Oil and gas development exposure and conservation scenarios for Greater sage-grouse: Combining spatially explicit modeling with GIS visualization provides critical information for management decisions

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Abstract

During the last quarter-century, global demand for energy has increased by more than 60%, and a similar increase is anticipated to occur by 2030 (Raymond, Deming, & Nichols, 2007). In the U.S., oil and gas development is projected to continue across western states within sage-grouse habitat. Greater sage-grouse, recently a candidate species for protection under the Endangered Species Act (ESA), have well documented negative responses to oil and gas disturbance. In this study, we create spatially-explicit oil and gas future development scenarios, baseline and high, and link them to sage-grouse population and habitat maps to quantify future exposure risk within Western Association of Fish and Wildlife Agencies (WAFWA) sage-grouse management zones (MZ) I and II. We then analyze recent land use

decisions from the Bureau of Land Management (BLM) along with enacted policy from the State of Wyoming to estimate how these management actions might minimize the exposure risk of sage-grouse to oil and gas development into the future. Our results show that BLM and Wyoming conservation plans could reduce the exposure of sage-grouse to oil and gas development from 15-27% to 11-17% (31-37% reduction) in MZ I and from 15-27% to 5-9% (64-68% reduction) in MZ II. Our estimates of exposure to future oil and gas development, and conservation measures designed to ameliorate those threats, represent the upper and lower extents of potential impacts within scenarios. Our work demonstrates how spatial modeling and GIS visualization can be used by managers to assess likely outcomes of conservation decisions.

1. Introduction

The global demand for energy is projected to grow ~60% by 2030 with an average annual growth rate of 2%. Oil and natural gas are forecast to meet over 50% of this projected growth in demand (Raymond et al., 2007). According to the BLM Energy Policy and Conservation Act Phase III assessment (EPCA III), the western region of the U.S. has the largest amount of Federal onshore oil and gas resources (DOI, USDA, & DOE, 2008). The states of Colorado, Montana, North Dakota, South Dakota, Utah and Wyoming are projected to produce 50.23 million barrels of oil equivalent (MMBOE) per year by 2030 (Vidas & Hugman, 2009). The anticipated result of this development across the west, termed energy sprawl (McDonald, Fargione, Kiesecker, Miller, & Powell, 2009), threatens western landscapes (H. E. Copeland, Pocerwicz, & Kiesecker, 2011). Unchecked, fluid mineral development is one of the interacting anthropogenic forces altering the form and function of the sagebrush (*Artemisia* spp.) ecosystem (Bunting et al., 2002; Connelly, Knick, Schroeder, & Stiver, 2004; Knick, 1999; Miller & Eddleman, 2000).

The Greater sage-grouse (*Centrocercus urophasianus*; sage-grouse) is the largest North American grouse species. Once widespread across the western U.S. and Canada, sage-grouse have experienced long-term population declines since pre-European settlement, which has led to concern about the species' conservation status (Connelly et al., 2004; Schroeder et al., 2004b). Oil and gas development has been occurring in sage-grouse habitats since the late 1800s (Connelly et al., 2004; IHS, 2014). Numerous studies have documented direct and indirect impacts on sage-grouse from oil and gas development. Sage-grouse and sage-grouse habitats are impacted through direct habitat loss from well pads, construction activities, seismic surveys, associated infrastructure (e.g., roads, power lines), and pipelines. Indirect impacts include noise, gaseous emissions, changes in surface water availability and quality, decreased habitat quality through increased exposure to invasive plants, predators, and disease, and increased human activity and presence (Aldridge, 1998; Aldridge & Brigham, 2003; Aldridge & Boyce, 2007; Braun, 1998; Connelly et al., 2004; Doherty, 2008; Holloran, Kaiser, & Hubert, 2007; Knick et al., 2003; Leu & Hanser, 2011; Lyon & Anderson, 2003a; Suter, 1978; Walker, Naugle, & Doherty, 2007; Zou, Miller, & Schmidtman, 2006). Impacts to sage-grouse from oil and gas development vary with development distance, density and infrastructure configuration (Doherty, 2010; Gregory & Beck, 2014). Currently, oil, conventional gas, and coalbed natural gas development is concentrated within sage-grouse MZs I and II (IHS, 2014; Manier et al., 2013).

In September of 2015, the U.S. Fish and Wildlife Service (USFWS) issued a decision that the Greater sage-grouse was not warranted for protection under the Endangered Species Act (USFWS, 2015). This decision followed years of collaborative planning designed to provide conservation benefits by conservationists, land owners, industry, states, and the federal government. This unprecedented partnership of diverse stakeholders was sparked by the 2010 USFWS determination that the species was warranted for listing, but precluded by higher-priority species efforts (USFWS, 2010). The 2010

warranted decision was grounded on analysis of existing threats to sage-grouse, as well as a lack of adequate regulatory mechanisms to conserve the species. In the 2010 decision, non-renewable energy development was one of the factors forecast to negatively impact sage-grouse populations. This was based on basic analysis by USFWS of well location data, GIS buffers, and lease data (USFWS, 2010).

The objective of this study is to provide estimates of future risk to Greater sage-grouse from oil and gas development. To do this we map the probability of oil and gas development across six western states and spatially refine this map into future development scenarios based on published recoverable resource area assessments. We quantify the exposure risk of sage-grouse populations and breeding habitat to these future oil and gas development scenarios, and estimate the reductions in exposure that might be achieved by proposed conservation actions. Our work demonstrates how spatial modeling and GIS visualization can be used by managers to assess likely outcomes of conservation decisions.

2. Methods

2.1. Site Description

The WAFWA Conservation Strategy for Greater Sage-grouse delineated seven sage-grouse management zones to guide conservation and management. The MZ boundaries were delineated based on their ecological and biological attributes (floristic provinces) rather than on arbitrary political boundaries (Stiver et al., 2006). We focused our analysis on sage-grouse MZs I and II located in eastern Montana, the far western and central portions of the Dakotas, all of Wyoming except for the far southeastern corner, the far northeastern corner of Utah, and northwestern Colorado. The four geologic basins most affected by oil and gas development; 1) Powder River, 2) Williston, 3) Southwestern Wyoming, and 4) Uinta–Piceance, are all located in MZs I and II (Figure 1). Compared with other areas

in the eastern part of the range, these basins coincide with the highest proportion of high-density areas of sage-grouse (Doherty, Tack, Evans, & Naugle, 2010).

2. 2. Development Potential Model

We used a classification model that combined producing well locations and predictive spatial data on the presence of oil and gas deposits to predict the probability of oil and gas development potential across the landscape (oil and gas Development Potential Model). We chose this approach because the development of oil and gas resources exhibits a spatially heterogeneous pattern across vast landscapes such as sage-grouse MZs (H. E. Copeland, Doherty, Naugle, Pocewicz, & Kiesecker, 2009; IHS, 2014). To account for the heterogeneous pattern, analysis of future risk to sage-grouse from oil and gas development cannot be based solely on estimates of oil and gas volumes extrapolated uniformly across geologic assessment units (DOI et al., 2008). While leased areas may provide an indication of where development could occur, not all leases in effect on Federal lands are drilled for production (BLM, 2014a). Additionally, land ownership, including surface management and subsurface mineral rights, are not necessarily indicative of where future development is more likely, as conflicting business incentives occur across the landscape. For example, although royalty payments on Federal lands are generally lower than on private or state lands, the permitting process on Federal lands often takes significantly longer (OIG & DOI, 2014).

We created our Development Potential Model following the published methods of Copeland et al. (H. E. Copeland et al., 2009). We used known locations of producing and non-producing oil and gas wells, along with geophysical, topographic, and geologic data important to predicting petroleum resource deposits. We statistically linked producing and non-producing well locations through September, 2014 to geologic characteristics at those locations to generate a 1-km² prediction map using

Random Forests statistical techniques. We predicted the probability (0-1) that each 1-km² area in our study area would have one or more wells developed. We purchased IHS proprietary well point locations (IHS, 2014) for six states (CO, MT, ND, SD, UT, WY) covering MZs I and II. We used well selection parameters from Copeland et al. (2009) to first filter for wells that were oil and gas wells (injection, water, storage, etc. wells were removed). We then used their filters to divide these wells (N=282,199) into those that were producing and non-producing. We included the six predictor variables used in the Copeland et al. (2009) model, but we updated the well depth surface to account for new wells drilled since 2008 (Table 1). We also added two new layers: 1) Rocktype, which is a higher resolution geologic layer, and 2) an aquifer permeability layer for a total of eight predictor layers (Table 1).

Table 1. Spatial data used in Random Forests to predict the probability of oil and gas development. All data were converted to 1-km² rasters.

Covariate Data	File Name and Description	Source
Generalized Geologic Map of the Coterminous United States	geology: Bedrock geology at a 1:5,000,000 scale.	http://nationalatlas.gov
Bouguer gravity	bouggrav: Bouguer gravity anomaly map corrects for influences of the Earth's tides and rotation, crustal density, and topography on gravity station values.	ftp://ftpext.usgs.gov/pub/cr/co/denver/musette/pub/GEOPHYSICAL_DATA/cdrom_DDS-9/GRIDS/ARC_INFO/
Isostatic residual anomaly	isograv: Isostatic residual anomaly data removes the long-wavelength part of the gravity field to	ftp://ftpext.usgs.gov/pub/cr/co/denver/musette/pub/GEOPHYSICAL_DATA/cdrom_DDS-9/GRIDS/ARC_INFO/

	correct for topographic load and provide for surface gravity mapping.	
Magnetic gravity	magneti: Residual total intensity of Earth's magnetic field.	ftp://ftpext.usgs.gov/pub/cr/co/denver/musette/pub/GEOPHYSICAL_DATA/cdrom_DDS-9/GRIDS/ARC_INFO/
Elevation	elevati: 30-m USGS National Elevation Data.	http://nationalatlas.gov
Depth to bedrock	WellTD2014: An natural neighbor interpolation of the total depth field found in the IHS well dataset. A surface created to model depth to bedrock.	https://www.ih.com/products/oil-gas-tools-enerdeq-browser.html
Aquifer permeability	aqpermnew: Aquifer permeability class ranging from 1 to 7, lowest to highest.	http://water.usgs.gov/GIS/metadata/usgswrd/XML/hlrus.xml#stdorder
Rocktype	rocktype: A combination of the predominant and second most predominant lithology found in the formation at scales ranging from 1:100,000 to 1:1,000,000.	http://mrdata.usgs.gov/geology/state/

We followed standard techniques to fit oil and gas predictor data to our well response variable. Our model relies on non-linear Random Forests statistical techniques to address over-fit and parameter sensitivity issues often found in Classification and Regression Trees (CART) models (Breiman, 2001). We first ran an algorithm in R to select a spatially and class-balanced subset of 40,000 well locations for our training data. By creating a balanced subset, we increased our statistical model's efficiency and ensured we included producing and non-producing wells. We limited these data so only one point

represented each 1 km² area (N = 18,000). If both producing and non-producing wells occurred within the same 1 km² space, we considered that area as producing. We then used spatial data (Table 1) as predictor variables within randomForest (Liaw & Wiener, 2014) with 300 bootstrap classification tree replications to statistically build relationships with producing and non-producing wells. We used the rf.modelSel model selection function within the R package rfUtilities to select final variables for modeling (Evans & Murphy, 2015). The best fit model included all of the predictor variables. Finally, we used R to predict a probability surface on a 0 to 1 scale based on the predictor GIS raster files. Our Development Potential Model provides a relative ranking of the probability that an area may experience future development, but it does not quantify how much development is projected to happen in the future.

We investigated both model fit and the ability to predict independent data using two separate methods. We analyzed our model fit using standard out-of-bag (OOB) testing techniques available with randomForest. These techniques provide internal model validation using response data that is held out of each bootstrap sample to estimate observed versus expected classification errors. We validated the model's predictive capability by building another model using the same eight covariates with wells permitted 1900-1993, and then compared the results to the locations of producing wells permitted 1994-2014. This assessment increased confidence in our predictions by validating our model with independent data. If our model accurately predicts the location of future producing wells, then low probability bins should correspond with a low number of future wells and higher probability bins should correspond to more producing wells. A chance assignment would show numbers of wells evenly distributed throughout the bins. To formalize this comparison, we applied the Boyce index (Boyce, Vernier, Nielsen, & Schmiegelow, 2002) to look at observed versus expected occurrence using the independent values from the 1994-2014 producing well points (N = 10,906) and the pre-1994 model probabilities

binned into deciles. The Boyce index uses Spearman's rho to compare ranks of increasing bins with the area-adjusted frequencies of producing wells found in those bins.

2. 3. Development Scenarios

Unlike Copeland et al. (2009), we did not simulate the location and density of future well locations. Our rationale for this is threefold: First, BLM resource management plan (RMP) reasonable foreseeable development (RFD) data (BLM & DOI, 2008) received from the BLM in early 2015 was inconsistent across the landscape with regard to development methodology and spatial resolution. The finest scale forecast by the BLM was the number of wells within a township, and the largest was a large field office boundary split into three polygons of low, medium, and high. Past literature and current oil and gas well locations clearly show that oil and gas development is clustered (H. E. Copeland et al., 2009; IHS, 2014), therefore we rejected the assumption that oil and gas development would be evenly distributed across a third of a BLM field office's area. Second, we recognized the difficulty in accurately simulating well locations across broad landscapes, because well spacing varies spatially by geology, resource type and recovery technology. For example, shallower fields may require tighter spacing, and coalbed methane fields typically have higher well densities than conventional gas fields (NRLC, 2002). The current shift from vertical to horizontal and directional drilling also allows multiple wells to be placed on one pad, and in some cases, a single horizontal well may take the place of 8 to 16 vertical wells (Applegate & Owens, 2014). Finally, well spacing rules are under the jurisdiction of state oil and gas commissions for non-Federal lands, and producers may petition these commissions for modifications to spacing rules to overcome engineering challenges.

Instead, we used USGS National Oil and Gas Assessment data (assessments) to define how much area is likely to experience development in the future (USGS, 2015). We used the assessments to

calculate three different scenarios (low, baseline and high) for the amount of area likely to experience future oil and gas development. We linked area estimates from our scenarios (i.e. how much area was estimated) with our Development Potential Model (i.e. probability of development) to produce estimates of the area and location of future energy development under three scenarios.

The USGS Energy Resources Program periodically assesses the potential for recoverable oil and gas resources within priority geologic provinces in the United States. Assessments are peer-reviewed, used widely, and published online (Charpentier & Cook, 2010, revised 2012). Assessments do not correspond to an exact time frame. Instead, they correspond to predictions about the amount of oil and gas resources within an assessment unit (AU) and the approximate number of wells required to extract the predicted resource, if all known resource areas were developed. These estimates are of technically recoverable oil and gas resources based on production data current at the time of the assessment (Charpentier & Cook, 2010, revised 2012). They include current technologies such as fracking and horizontal drilling, but do not include predictions about technologies that do not currently exist, or changes in economic conditions. While USGS estimates do not correspond to an exact timeframe, we concluded that they were the best publically available estimates of potential future development. We collaborated with USGS Central Energy Resources Science Center staff to create formulas from their published assessments to estimate the total area likely to have recoverable resources within continuous and conventional AUs located within MZs I and II (Figure 1). The formulas we developed are found in the sections below.

Figure 1. Geological provinces and assessment units. Provinces are labeled, and those used for conventional area calculations are hatched. Overlapping assessment units are shown in solid gray with dashed outlines. Provinces within MZs I and II that lacked conventional field polygons representing area discovered included Bighorn Basin and Wind River Basin. North-Central Montana had no conventional volume discovered estimates.

After we quantified the area of potential future development from the assessments, we used GIS routines to select areas from the Development Potential Model that had the highest oil and gas development potential within each AU based on continuous and conventional estimates. This allowed us to spatially refine the areas within each AU into three scenarios of oil and gas development (low, baseline, and high). This was important, because AU boundaries are large and, as previously mentioned, development within them is heterogeneous.

We compared our low, baseline and high development scenario results to producing well locations and determined that over half of the predicted low scenario locations were already producing. Because of this, we focused our exposure analysis on the baseline and high scenarios, which had less areas predicted for future development already in development.

2. 3.1. Area of Development Data & Equations for Continuous Oil and Gas Development

We used the USGS Oil and Gas Assessment map interface to download assessment tabular data (i.e. inf####.tab files) for continuous assessments within our study area (USGS, 2015). There were 63 AUs within 9 provinces with assessment data (Figure 1). Note that the USGS also identifies hypothetical plays but does not estimate undiscovered resources. If hypothetical plays are found to contain significant resources in the future, our area estimates may be low. Assessment units are defined as a mappable volume of rock within a total petroleum system that encompasses fields (discovered and undiscovered) that share similar geologic traits and socio-economic factors (Klett, Schmoker, Charpentier, Ahlbrandt, & Ulmishek, 2005). We downloaded GIS polygons of AUs from the USGS Oil and Gas Assessment map interface (USGS, 2015). An important point about AUs is that many overlap spatially. For our final scenarios, if a grid cell was selected based upon one or more AUs, it was included as a future development area within that scenario.

There are four data fields required for our calculations within each .inf file. These include the total AU area in acres (TAA), the estimated percentage of untested AU area (TAAU), and the percentage of untested area with the potential for additions to reserves, which incorporates success ratio calculations (UAAP). Additionally, we used the geologic probability (Geoprob % - based on the product of charge, rocks and timing probabilities) that there could be at least one undrilled well as a fractional value from 0 to 1 (Klett, Charpentier, & Le, 2003). Data are represented as a minimum (F100), median (F50) or mode, and maximum (F0) value. These correspond to estimates of three different probabilistic outcomes; minimum (F100) and maximum (F0) denote actual minimum and maximum values of the distribution, with a central value of either the median or mode. For standardization of earlier assessment with newer assessment data, we converted all mode and median values to mean values using the arithmetic average of the triangular probability distribution (Schmoker & Klett, 2000). We defined our low scenario using the minimum values, the baseline scenario from the mean values, and our high scenario from the maximum values.

We calculated the untested area predicted to have resources and be successful as:

$$TAA * TAAU * UAAP \quad (1)$$

The tested area as:

$$TAA * (1 - TAAU) \quad (2)$$

For min calculations, we subtracted max TAAU from 1. For max calculations, we subtracted min TAAU from 1. We did not need to provide any adjustment for mean calculations.

The total area predicted to be developed was derived by putting the two equations together as:

$$(TAA * TAAU * UAAP) + [TAA * (1 - TAAU)] \quad (3)$$

We needed to adjust for geologic probability not equal to 1. For geologic probabilities less than 1, the total minimum area predicted to be developed became 0, and the mean total predicted area was multiplied by the Geoprob% fraction. Geologic probabilities less than 1 had no effect on maximum values.

Finally, we derived the proportion of a given AU predicted to have resources, and used this in our GIS routines to linking assessment area to the Development Probability Model. This was calculated as total area predicted to be developed divided by total area:

$$((TAA * TAAU * UAAP) + [TAA * (1 - TAAU)]) / TAA \quad (4)$$

2.3.2 Area of Development Data & Equations for Conventional Oil and Gas Development

USGS assessments of conventional oil and gas resources differ from continuous estimates in that they are based on volumes of resources, not areas discovered and undiscovered within AUs. Our conventional calculations differ in that they are calculated by geologic province and not AU. Provinces are defined geologically, and most province boundaries are defined by major geologic changes and are larger in size than AUs (Figure 1).

Conventional oil and gas assessments were generated under older methodologies and do not include area estimates. Instead, they report the volume of discovered and undiscovered resources. In order to generate an area estimate from published assessments, we assumed it was reasonable that the ratio of undiscovered vs. discovered area would be roughly equivalent to the ratio of undiscovered vs. discovered volume of oil and gas resources. For example, if a hypothetical conventional field required 100 km² to obtain 50% of the estimated resource, we would assume it would take an equivalent area to obtain the remaining 50% of the resource. Based on this assumption, we defined the following formula to calculate conventional area undiscovered (Au) for each province: (Volume Undiscovered/Volume

Discovered) = (Area Undiscovered/Area discovered) or $V_u/V_d = A_u/A_d$. This was then rearranged to provide an estimate of the area of undiscovered conventional oil and gas:

$$A_u = A_d * V_u/V_d \quad (5)$$

Where A_d = area discovered, V_u = volume undiscovered, and V_d = volume discovered.

We used conventional field polygons downloaded for each province from the U.S. Energy Information Administration (EIA, 2015) to define the area discovered (A_d). We used this data source because A_d was not available within USGS assessment tabular files. For volume discovered (V_d), we used the USGS Oil and Gas Assessment map interface to download assessment tabular data (“kvol####.tab” files, USGS, 2015). Volume discovered (V_d) was tabulated from the kvol####.tab files for assessments labeled as conventional by totaling the “KRPET MMB” values for all conventional AUs by Province. KRPET MMB represents known recoverable petroleum (oil, gas, and NGL) volume (cumulative production plus remaining reserves) from the reported reservoirs in the AU (Klett et al., 2003). This volume is in million barrels of oil equivalent.

For volume undiscovered (V_u), we used the map interface to download assessment tabular data (“vol####.tab” files, USGS, 2015), which contain estimates of undiscovered petroleum resources in several fields (Klett et al., 2003). From these files we summed fields from AUs labeled as conventional as:

$$OILF_{##} \text{ MMB} + NGLF_{##} \text{ MMB} + LIQF_{##} \text{ MMB} + (AGF_{##} \text{ BCF}/6) + (NGF_{##} \text{ BCF}/6) \quad (6)$$

Where $OILF$ = undiscovered oil, $NGLF$ = undiscovered natural gas liquids, $LIQF$ = undiscovered liquids (oil and NGL in gas accumulations), AGF = undiscovered associated/dissolved gas (gas in oil accumulations), NGF = undiscovered non-associated gas (gas in gas accumulations).

Gas fields represented as billions of cubic feet (BCF) were divided by 6 to convert to MMBOE before summing. We did this for each combination of F95, mean, and F5 fields, represented above by “##” in the field names. As described above, “F” values represent probabilistic outcomes. Here, F95 represents a 95-percent chance of at least the amount tabulated and F5 represents a 5-percent chance. Therefore, these values are not true minimums and maximums. To standardize with continuous assessment outcome values, we defined our low scenario using F95 values, the baseline scenario from mean values, and the high scenario from F5 values. We calculated total province area (Pa) with GIS using downloaded province polygons (USGS, 2015).

Our final calculation was proportion province undiscovered, calculated as:

$$(Ad * Vu/Vd) / Pa \quad (7)$$

2. 4. GRSB Breeding Habitat and Population Exposure

We quantified exposure based on the co-location of sage-grouse with predicted oil and gas development scenarios to minimize our study assumptions. This is in contrast to prior studies that modeled population loss estimates in relation to oil and gas development potential. We used GIS overlay analysis to calculate the percent of population exposed by summing sage-grouse population index values overlaying the baseline and high future oil and gas scenarios and dividing by the total summed value of the population index within each management zone. This allowed us to understand the percent of the population that was exposed to future energy development. We applied similar overlay analysis to sage-grouse breeding habitat to determine the percent area of breeding habitat exposed. Here we summed the area of breeding habitat overlaying each scenario and divided by the total area of breeding habitat within

each management zone. We found similar results for both sage-grouse metrics, with slightly lower exposure percentages for breeding habitat.

We used spatial layers developed by Doherty et al. (Doherty, Evans, Coates, Juliusson, & Fedy, 2015) to quantify the co-location of sage-grouse breeding habitat and population within MZs I and II. Doherty et al. (2015) developed two spatial models: 1) Occupied Breeding Habitat Model, and 2) Population Index Model. They built these models within MZs because wide variation exists in occupied habitats across the range, and risks to sage-grouse vary across MZs. These models were developed for conservation planning and risk analyses, because not all areas within the current occupied distribution (Schroeder et al., 2004a) are sage-grouse habitat, and some areas within occupied habitats contain a disproportionate number of birds (Connelly et al., 2004; Doherty et al., 2010). The Doherty et al. (2015) Population Index Model allows better spatial understanding of how risks to sage-grouse align with population centers of sage-grouse. For example, strong documented negative effects of oil and gas within the literature (Aldridge & Boyce, 2007; Braun, 1998; Connelly et al., 2004; Doherty, 2008; Holloran et al., 2007; Knick et al., 2003; Leu & Hanser, 2011; Lyon & Anderson, 2003b; Walker et al., 2007; Zou et al., 2006) do not necessarily translate to population impacts across vast areas such as the entire sage-grouse range. We would expect high levels of future impacts to occur if current sage-grouse population centers overlap areas with areas defined by our oil and gas scenarios and development occurs at high densities. Conversely, we would expect future impacts to be low, if these population centers do not overlap areas defined by our scenarios. It is important to note that our oil and gas predictions estimate only the colocation (i.e., exposure) of oil and gas development with sage-grouse. It is unlikely that exposure to oil and gas development will result in 100% impact to populations, as past research has shown varied levels of impact dependent on many factors, such as development density and footprint size (Applegate & Owens, 2014; Doherty, 2008; Gregory & Beck, 2014), landscape features (Dinkins,

Conover, Kirol, Beck, & Frey, 2014), potential co-stressors (Taylor, Tack, Naugle, & Mills, 2013) and site mitigation practices used by industry (Fedy, Kirol, Sutphin, & Maechtle, 2015; Kirol, Sutphin, Bond, Fuller, & Maechtle, 2015). Thus, our exposure estimates serves as an upper extent of potential impacts within scenarios.

2. 5. Conservation from Federal land use plans and the Wyoming core area strategy

We evaluated the two major conservation planning efforts developed specifically for sage-grouse: The U. S. Bureau of Land Management (BLM) Land Use Plans (LUP, BLM, 2014b; BLM, 2014b; BLM & USFW, 2015; BLM & USFW, 2015; LUP, BLM, 2015a; BLM & USFS, 2015a; BLM & USFS, 2015a; BLM, 2015b; BLM & USFS, 2015b; BLM, 2015b; BLM & USFS, 2015b; BLM, 2015c; BLM & USFS, 2015c; BLM, 2015c; BLM & USFS, 2015c; BLM, 2015d; BLM, 2015d; BLM, 2015e; BLM, 2015e; BLM, 2015f; BLM, 2015f; BLM, 2015g; BLM, 2015g; BLM, 2015h; BLM, 2015h) and the Governor of Wyoming's core area strategy (State of Wyoming, 2011). We recognize there are other conservation measures for sage-grouse; however, they are smaller in scale and not within the scope of this study. The National Greater Sage-Grouse Land Use Planning Strategy is a planning framework designed to incorporate sage-grouse conservation measures into regulatory mechanisms within BLM LUPs. We focused on the land use categories that had clear, published links between conservation actions and sage-grouse responses, and were consistently applied across field offices. BLM provided GIS data for four categories of oil and gas land use plan decision data. 1.) areas open to leasing, with standard constraints; 2.) areas open to leasing, subject to moderate constraints; 3.) areas open to leasing, subject to major constraint, such as no-surface-occupancy stipulations; and 4.) areas closed to leasing. We focused our analysis on "open, subject to major constraints" (no surface occupancy; NSO) and "closed" categories, as these generally eliminate surface disturbances associated with energy development. We did not analyze the BLM class "open, subject to moderate constraints", which

includes restrictions such as timing limitations and controlled surface use (CSU), e.g. 0.6 mile NSO around lek (breeding area), because there is wide variation in actual restrictions at the local level, and the literature has shown impacts to sage-grouse at distances exceeding CSU buffers (Aldridge & Boyce, 2007; Carpenter, Aldridge, & Boyce, 2010; Harju, Dzialak, Taylor, Hayden-Wing, & Winstead, 2010; Holloran, 2005; Naugle, Doherty, Walker, Holloran, & Copeland, 2011).

The Greater Sage-Grouse Core Area Strategy is the State of Wyoming's primary regulatory mechanism to conserve sage-grouse. This is embodied under the Governor's Executive Order 2008-5, updated in 2011 (State of Wyoming, 2011). The Wyoming core area strategy has been adopted by the Wyoming BLM as a primary method to address the conservation of sage-grouse habitat (BLM, 2012). It is also identified as a conservation mechanism in the final Lander RMP Record of Decision (BLM, 2014b), as well other proposed Wyoming land use plans (BLM, 2015a; BLM & USFS, 2015c; BLM, 2015g). The core area strategy limits the density of infrastructure development, including oil and gas, within areas having the highest sage-grouse breeding population densities (Doherty, Naugle, Copeland, Pocerwicz, & Kiesecker, 2011). Although the Wyoming core area strategy does not provide complete closure to oil and gas development, the literature supports the considerable conservation benefit that reducing overall habitat disturbance (Page 12 of Executive Order 2011-5 – not to exceed 5%) and oil and gas development density (1 well pad per section) provides to sage-grouse populations (H. E. Copeland et al., 2013; Doherty, 2010; Gregory & Beck, 2014). We wanted to understand the amount of oil and gas exposure to sage-grouse from our scenarios, that were also subject to conservation measures from the BLM LUPs and the Wyoming core area strategy. We felt this was important, as these plans were specifically designed to reduce or ameliorate anthropogenic impacts to sage-grouse, including those from oil and gas development.

We received proposed LUP decision data from the BLM in March, 2015, and used GIS overlay analysis to examine what portion of the exposed population and breeding distribution would be subject to BLM LUP land use decisions that could mitigate or reduce impacts of oil and gas development. We calculated the percent reduction of population exposed for each decision by summing the sage-grouse population index values overlaying *both* the land use decision and each oil and gas scenario and dividing by the total summed value of the population index exposed within the respective scenario for each management zone. Finally, we multiplied the proportion found above by the percent oil and gas exposure to get the percent reduction for each scenario. A similar overlay analysis was used to determine the percent reduction of breeding habitat exposed for each decision. Here we summed the area of breeding habitat overlaying *both* the decision and each oil and gas scenario and divided by the total summed exposed area within the respective scenario for each management zone. Finally, we multiplied the proportions found above by the percent oil and gas exposure to get the percent reduction for each scenario.

We obtained State of Wyoming core area polygons and, using the methods described above, calculated the percent reduction in exposure of sage-grouse population and breeding habitats to oil and gas development scenarios after the core areas were applied. We then analyzed the results of the BLM land use decisions and Wyoming core polygons together to determine residual exposure. First, we removed areas of the Wyoming core polygons that overlapped BLM closed or major constraints to avoid double counting, and then calculated percent reduction for those areas. We next calculated the residual exposure of sage-grouse population and breeding habitats to baseline and high oil and gas development scenarios by summing the percent reductions for closed, major constraints and WY core, and subtracting this from total oil and gas exposure. We define residual exposure as sage-grouse population or breeding habitat that exists within future oil and gas development scenarios and is *not* subject to conservation.

Finally, we calculated the overall percent oil and gas exposure reduction from the original exposure and residual exposure percentages. Our residual exposure estimates serve as the lower extents of potential impacts within scenarios.

3. Results

Model fit statistics and independent validations indicated that the Development Potential Model has good model fit and predictive ability. We observed an Out-of-bag error rate of 20.44% from our bootstrap samples. Additionally, we showed that errors were balanced across producing (0.25) and non-producing (0.17) classes. Independent producing wells from 1994-2014 followed the same pattern as those from 1900-1993 when classified into quintile bins based on the 1900-1993 probabilistic surface (Figure 2). The highest two bins included 87.6% of all producing wells with a clear pattern showing avoidance of development with fewer wells than expected by chance in bins 1 to 3. Bin 4 showed slightly more wells than would be expected by chance, while bin 5 had over three times the number of wells expected by chance. Our results showed a highly significant model with Boyce index = 1.0; $P < 0.001$ (Boyce et al., 2002), thus we feel comfortable using our model for future predictions.

Figure 2. Comparison of producing wells permitted pre-1994 with producing wells from 1994-2014. Frequency of wells based on categories numbered 1 to 5 showing quintile breaks of equal area for 1900-1993 model predictions.

Figure 3. Oil and gas development potential model in sage-grouse management zones I and II. This map shows the potential for oil and gas development in quintile categories from low (teal) to high (brown). This model shows the probability of oil and gas development is highly clumped across the landscape and high values correlate well with areas of known production.

Figure 4. Oil and gas development potential model refined into scenarios of baseline and high in sage-grouse management zones I and II identifies landscapes both with and without producing wells. (a) Baseline development potential in light green and baseline areas with producing wells in dark green. (b) High development potential in light red and high areas with producing wells in dark red. The high scenario shows more area than the baseline with development potential not already in production.

Our exposure predictions quantify a colocation of oil and gas development potential and sage-grouse. Sage-grouse exposure results show that 12-25% of occupied breeding habitats in MZs I and II are predicted to be exposed to baseline and high oil and gas development in the future (Table 3). When BLM closed and major constraints LUP decisions are combined with Wyoming core area protections, residual exposure falls to 6-14% across MZs (Table 3). This translates to a 29-35% and 58-63% reduction in the amount of the breeding habitat exposed for MZs I and II, respectively (Table 3). It is important to note that protections from the Wyoming core area strategy contribute more to exposure reductions in MZ II than MZ I, because MZ II has a higher proportion of its area covered by Wyoming. Our analysis did not include conservation from a similar core area strategy released by the state of Montana after completion of our results.

Table 3. Percent of sage-grouse occupied breeding habitat exposed to oil and gas development before and after conservation. Exposure is the overlap of each development scenario with breeding habitat in occupied range. Residual exposure equates to areas exposed to future oil and gas development scenarios *not* subject to conservation from the Bureau of Land Management land use plans, the Wyoming core area strategy, or the two combined. Exposure reduction is the percent exposure that is subject to conservation.

	Oil and Gas Exposure	BLM LUP Conservation	WY Core Conservation ¹	BLM & WY Core Conservation ²
Management Zone	Exposure %	Residual Exposure (Exposure Reduction) %	%	%
MZ I				
High	21.6	17.0 (21.1)	18.1 (16.2)	14.0 (35.0)
Baseline	12.0	9.9 (17.4)	10.4 (13.0)	8.5 (28.9)
MZ II				
High	24.7	18.5 (25.2)	11.9 (51.7)	9.1 (63.2)
Baseline	14.1	10.9 (22.3)	7.3 (48.1)	6.0 (57.7)

¹ Wyoming core area conservation only applies to areas within MZ I and II that are within Wyoming.

² 24% of Wyoming core area overlaps with BLM LUP decisions. We removed this overlap to avoid double counting exposure.

Sage-grouse population exposure is slightly higher than habitat results with 15-27% predicted to be exposed to baseline and high oil and gas development in the future (Table 4; Figures 5a and 6a). When conservation protections are applied, residual exposure falls to 5-17% for both MZs (Table 4; Figures 5b and 6b). Reduction in the percent oil and gas exposure to sage-grouse population from conservation is 31-37% in the baseline to high scenarios in MZ I, and 64-68% in MZ II (Table 4). These results show that the relative impact of conservation, demonstrated through oil and gas exposure reduction (BLM and WY core), increases an average of 5% in the high over the baseline scenario in both MZs. This trend is also seen when reviewing exposure reductions of the individual BLM land decision and the WY core area strategy.

Table 4. Percent of sage-grouse modeled population exposed to oil and gas development before and after conservation. Exposure is the overlap of each development scenario with modeled population in occupied range. Residual exposure equates to areas exposed to future oil and gas development scenarios *not* subject to conservation from the Bureau of Land Management, the Wyoming core area strategy, or the two combined. Exposure reduction is the percent exposure that is subject to conservation.

	Oil and Gas Exposure	BLM LUP Conservation	WY Core Conservation ³	BLM & WY Core Conservation ⁴
Management Zone	Exposure %	%	Residual Exposure (Exposure Reduction) %	
MZ I				
High	26.7	20.4 (23.7)	22.7 (14.9)	16.9 (36.5)
Baseline	15.1	12.3 (18.1)	12.9 (14.3)	10.5 (30.5)
MZ II				
High	26.6	18.4 (30.7)	11.7 (55.9)	8.5 (67.8)
Baseline	14.9	10.7 (28.5)	6.7 (54.8)	5.4 (64.0)

³ Wyoming core area conservation only applies to areas within MZ I and II that are within Wyoming.

⁴ 24% of Wyoming core area overlaps with BLM LUP decisions. We removed this overlap to avoid double counting exposure.

Figure 5. GIS based visualizations help demonstrate Sage-grouse population exposure to Baseline scenarios of oil and gas development potential, and how BLM land use plans and the Wyoming Core Area strategy could reduce that exposure. All raised areas indicate exposure to oil and gas development *without* any conservation actions (a), and reduction in exposure *when* conservation actions reduce or eliminate development intensity within designated conservation areas (b). The height and color indicate the amount of sage-grouse exposed in 10% population bins (Doherty et al., 2016), with warmer colors and higher areas representing larger numbers of sage-grouse.

a. MZ I: High Oil & Gas Exposure = 26.7% of the Population

b. MZ I: High Oil & Gas Residual Exposure = 16.9% of the Population

Figure 6. GIS based visualizations help demonstrate Sage-grouse population exposure to High scenarios of oil and gas development potential, and how BLM land use plans and the Wyoming Core Area strategy could reduce that exposure. All raised areas indicate exposure to oil and gas development *without* any conservation actions (a), and reduction in exposure *when* conservation actions reduce or eliminate development intensity within designated conservation areas (b). The height and color indicate the amount of sage-grouse exposed in 10% population bins (Doherty et al., 2016), with warmer colors and higher areas representing larger numbers of sage-grouse.

4. Discussion

In this study we develop novel scenarios of future oil and gas development potential, quantify how these scenarios overlap sage-grouse breeding habitat and populations, and then analyze how proposed and enacted conservation strategies are likely to reduce risk. We show that risk of oil and gas exposure to sage-grouse populations is spatially heterogeneous and varies widely across the vast extents of management zones I and II (Figures 5a and 6a). We also show, when implemented, the Federal fluid mineral decisions and the Wyoming Core Area Strategy will minimize the exposure risk of sage-grouse to oil and gas development (Figures 5b and 6b). We estimate these conservation strategies in concert could reduce sage-grouse population exposure to oil and gas development by roughly 31-37% in MZ I and 64-68% in MZ II, respectively (Table 4).

Land managers and policy makers are frequently under mandate to make conservation decisions in circumstances of considerable uncertainty. To reduce uncertainty around management decisions, risk assessments must be structured into a set of plausible alternative scenarios that quantify both exposure of priority areas to future risk and land management strategies designed to alleviate those risks (Duggan, Eichelberger, Ma, Lawler, & Ziv, 2015; Mahmoud et al., 2009). This involves assessing the

vulnerability of species to future threats and modeling techniques to predict the both the locations of priority species, and the location and intensity of future threats. Vulnerability of sage-grouse populations to oil and gas development is well documented (Aldridge, 1998; Aldridge & Brigham, 2003; Aldridge & Boyce, 2007; Braun, 1998; Connelly et al., 2004; Doherty, 2008; Holloran et al., 2007; Knick et al., 2003; Leu & Hanser, 2011; Lyon & Anderson, 2003a; Suter, 1978; Walker et al., 2007; Zou et al., 2006). We used new sage-grouse breeding population models (Doherty et al., 2015), and publically available USGS National Oil and Gas Assessment data (USGS, 2015) to develop the most robust and seamless estimates of how much oil and gas development may occur in the future. We updated a previously published modeling approach that identified landscapes where the oil and gas risk is more likely to occur (H. E. Copeland et al., 2009) to understand the locations of the landscapes most likely to produce future oil and gas resources. We then organized our model results into scenarios to provide a structure that allows managers to explore uncertainty via alternative potential outcomes (Drielsma & Ferrier, 2006; Peterson, Cumming, & Carpenter, 2003).

Model scenarios are plausible alternate future outcomes given different assumptions (Mahmoud et al., 2009). Assumptions help us simplify our real world system to a representation designed to solve a problem (Starfield, 1997), therefore it is critical to understand our assumptions and their strength, and leave out weak ones. By intent, we attempted to minimize our assumptions by avoiding speculation on well spacing densities, which vary across the landscape and are subject to change based on recovery technologies (Applegate & Owens, 2014; NRLC, 2002). For these reasons we did not estimate percent of the population impacted, instead we quantified the percent of the population that could be exposed to oil and gas in the future under varying exposure scenarios. Our results should not be interpreted as estimates of population loss, because they do not explicitly model the relationship of exposure to population decline. It is well documented that the level of negative impact from sage-grouse exposure to

oil and gas is dependent on multiple variables, with impacts increasing with higher development intensities (Dinkins et al. 2014; Doherty 2010; Gregory and Beck 2014; Harju et al. 2010; Hess and Beck 2012; Holloran 2005; Kirol 2012; Taylor et al. 2013). Reducing exposure to high development intensities will certainly reduce impacts to sage-grouse, however only monitoring through time will indicate if the level of development allowed within Wyoming Core Areas alleviates versus reduces the impacts associated with oil and gas development. Thus, our scenario-based estimates and resulting GIS based visualizations help managers bound the potential risk of future energy develop and allow land managers to better account for the uncertainty inherent in this analysis, as well as in their ultimate conservation decisions (Peterson et al., 2003).

Despite methodological differences in defining the amounts of future oil and gas development and simulating well spacing, our results are generally consistent with Copeland et al.'s work analyzing impacts to sage-grouse (H. E. Copeland et al., 2009) and potential conservation benefits (H. E. Copeland et al., 2013). We estimate 22-25% exposure of occupied breeding habitat to the high scenario in MZs I and II, which is comparable to the range predicted by the only other MZ I and II scale estimate published in 2009 by Copeland et al. Copeland et al. (2009) found 14–19% of their study area has high future oil and gas development potential (Copeland et al. 2009). In the same study, Copeland et al. (2009) showed an expected 7-19% population decline from future oil and gas development. Our population exposure estimates are similar at 15-27% under both scenarios. Copeland et al. (2013) found that the Wyoming core area strategy was important in both short-term and long-term reduction of male sage-grouse population declines, and was more important than targeted easements. When compared with no conservation, they found that the core area policy alone reduced statewide population decline by 21% in the short-term, and 38% in the long-term (Copeland et al. 2013). These results are bounded by our results, which show population exposure reductions of 14% and 55% in the baseline and 14% and 57%

in the high oil and gas scenarios under Wyoming's core area strategy in MZs I and II, respectively (Table 4). Our calculated reductions in population exposure of Wyoming core areas along with BLM closed and major constraints are consistent with these percentages at 30% and 64% population exposure reductions in the baseline and 37% and 68% in the high oil and gas scenarios for MZs I and II, respectively (Table 4). Having similar, but different methodologies arrive at consistent answers (i.e. Copeland et al. 2009 and this study) allows decision makers to have more confidence in both analyses.

Oil and gas development is known to negatively affect a wide variety of species, thus our oil and gas scenarios could have utility for a much wider range of priority species in the western U.S. Energy development directly impacts wildlife by altering habitat use (Sawyer, Nielson, Lindzey, & McDonald, 2006; Sawyer, Kauffman, & Nielson, 2009) and population dynamics (Sorensen et al., 2008). It indirectly impacts wildlife by facilitating spread of nonnative invasive plants (Bergquist, Evangelista, Stohlgren, & Alley, 2007) and diseases such as West Nile virus in North America (Naugle et al., 2004; Zou et al., 2006). The development of spatially explicit models for other priority species would be useful for estimating oil and gas exposure scenarios for these species using our model. Likewise, our model could be integrated with new models being developed to understand resistance and resilience of sage-grouse to invasive plants in the eastern part of their range, and then develop mitigation strategies in areas likely to experience future energy development.

The conservation strategies designed for sage-grouse evaluated in this paper may also protect other species from oil and gas development. For example, past research has evaluated sage-grouse as an umbrella species for sagebrush associated species and found sage-grouse habitat would provide conservation benefits for sagebrush obligates; however, little support was found for benefits to associated species with different land cover affinities (Rowland, Wisdom, Suring, & Meinke, 2006). Likewise, sage-grouse core areas in Wyoming have been shown to offer protection to mule deer

(*Odocoileus hemionus*) in areas that overlap their wintering grounds and migration routes (H. Copeland et al., 2014). Similarly, Hanser and Knick (2011) found a high overlap of passerine birds with the wide range of sagebrush habitats used by sage-grouse; however, they caution that management areas not based on a multiscale organization of habitats would likely be less effective at providing umbrella protections than those implemented at a landscape level (Hanser & Knick, 2011). The success sage-grouse conservation areas will have at providing umbrella protection against oil and gas development is yet to be seen, and should be an area of future research. Because priority sagebrush species may be limited by ecological factors unique to their specific life histories and land cover affinities (Roberge & Angelstam, 2004), and because the potential for oil and gas development in MZs I and II lies partly outside of sage-grouse conservation areas, the umbrella value of sage-grouse may not be as high as we would like, with some species even experiencing negative impacts following limits to oil and gas development in sage-grouse habitat.

Our model is another step forward in bounding uncertainty about potential future effects of development as land managers try to balance competing interests and resource needs across the landscape.

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