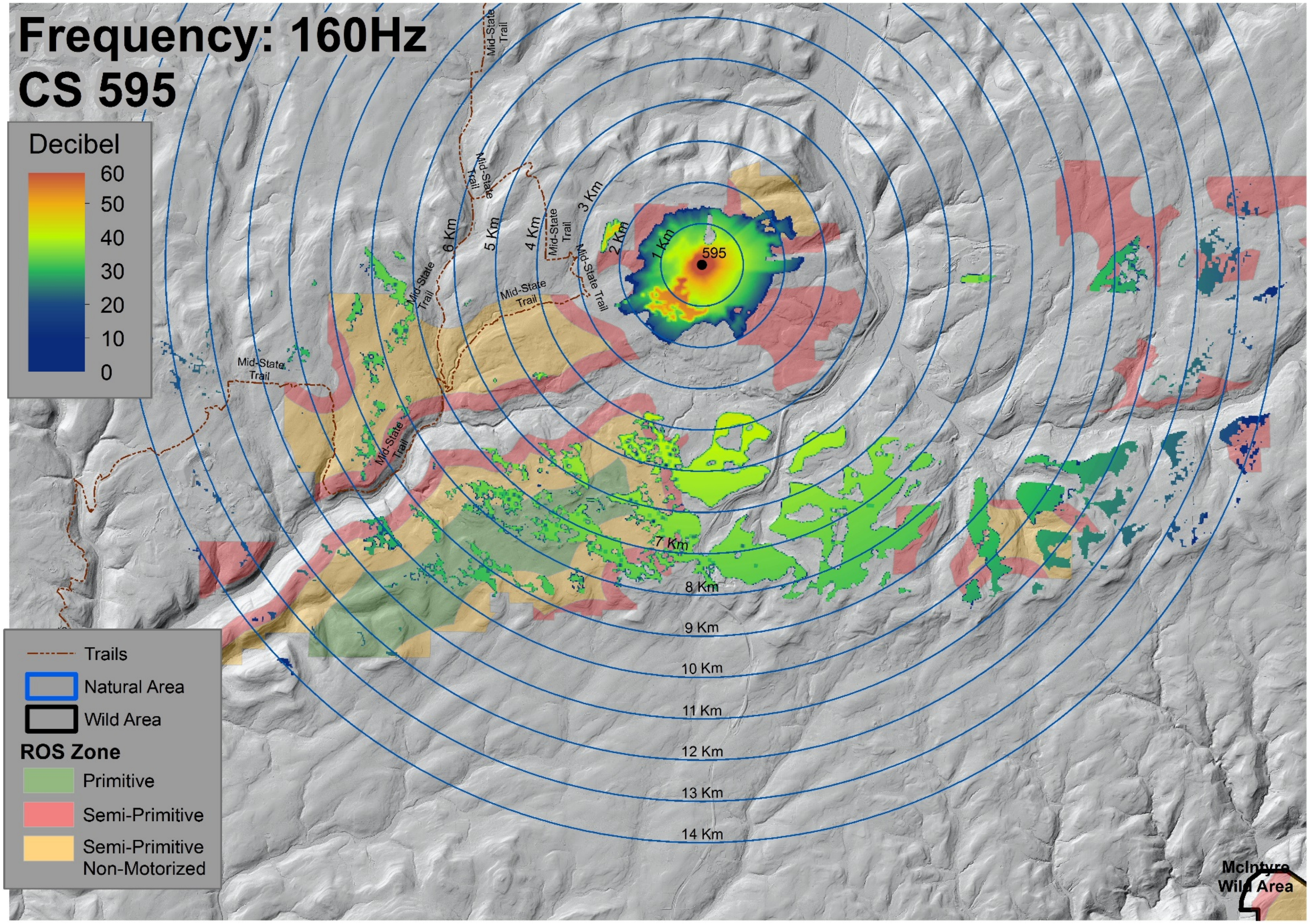

*Figure 21. Noise propagation model of CS 595 displaying overlap with ROS area classifications.*

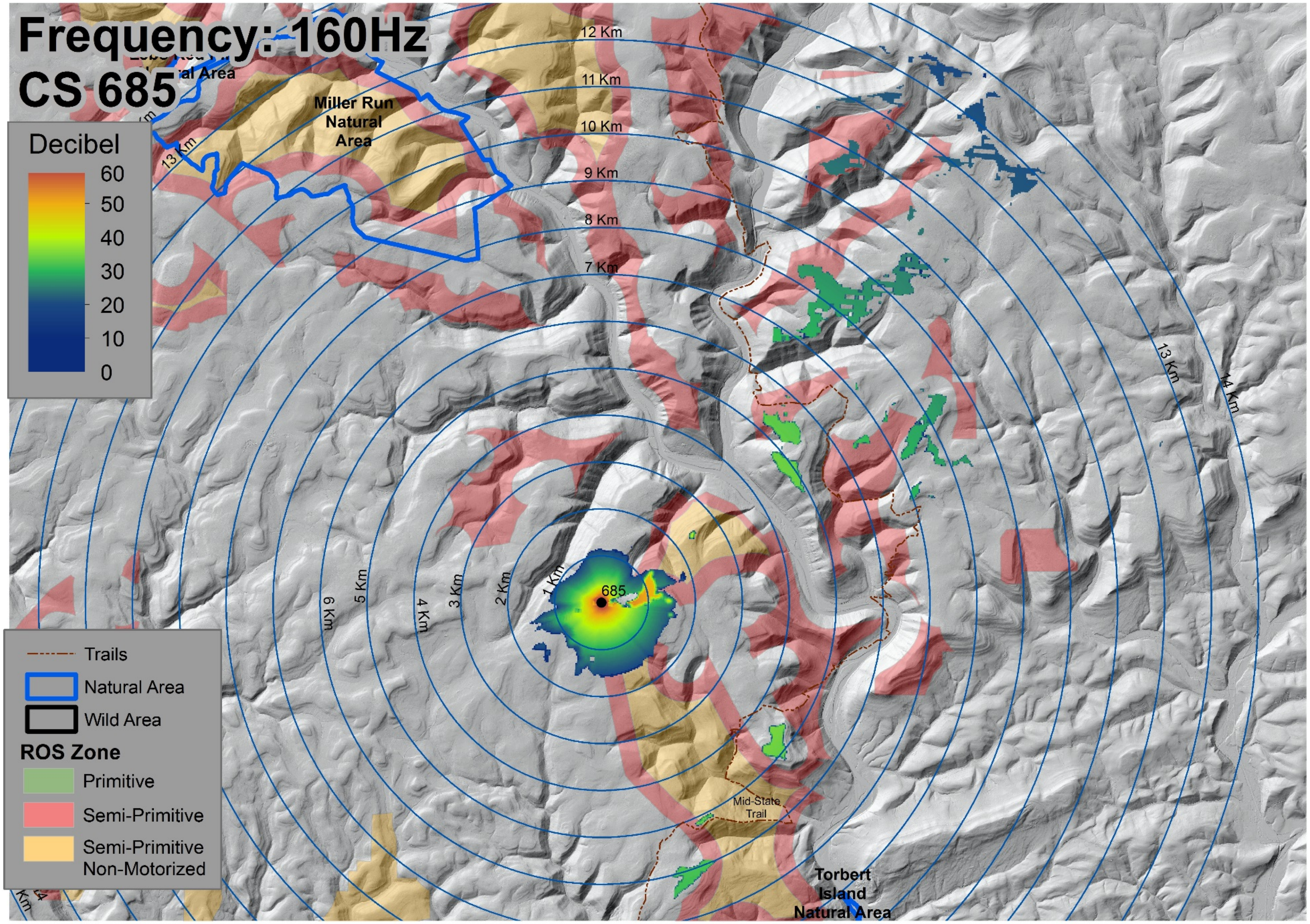

*Figure 22. Noise propagation model of CS 685 displaying overlap with ROS area classifications.*

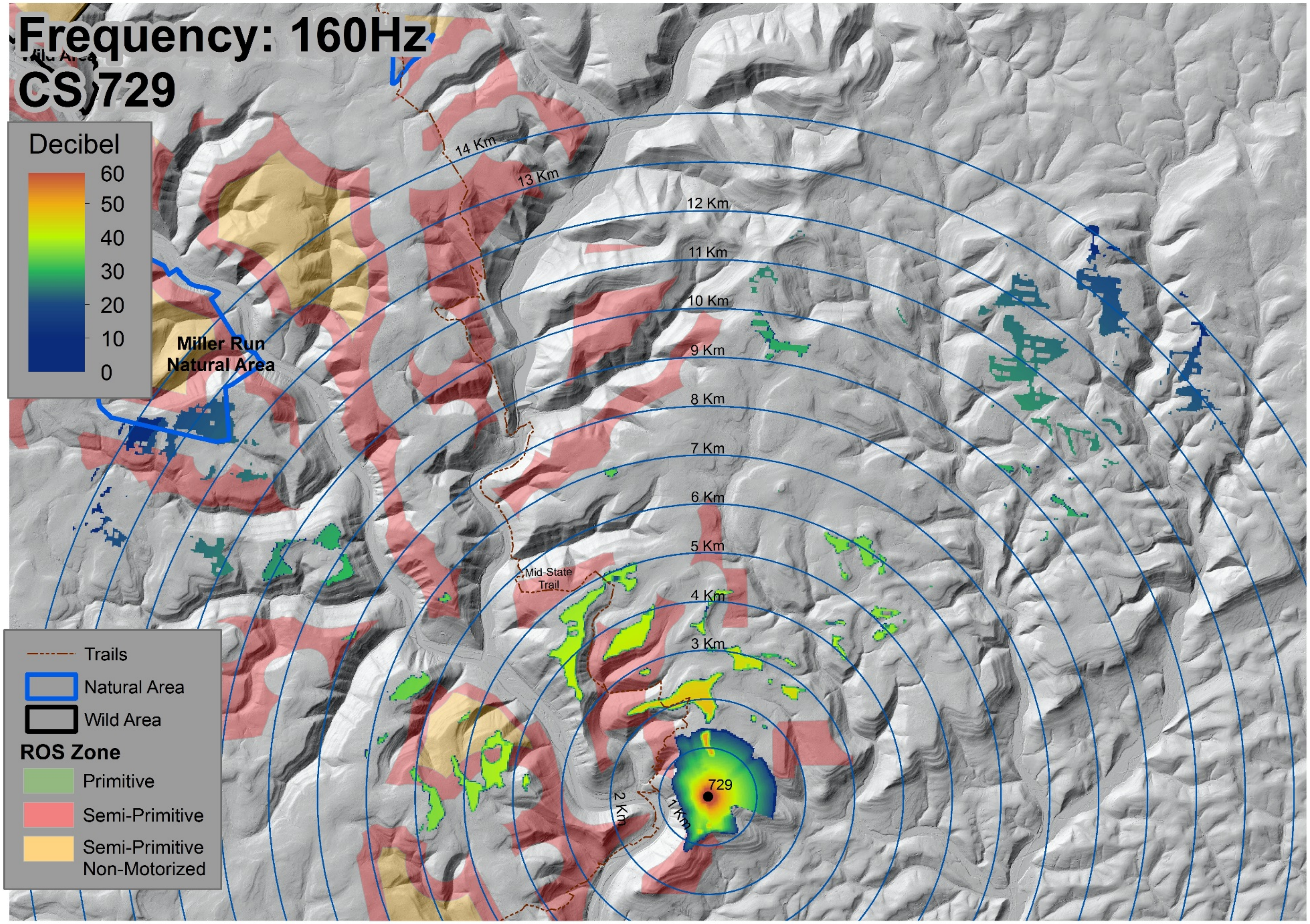

*Figure 23. Noise propagation model of CS 729 displaying overlap with ROS area classifications and Miller Run Natural Area.*

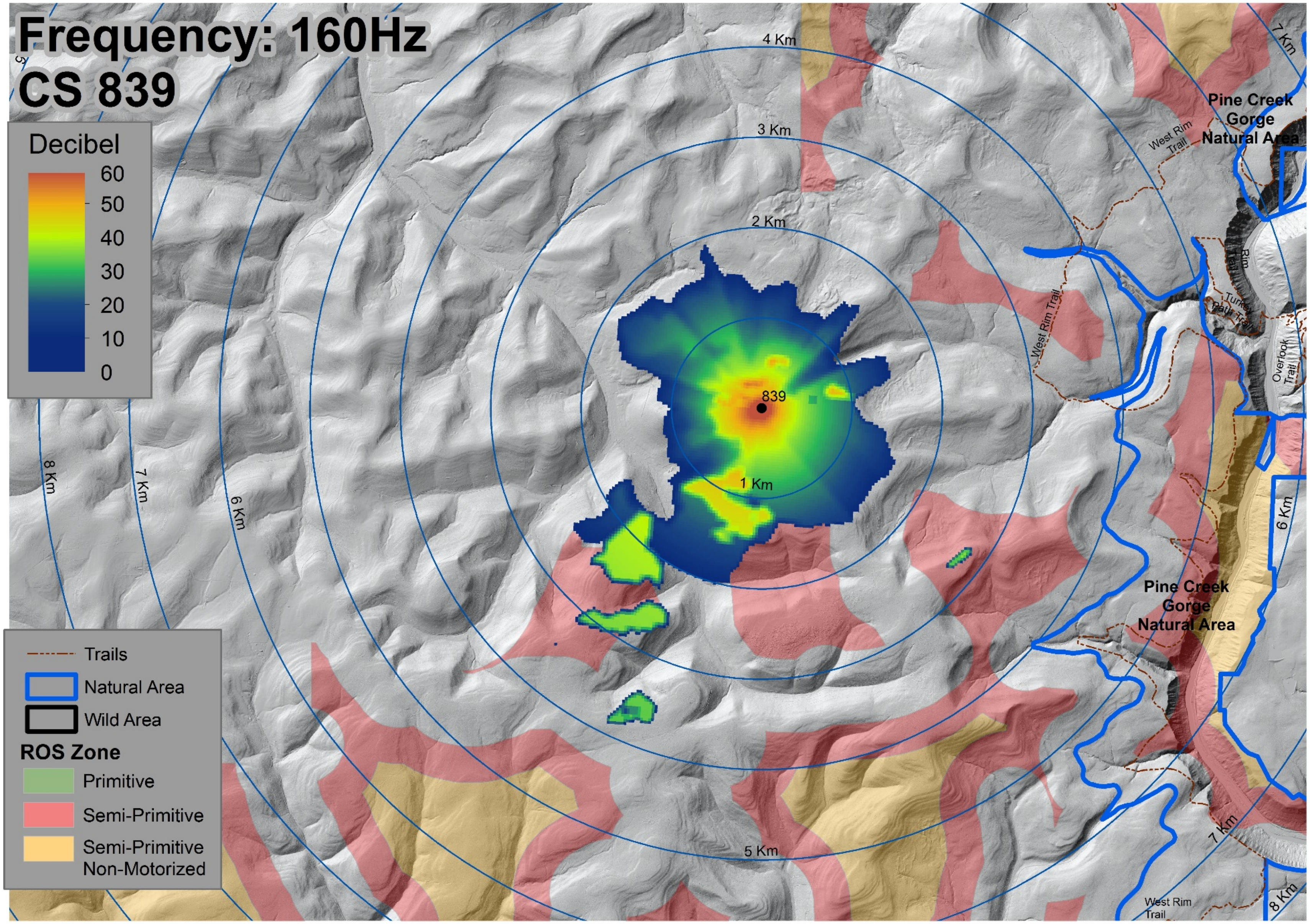

*Figure 24. Noise propagation model of CS 839 displaying overlap with ROS area classifications.*

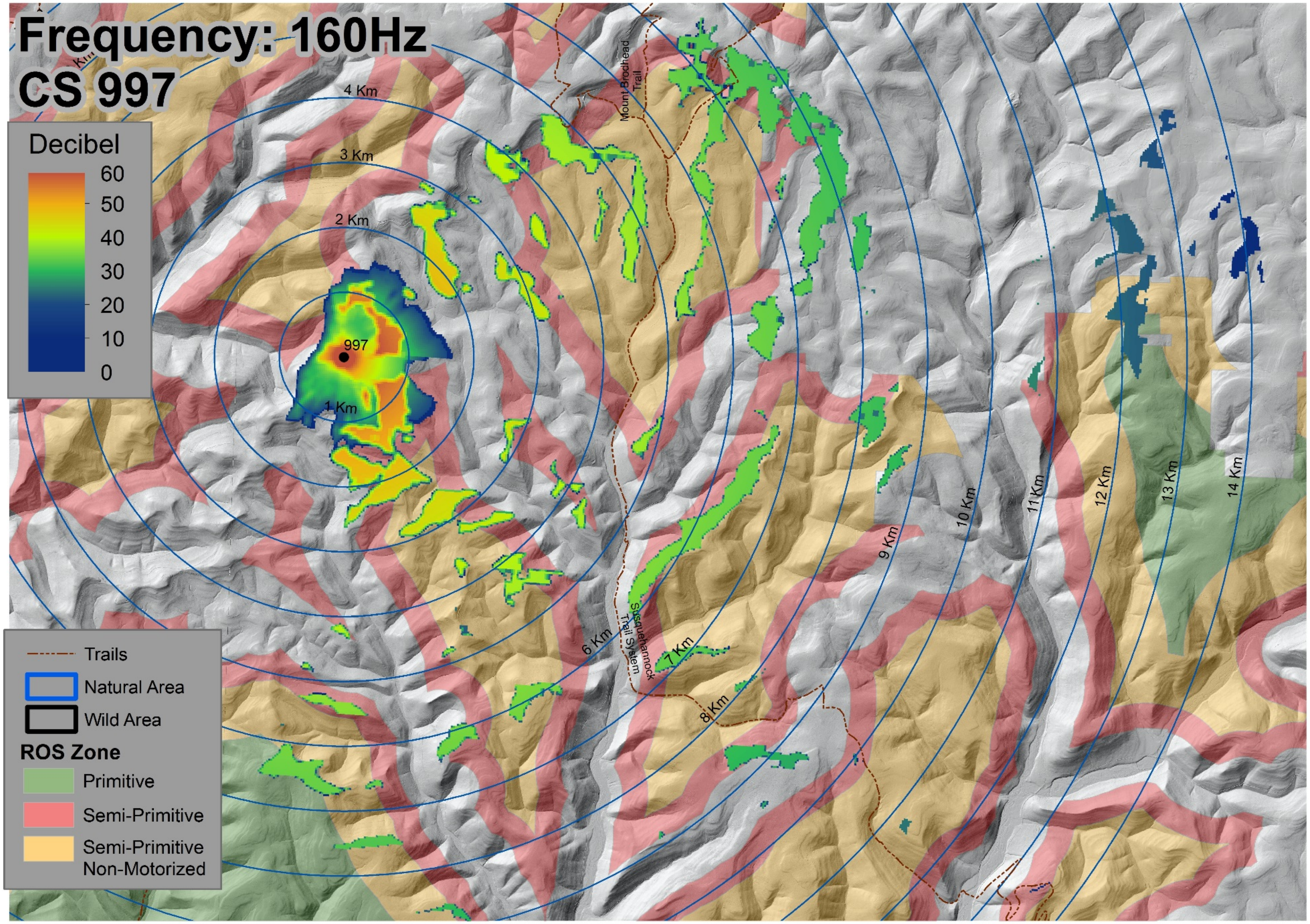

*Figure 25. Noise propagation model of CS 997 displaying overlap with ROS area classifications.*

## Topographic Effects

Based on visual analysis of the noise propagation models, it appears that the topography surrounding the compressor station has a large influence over the spatial extent of the model. When CS 289 was compared to a hypothetical location 3km to the east and placed at the bottom of a river basin, the spatial extents of the models differed greatly (Figure 26). The CS 289 model still exhibited a maximum 11km spread (Table 7), whereas the hypothetical river basin location demonstrated a far reduced range, about 2.5km maximum distance. It appears that the riverine basin ridgelines limited the majority of the noise spread, allowing the noise area to move primarily in the up and downstream directions. The hypothetical river basin location was set at an elevation of 1150ft, and the noise propagation model did not exceed 1900ft along the riverine ridgelines, therefore, it is possible that spread of noise at 160Hz could be minimized by a landscape feature only 700-800ft higher than the sound source location.

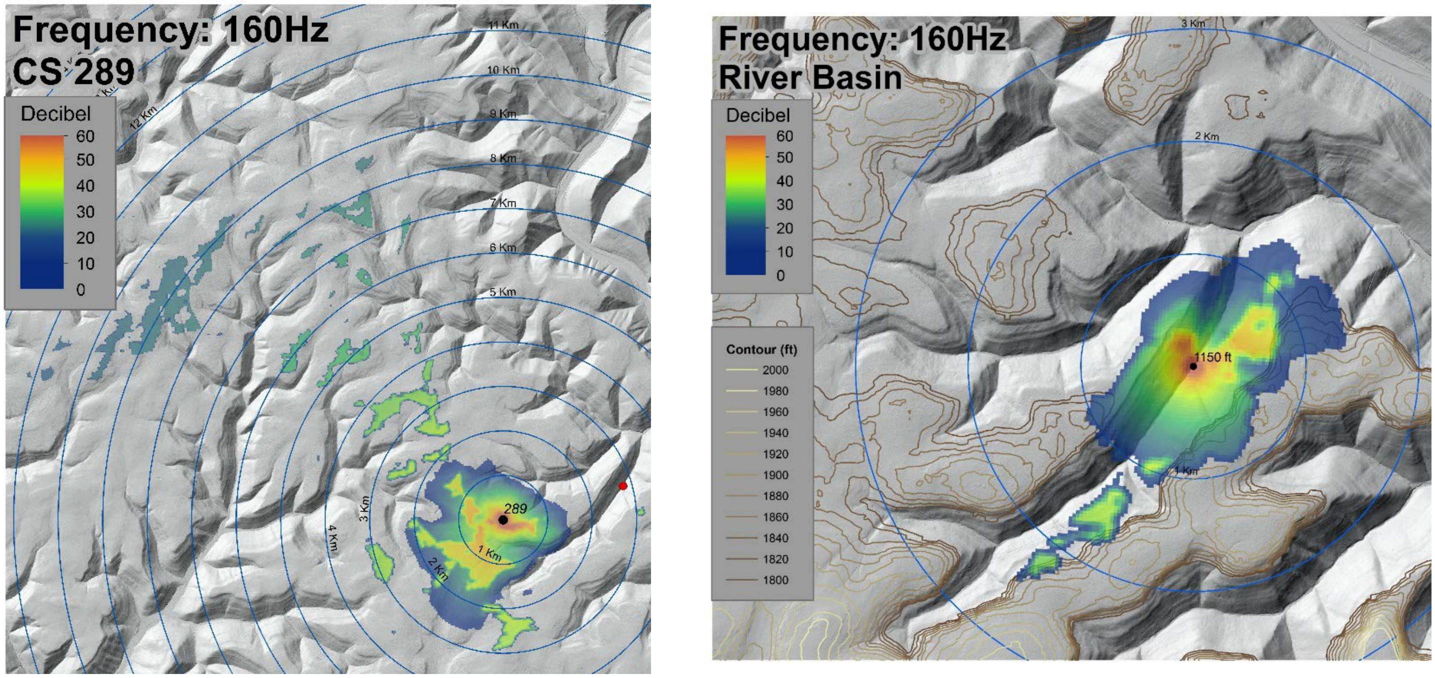

*Figure 26. Noise propagation models for CS 289 (left) and a fictitious point 3km away in a river basin (right). The location of the fictitious point in relation to CS 289 is displayed as a red point (left)..*

A similar effect of topography limiting the spread of noise propagation models can be seen for the two compressor stations with the largest spatial extents— CS 587 and CS 595 (Figures 27 and 28). Using 3-Dimensional imagery produced in ArcScene (with a 5x elevation exaggeration), the noise propagation models appear to be limited by their southerly ridgelines, where the noise skirts the edge of the ridges but does not extend past this landscape feature.

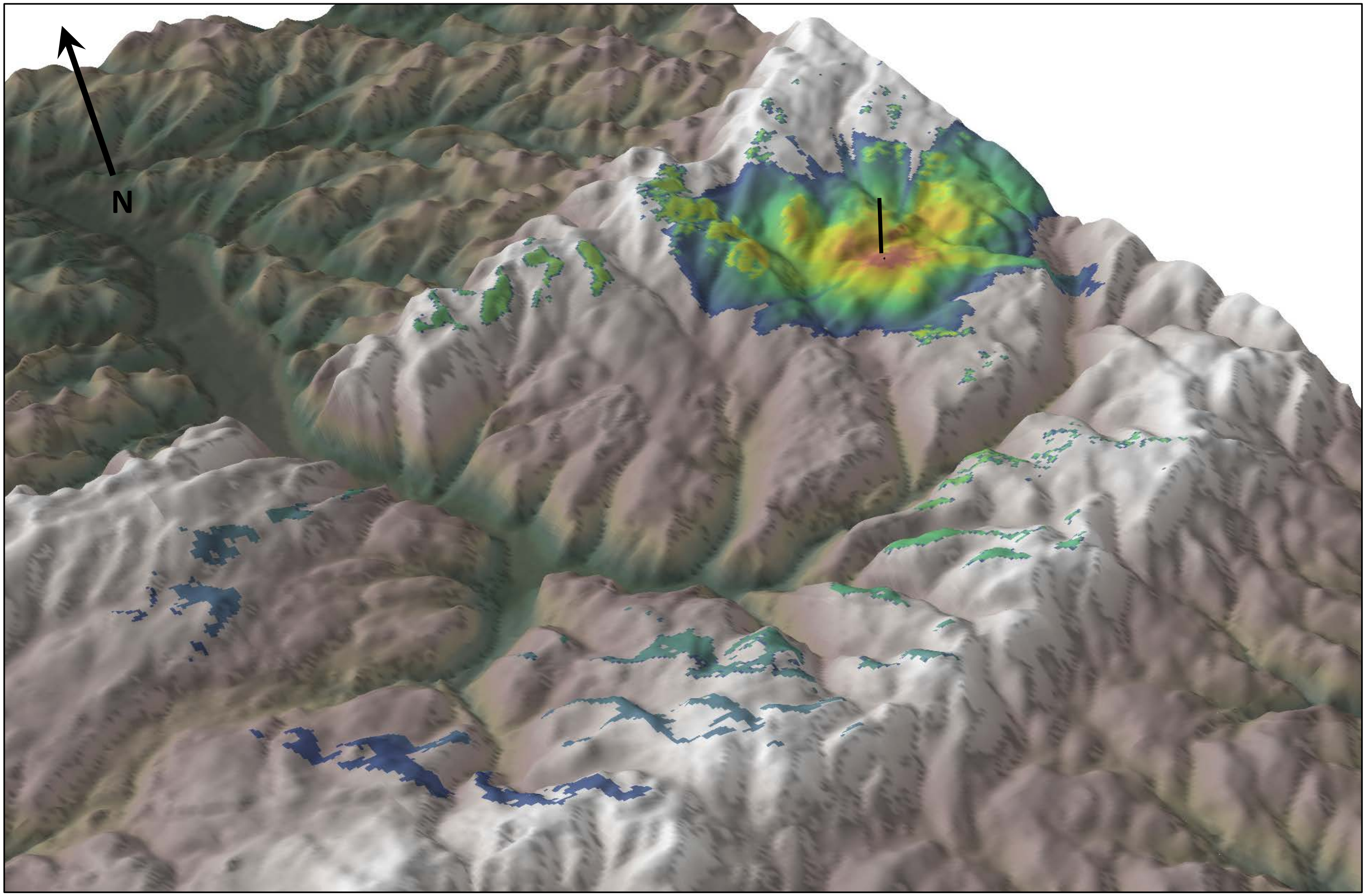

*Figure 27. Noise propagation model for CS 587 at 160Hz, draped over the elevation model in ArcScene (with a 5x elevation exaggeration). The black line represents the compressor station location. Note the distribution of the sound model along the rim of the basin in the southwest of station.*

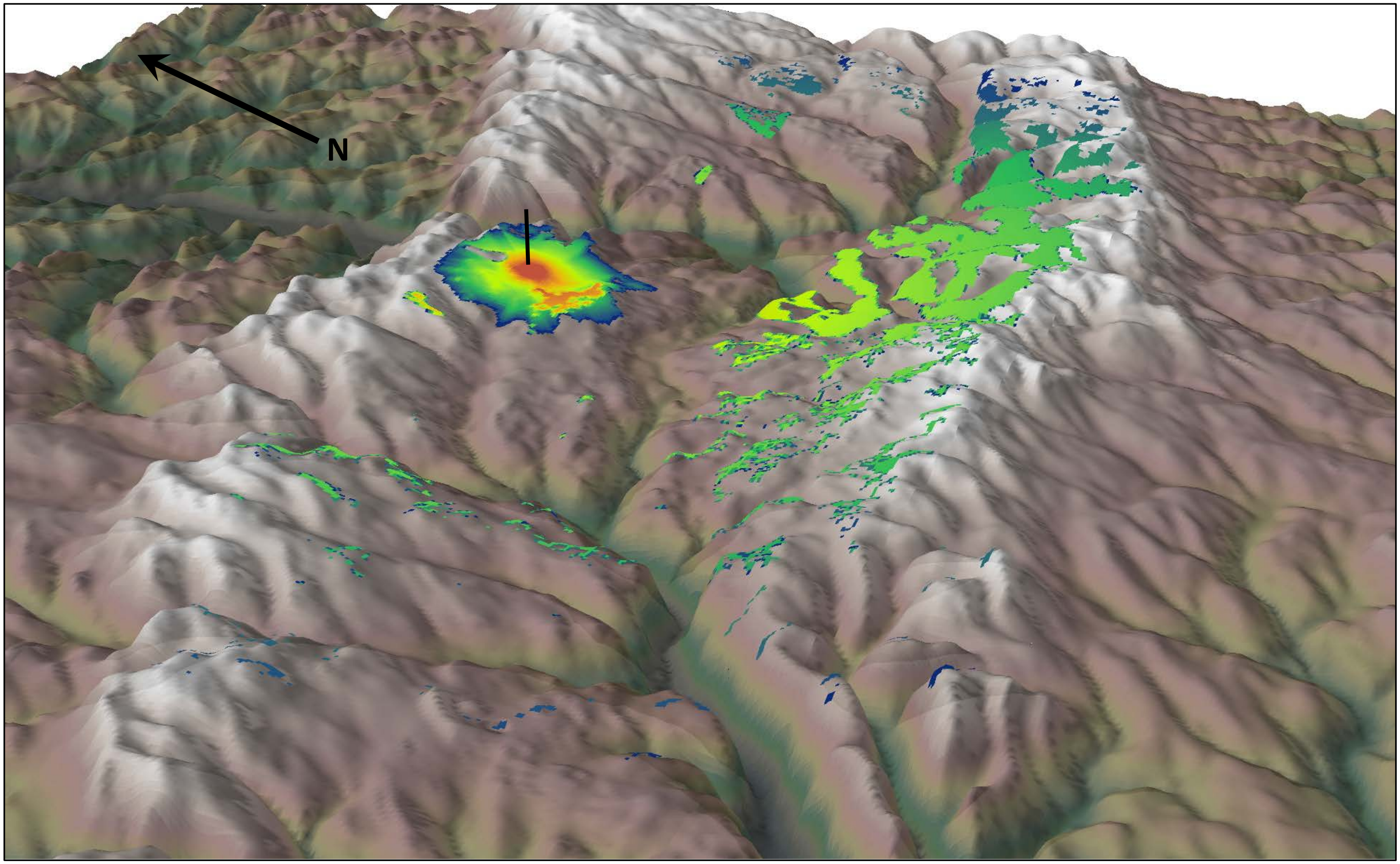

*Figure 28. Noise propagation model for CS 595 at 160Hz, draped over the elevation model in ArcScene (with a 5x elevation exaggeration). The black line represents the compressor station location. Note the distribution of the sound model along the northerly slope face of the ridgeline.*

## DISCUSSION

The noise propagation models for CS 289 revealed that high frequency compressor station noise travels around 1-2km, whereas low frequency noise emitted from the station can travel up to 5-10 times the distance of higher frequencies, around 11km. Furthermore, the noise propagation area was about 15 times greater for lower than higher frequencies. This same trend was seen across all compressor stations modeled, with both area and distance decreasing with increasing frequency. The one unique frequency in the noise propagation models across all compressor stations was at 160Hz, which exhibited the highest spatial extent of all frequencies measured. This finding corresponded to the peak in acoustical power of the compressor station engine exhaust noise from the empirical data.

Overall, the SPreAD-GIS model appeared to correspond well to the empirical data values when measured at the recording location, and may in fact, underestimate the true sound levels across the landscape. However, the model was only evaluated at the 300ft recording location and could differ from actual noise levels at greater distances. Additional research and ground-truthing may be needed to determine how closely the model represents the sound spread and sound levels detected in the field. Further investigation into the ambient sound levels may also be required to fully understand which model output would be the most appropriate for further evaluation of noise propagation for the compressor stations. The results of which would greatly influence the amount of overlap of the noise propagation extents with areas of particular concern on the state forest lands.

Under the current requirements of the Recreation Opportunity Spectrum land classifications, construction of oil and gas infrastructure is prohibited on semi-primitive non-motorized and primitive categorized lands. However, based on the SPreAD-GIS model, noise from the compressor stations analyzed in this study could travel as far as these prohibited areas (based on the assumptions set for the model). Although the impacts are currently unknown, and further ground-truthing is needed, it is possible the low frequency noise produced from the already constructed compressor stations on state forest lands could reach sensitive lands. Of the 14 compressor stations evaluated, nine exhibited propagation areas that extended into semi-primitive non-motorized land classes and of these, three also three reached primitive lands; the most protected interior forest habitats. Therefore, it is possible that the current ROS does not fully consider the impacts of low frequency sounds—noise that can travel far distances. Low frequency sounds in this study were shown to travel up to 14km (8.6 miles) (11km for CS 289) and would certainly exceed the distance requirement for the primitive classification of one mile from a sound source (road, trail or railroad).

Topography does appear to influence the spatial spreading of the compressor station noise propagation, and could in fact, significantly aid in limiting the extent of the noise. The preliminary analysis revealed that basins of at least 800ft difference in elevation from the basin edge to the bottom of the basin was enough height difference to minimize the noise spread by about 8km, limiting the extent to 2-3km versus 11km or more (when the river basin point was compared to CS 289). Therefore, it may be recommended for future compressor station sites to be placed in basins or valleys, rather than ridgelines to minimize the spatial extent of the noise produced by the stations. It may also be recommended that the compressor station housings be modified to minimize noise, using baffling or other noise dampener, to mitigate the spread of noise across the landscape.

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