

SUPPLEMENTARY INFORMATION

Impacts of Cattle, Hunting, and Natural Gas Development in a Rangeland Ecosystem

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Supplemental Information

Section SI1 explains in detail the adjustments made to GEEM to account for the nitrogen uptake of plant species. Section SI2 presents the steps taken to estimate the existence value of sage grouse using benefit transfer. In section SI3, we discuss strategies for government agencies to mitigate the adverse impacts of natural gas development (NGD); we also explore here what would happen if government officials, instead of maximizing societal welfare, maximize the net benefits of the actors that they represent. Finally, section SI4 shows the sensitivity of key predictions when certain parameters and select modeling assumptions are varied. Table SI1 shows the sources of the parameters associated with energy content, biomass, population densities, average lifespans, plant parameters, and some other variables that arise from the calibration of the model. The hunting rates of elk, antelope, and mule deer can be found in table SI2.

SI1 Nitrogen Uptake

This section discuss the role of macronutrient restrictions in GEEM using nitrogen as an example of a relevant nutrient (Finnoff and Tschirhart, 2011). The availability of nitrogen is the primary factor limiting plant growth in many ecosystems (Chapin et al., 1986; Tilman et al., 1996), and in a prairie system the competition between grasses and shrubs is strongest for nitrogen (Köchy and Wilson, 2000). In the original version of the model, any type of disturbance causes the population of one plant species to continuously grow and displace the other species when light is the only resource that plants require. This result is consistent with the resource/ratio hypothesis which states that the number of competing plant species can be no greater than the number of limiting resources (Tilman, 1985; Miller et al., 2005). GEEM is consistent with the resource/ratio hypothesis (Finnoff and Tschirhart, 2009); therefore, because there are two plant species in the ARNG model, nitrogen is introduced as a second resource to allow coexistence of the plant species. The model includes a restriction that

limits how much nitrogen can be absorbed from different layers of soil according to the grass and shrub root structures and biomass accumulations. This absorption of nitrogen regulates plant growth and biomass accumulation.

The estimation of the nitrogen uptake parameters can be calculated independently of the model calibration since we are assuming that the nitrogen restrictions do not bind at the steady state. We used the information gathered by Ares (1976), Sturges (1977), and Smika et al. (1961) to estimate the nitrogen parameters. The range of the soil layers used by Smika et al. (1961) do not exactly match the segments used by Ares (1976) and Sturges (1977). Therefore, we decided to adapt the ranges according to the Smika layers, 8 in total. The information used is depicted in figures SI2, SI3, and SI4, where the nitrogen uptake proportion of plant species i from soil layer l is represented by $\gamma_{i,l}$.

For the blue grama species, the distribution of the root's weight is divided in segments of 0.05 m with missing information between 0.05-0.1, 0.15-0.4, and 0.45-0.91 m; there are 5.22, 3.19, and 0.49 g between 0-0.05, 0.1-0.15, and 0.4-0.45 m, respectively (Ares, 1976). This grass species does not uptake nitrogen after 0.85 m depth ($\gamma_{Gr,6} = \gamma_{Gr,7} = \gamma_{Gr,8} = 0$) since its roots spread widely in the surface soil, often to distances of 0.3-0.46 m, yet the maximum depth is 0.91 m (Weaver, 1926, chap. IV). We extrapolated the observations to obtain the missing segments assuming that

$$\int_0^{0.05} \omega(x)dx = 5.22; \int_{0.1}^{0.15} \omega(x)dx = 3.19; \int_{0.4}^{0.45} \omega(x)dx = 0.49; \omega(0.85) = 0 \quad (SI1)$$

where $\omega(x)$ is the instantaneous weight of grass' roots at depth x and $\int_{h_0}^{h_1} \omega(x)dx$ is the weight of grass' roots between h_0 and h_1 depths into the soil. We estimated the proportion of nitrogen that an average grass individual uptakes from the 8 soil layers by assuming the following: $\omega(x) = \omega_0 + \omega_1x + \omega_2x^2 + \omega_3x^3$, where the ω parameters can be estimated; and the nitrogen uptake of plants at each soil layer follow the same pattern as the distribution of the roots' weight. Our estimations are shown in the fourth column of figure SI1.

In the case of the shrub species, the distribution of root's weight is divided in segments

of about 0.3 m (Sturges, 1977, p. 272). This distribution fits the Smika layers 5, 6, 7, and 8, but the rest of the layers do not match the segments used in Smika research. Since the average total weight of shrub's roots is 82.76 g (Sturges, 1977, p. 272) (and by assuming that the nitrogen uptake follows the same pattern as the distribution of the roots' weight), then the uptake proportion is simply calculated by dividing the weight in each segment by the total. Our estimations are shown in the last column of figure SI1. The uptake proportion in layers 1-4 is still unknown because the Smika layers 1 and 2 are exactly contained in the first Sturges segment and Smika layers 3 and 4 are exactly contained in the second Sturges segment. Since there are 42.53 and 25.63 g in the first and second segments, we get that $\gamma_{\text{Sh},1} + \gamma_{\text{Sh},2} = \frac{42.53}{82.76} = 51\%$ and $\gamma_{\text{Sh},3} + \gamma_{\text{Sh},4} = \frac{25.63}{82.76} = 31\%$.

The nitrogen uptake proportions are necessary to model the balance between the nitrogen that a plant loses and the nitrogen that the plant maintains internally. Plants use nitrogen to produce biomass, and they continuously lose nitrogen for chemical and predatory reasons (Berendse and Aerts, 1987). The nitrogen uptake of plant species i from layer l is

$$\eta_{i,l} = \vartheta_i n_i x_i \gamma_{i,l} \tag{SI2}$$

where ϑ_i is the minimum requirement of nitrogen for every kilogram of biomass (x_i) that the plant accumulates to satisfy the loss of nitrogen and production of biomass; and $\gamma_{i,l}$ is the uptake proportion that plant species i uptakes from the l -th soil layer. To estimate the missing proportion nitrogen uptake of shrubs ($\gamma_{\text{Sh},i}$ for $i = 1, 2, 3, 4$) and the minimum requirements of nitrogen per kg ($\vartheta_{\text{Gr}}, \vartheta_{\text{Sh}}$), we solve for

$$\begin{aligned}
& \min_{\substack{\{\vartheta_i | i \in \text{SP}\} \\ \{\gamma_{\text{Sh},l} | l \in \{1,2,3,4\}\}}} \left(\frac{N_1 - \eta_{\text{Gr},1}^{\text{SS}} - \eta_{\text{Sh},1}^{\text{SS}}}{N_1} \right)^2 + \left(\frac{N_2 - \eta_{\text{Gr},2}^{\text{SS}} - \eta_{\text{Sh},2}^{\text{SS}}}{N_2} \right)^2 \\
& \text{s.t.} \quad \frac{\eta_{\text{Gr},1}^{\text{SS}}}{\eta_{\text{Sh},1}^{\text{SS}}} \geq 23 \text{ and } \frac{\eta_{\text{Gr},2}^{\text{SS}}}{\eta_{\text{Sh},2}^{\text{SS}}} \leq 1.7 \\
& \quad \gamma_{\text{Sh},1} + \gamma_{\text{Sh},2} = 0.51 \text{ and } \gamma_{\text{Sh},3} + \gamma_{\text{Sh},4} = 0.31 \\
& \quad N_l \geq \eta_{\text{Gr},l}^{\text{SS}} + \eta_{\text{Sh},l}^{\text{SS}} \text{ for } l \in \{3, 4, 5, 6, 7, 8\} \\
& \quad \vartheta_i > 0 \text{ for } i \in \text{SP} \\
& \quad \gamma_{\text{Sh},l} > 0 \text{ for } l \in \{1, 2, 3, 4\}
\end{aligned}$$

where SS indicates that the nitrogen uptakes are at the undisturbed steady-state and N_l is the available nitrogen in the whole ARNG in the l -th soil layer.

The objective function of the minimization problem is the square of the difference between the nitrogen available and the total nitrogen uptake from layers 1 and 2 weighted by the available nitrogen. It is important to mention that there is no solution where the plants absorb exactly the amount of available nitrogen in layers 1 and 2; therefore, we chose this objective function so plants uptake an amount of nitrogen as close as possible to the nitrogen available. The underlying assumption is that competition over nitrogen at the undisturbed steady-state is fiercer in the soil layers closer to the surface (layers 1 and 2) while availability of nitrogen in layers 3 to 8 is not restrictive.

The first pair of restrictions of the minimization problem refer to the nitrogen uptake ratio of grass to shrubs in layers 1 and 2. A new steady state after any disturbance (hunting, change of cattle density, energy development) can only be reached if the ratio of nitrogen uptake from layer 1 is over 5 and the ratio in layer 2 is below 1.8. Nonetheless, the lower the ratio in layer 1, the longer it takes to reach a new steady state. We chose a ratio of 23 and 1.7 to have a tractable model where it takes about 300 periods to reach a new steady state.

The optimal solution to the minimization problem (the solutions are shown in figure SI1

and table SI1) is such that there is an extra 9% of the nitrogen in layer 1 available for plants, but plants uptake more nitrogen from layer 2 than the actual nitrogen available (8%). For this minimization problem there is no solution where the uptake is lower than the nitrogen available for both soil layers, therefore, we allowed for solutions where uptakes can be greater than the nitrogen available as long as they are close enough.

The solution along with our estimations of nitrogen uptake of grass are consistent with Sala et al. (2012); their experimental evidence of mineral nitrogen and absorption patterns indicated that grasses showed a disproportionately large absorption from the uppermost layer, a smaller value at 0.3 m, and practically no absorption after 0.6 m of depth; meanwhile, shrubs showed no absorption in the shallow layers and most of the absorption occurred between 0.3 and 0.6 m of depth.

Since the growth of plants is already restricted at the undisturbed steady-state by the limited amount of vertical space, we allowed for some flexibility by assuming that there is an extra 1% of the nitrogen uptake of plants in layers 1 and 2 with respect to the undisturbed steady-state such that

$$N_l^* = 1.01 (\eta_{Gr,l}^* + \eta_{Sh,l}^*) \text{ for } l \in \{1, 2\} \quad (\text{SI3})$$

where the asterisk indicates that the biomass accumulations and the populations are at the undisturbed steady-state and that the optimal solution to the minimization problem is being considered; N_l^* is the adjusted available nitrogen in the ARNG in the l -th soil layer. In the main text and the sensitivity analysis, we refer to these optimal parameters without indicating the asterisk (N, ϑ, γ).

SI2 Benefit Transfer & Existence Value

The sage grouse is a high-profile species whose value must be considered among the ecosystem services affected by NGD. No study that we know of has estimated the specific willingness to pay (WTP) of households to secure the existence of a healthy population of sage grouse.

Nonetheless, a study done by Richardson and Loomis (2009) updates a 1996 meta-analysis of studies using the Contingent Valuation Method to value threatened, endangered, and rare species. The authors found that variables such as the change in the size of the species population, payment frequency, survey mode, response rate, type of respondent, type of species, “charisma”, whether the species has use and nonuse value versus nonuse value only, and year of the study significantly influence WTP. We use this model in a benefit transfer to estimate WTP for sage grouse in the ARNG.

We decided to use the linear regression model in which variables that that are not statistically different from zero at standard significance levels of 5% were not included. According to Richardson and Loomis (2009, p. 1544, table 6), this is the best fitting model to explain WTP for threatened and endangered species for benefit transfer purposes:

$$\begin{aligned} \text{WTP} = & \beta_0 + \beta_1 \text{CHANGESIZE} + \beta_2 \text{PAYFREQUENCY} + \beta_3 \text{FISH} + \beta_4 \text{MARINE} \\ & + \beta_5 \text{BIRD} + \beta_6 \text{CONJOINT} + \beta_7 \text{NONUSE} + \beta_8 \text{VISITOR} * \text{CHANGESIZE} \end{aligned} \quad (\text{SI4})$$

where CHANGESIZE represents the change in the size of the species population being valued; PAYFREQUENCY is a dummy variable coded 1 for a one-time payment or purchase of a lifetime membership and 0 for an annual payment amount; FISH, MARINE, and BIRD represent dummy variables broken down by groups of similar species being valued, where MAMMALS is the omitted category from the model; CONJOINT represents surveys which used a conjoint or choice experiment technique; NONUSE is a dummy variable coded 1 for species having non-use value only and 0 for those having both use and non-use value; finally, VISITOR is a dummy variable that indicates whether the survey respondents were visitors, coded 1, or households, coded 0.

It is important to mention that, while some threatened and endangered species have use values such as viewing, hunting, and eating; others have non-use value only (Richardson and Loomis, 2009, p. 1541). In the ARNG case, we were more interested in capturing only the non-use value of sage grouse.

To estimate the WTP per household of maintaining a stable population of sage grouse at their undisturbed steady-state, we assumed a zero change in the population with an annual payment amount for a bird species with non-use values. We also used the sample mean of the CONJOINT variable (0.075), which results in an \$11.38 WTP per household from the following equation:

$$\begin{aligned} \text{WTP} = 11.38 = & - 4.7 + 0.101(0) + 50.778(0) + 42.641(0) + 47.745(0) + 40.280(1) \\ & + 198.189(0.075) - 39.069(1) + 0.583(1)(0). \end{aligned} \quad (\text{SI5})$$

In the spirit of Loomis (2000), we measured the “relative benefit gradient” associated with the existence value of the sage grouse species as a function of residential location. By controlling for the quantity of public good being offered, and other variables reflecting individual’s tastes and preferences, the author ran a regression to measure how WTP decreases with respect to distance from the study area. Loomis (2000, p. 318) calculated the WTP per household at 100 mile distance intervals from 100 miles to 2,500 miles.

Figure SI5 shows the assumed relationship between household WTP and distance. The benefits received by local households (defined as those living within 100 miles of the ARNG region) was set at 100%. The figure plots the percent of local household WTP for respondents living at the other distances from the ARNG. As a reference, the percent of household benefits drop faster than the Mexican Spotted Owl analyzed by Loomis (2000), implying zero benefits per household beyond 1,800 miles from the Carbon County (e.g., households in Alaska receive no benefit per household).

To replicate their methodology, we gathered the housing unit estimate per county as of July 1, 2017 in the entire United States from the U.S. Census Bureau Population Division (2018). Then, we proceeded to calculate the distance “*as the crow flies*” between the county where the ARNG project is located, Carbon County, WY, and each of the 3,142 counties in the U.S., by using the tool “How far is it between” (Free Map Tools, 2018).

Counties between 0 and 1,800 miles are assigned a percentage of WTP according to the

curve in figure SI5. For example, New York City has 886,408 housing units and is 1,704 miles away from Carbon, WY. According to the polynomial curve in figure SI5, 5.72% of the WTP should be attributed to households residing in NYC with a total willingness to pay of \$576,591 to maintain the population of the sage grouse at the ARNG region. Adding the distance-weighted WTP of all households across the U.S., we obtain a total value of \$264,180,054.

To translate this value into WTP per bird, we simply divide the total value by the population of sage grouse in the ARNG region (2,732 birds), leading to a WTP/bird of \$96,683. It is important to mention that we are treating this as a lifetime value, not an annual flow.

SI3 Optimal Mitigation of Ecosystem Externalities & Coordination Failure

In this section, we discuss possible mitigation strategies for the U.S. BLM and WGFD to counteract some of the adverse impacts associated with NGD in the ARNG. We begin by noting that the spatial impact of the gas wells and other anthropogenic features are not fully incorporated into the model (Leu et al., 2008). For example, while we account for overlap in the DAs (see figure 2 of the main text), the simulations do not consider other spatial aspects such as the impact of having eight separated clusters with different degrees of development (see figure 3 in the main text). In future research, we intend to consider a spatial model that respects well spacing, impacts on migration patterns of species, effects of roads, and possible optimization of well location to maximize the ecosystem service benefits.

We also explore in this section what would happen if BLM and WGFD officials, instead of maximizing societal welfare (as defined by the value of ecosystem services) after the introduction of NGD, maximize the net benefits of the actors that they represent. If the BLM represents the interests of ranchers and the WGFD represents the interests of hunters, then a coordination failure could arise since cattle ranching and hunting impose ecosystem exter-

nalities on one another. The aforementioned ecosystem externalities are present even before the introduction of NGD, but are likely to be exacerbated after the introduction of such a large disturbance to the ecosystem.

Can government agencies coordinate to vary cattle stocking and hunting rates in the ARNG region to increase the benefits that society derives from the rangeland ecosystem? The question is complicated because of all the intra- and inter-species competition for resources and the possible coordination difficulties across government agencies. In terms of grazing, adding more cattle to the ecosystem may increase rancher profits because there are more cattle to sell, but it also adds more competition for grass so cattle gain less weight that reduces profit per head. Moreover, if the BLM reduces the cattle density, it may decrease cattle profits, but there will be more grass available for other grass-eating species, such as elk. In terms of WGFD management, changing the number of hunting licenses impacts rancher profits. Issuing fewer elk (pronghorn and mule deer) licenses and increasing the herds imposes a negative (positive) ecosystem externality on rancher profits. This follows because more elk makes grass less abundant for cattle, and more pronghorn and mule deer makes grass more abundant for cattle because it decreases shrub density, which in turn decreases the grasses' loss of energy from shading and increase its biomass.

In a first attempt to address the coordination question, we perform a grid search to find the optimal combination of cattle density and pronghorn hunting rates with GEEM, assuming, for simplicity and tractability, that the elk and mule deer hunting rates remain fixed. The pronghorn hunting rate and cattle density are selected in each simulation's first period, remain constant at those levels, and then the simulation runs until the ecosystem reaches a steady state. The objective is to maximize the annual value of ecosystem services at the post-development steady-state and reach the social optimum. We defined the optimization problem with a constraint on the population of animal species. We performed a grid search subject to the restriction that the population of no animal species can fall below 50% of the original undisturbed steady-state. If the restriction binds, the simulation stops and the value

of ecosystem services is set to zero for the rest of the planning horizon. This is important because otherwise it may be optimal to drive the populations of species to zero which violates the U.S. Endangered Species Act and international treaties such as the 1940 Convention on Nature Protection and Wildlife Preservation in the Western Hemisphere which states that the Governments of the American Republics commit “to protect and preserve in their natural habitat representatives of all species and genera of their native flora and fauna”.

The unconstrained optimization (not shown here) produces a extremely high hunting rate that yields an immediate sharp drop in the pronghorn population, and has the potential of irreversibly disrupting the ecosystem and driving the populations of grass and pronghorn to zero. Also, with sufficient nitrogen another extreme scenario arises where grass completely crowds out shrubs and the shrub-eaters (i.e., sage grouse, pronghorn and deer) also would go extinct. Therefore, we consider an optimal management strategy where there is balanced combination of pronghorn hunting and cattle density that can be maintained before the restriction binds.

To keep the social planning problem tractable we restrict policy to only consider time-invariant hunting and cattle stocking rates. This lack of flexibility imposed on the WGFD and BLM may result in second-best outcomes. We hypothesize that the first-best strategy might specify a higher cattle density in the short run while the grass is abundant, and then slowly decrease cattle density, once hunting has reduced the population of herbivores and the forage pressure on plants. We hope to consider time-varying strategies for future research.

Table SI3 shows the outcomes of a non-cooperative game between the BLM and the WGFD at the post-development steady-state. The rows represent the possible pronghorn hunting rates that the WGFD indirectly chooses by issuing hunting permits. The columns represent the possible cattle densities that are implied by the public grazing permits issued by the BLM. Inside each cell there are four values, all measured in millions of dollars: the top left indicates the annual net benefits from hunting for elk, pronghorn, and mule deer if the elk and mule deer hunting rates remain fixed according to the 2014 data (WGFD, 2014); the

top right indicates the annual profits of cattle ranching; the lower left is the annual existence value of sage grouse; and the lower right is the annual value of ecosystem services. The bold values are the best response of the WGFD to each action of the BLM and vice versa. The shaded cells represent the Nash equilibrium (NE) whereby the strategies of both the BLM and WGFD are best responses. The underlined value marks the social optimum that considers all ecosystem services. Cells of only zeros represent combinations of hunting rates and cattle densities that violate the population constraint.

As a point of clarification, consider the possibility where the WGFD issues enough pronghorn hunting permits to allow a 22.61% annual reduction in the pronghorn population and the BLM issues enough grazing permits to allow a seasonal cattle density of 0.0205 per ha. In this case, the benefits would be: \$1.887 million for hunting net benefits, \$2.665 million for cattle ranching profits, \$9.4 for the existence value of sage grouse, and \$13.95 million for annual value of all ecosystem services.

Some important remarks on table SI3: (1) when holding constant the hunting rate of pronghorn (fixed on rows), increasing the cattle density puts extra foraging pressure on grass which leads to a decrease of grass biomass (negatively affecting grass-eaters) and an increase of shrub biomass (positively affecting shrub-eaters). This increases the net benefits of pronghorn and mule deer hunting but decreases the benefits of elk hunting. The former impact is greater than the latter impact and the total net benefits slowly increase with cattle density. (2) When holding the cattle density constant (fixed on columns), increasing the hunting rate has no effect on the profits of cattle grazing because cattle are already satiated on grass. The hunting rate has an impact on cattle ranching profits only at higher cattle densities.

The main message from table SI3 is that public policy without coordination between the BLM and WGFD could lead to suboptimal outcomes. If WGFD and BLM officials coordinate and respond immediately after the introduction of NGD, they can mitigate the negative impacts of NGD on the ecosystem. Notice that the social optimum (hunting rate

of 0.2262 and cattle density of 0.032) of \$15.7 million will not be chosen by the agencies (because it is not a NE). In general, the most favorable outcomes (or NE) for the WGFD are also the least favorable for the BLM and vice versa. There is no guarantee that the social optimum will be selected if the two agencies do not coordinate.

SI4 Sensitivity Analysis

The application of GEEM in the estimation of impact of NGD relies on a number of modeling assumptions and parameters. While some of the parameters were culled from ecological and biological research papers, others had to be assumed within reasonable bounds. To account for this inherent uncertainty, in this section we investigate how the predictions of the model are altered when certain model assumptions or relevant parameters are changed.

First, we begin the sensitivity analysis in terms of one-time shocks on the populations of the species in the sagebrush ecosystem. Here, the population shocks are not meant to represent hunting or human gathering. The goal of introducing these type of shocks in the model is to show the capacity of the system to self regulate and to isolate clearly two effects: the short-run impacts versus the long-run impacts or the differences between steady states.

The population shocks were introduced into an ecosystem with no disturbances (i.e. no cattle grazing, no hunting, and no NGD). Therefore, the cattle grazing profits and the hunting benefits remain at zero and the value of ecosystem services depends only upon the populations of sage grouse (existence value).

Table SI4 shows the discounted value of sage grouse existence value for different shock scenarios. Each row represents a shock scenario, except for the first one that represents the case where no shock is introduced to the ecosystem; the first column describes which species are affected by the shocks and the second column indicates the magnitude of the shock. The discounting considers all time periods between the introduction of the population shock (i.e. the short run impacts on all the species and the associated ecosystem services), and the time

period when the ecosystem reaches a new steady state (long-run impacts).

Notice that big shocks do not necessarily translate into big changes in the value of ecosystem services. For example, a 10% shock in the population of elk leads to a TDVES decrease of about \$0.694 million with respect to the baseline scenario (\$264.18 million minus \$263.486 million), while a 50% shock in the population of elk leads to a TDVES decrease of less than \$3.948 million (\$264.18 million minus \$260.232 million).

In the remainder sensitivity analysis, we are interested in analyzing how our estimate of the negative impact of NGD changes with respect to the modeling assumptions and parameter values. To do so, we estimated two discounted values: the discounted value of ecosystem services already at the pre-NGD steady state (i.e. the value if NGD had never occurred), and the discounted value after NGD is introduced to the ecosystem. Notice that the former value considers annual flows that are constant, while the latter considers the adjustment and responses of all the species.

The second sensitivity analysis varies the species that are affected by NGD. Table SI5 shows the discounted value of hunting benefits, cattle grazing profits, sage grouse existence value, and the sum of all ecosystem services for different sensitivities to NGD for the key species: mule deer, elk, and sage grouse. Each row represents a scenario; the first row represents the undisturbed scenario. This scenario is not affected by NGD because the species experience no stress when foraging in the DAs. The first column describes which species are affected by NGD. The second, third, and fourth columns indicate the stress that the species experience when foraging in the DA3, DA2, and DA1, respectively. The discounting in the fifth, sixth, seventh, and eighth columns considers all periods between the introduction of NGD (i.e. the short run impacts on all the species and the associated ecosystem services), and the period when the ecosystem reaches a new steady state (long-run impacts). Finally, the last column shows the estimated impact, which is calculated by subtracting the discounted value of the introduction of NGD from the discounted value at the pre-NGD steady state. The impact of NGD typically ranges between \$0.124 and -\$81.674 million.

The third sensitivity analysis considers changes in the parameters associated with the root structure of the plant, which affects their capacity to uptake nitrogen from each soil layer, and the nitrogen available in the soil layers. Table SI6 shows the discounted value of hunting benefits, cattle grazing profits, sage grouse existence value, and the sum of all services for scenarios associated to the nitrogen availability and uptake ratio of plants. Some scenarios assume higher or lower uptake ratios of nitrogen from the first and second soil layers, others assume that there is more nitrogen available in the soil with respect to the undisturbed scenario.

Each row represents a different nitrogen scenario and the first row is the baseline. Unlike the sensitivity analysis described previously (species affected by NGD), changes in the parameters associated to nitrogen uptake and availability do affect the pre-NGD steady state. Because cattle are assumed to gain 180 kg of weight when only that economic activity is introduced into the ecosystem (see main text). The first, second, and third columns describe what parameters change and the fourth column indicates the type of steady state described. The discounting for the "Cattle Grazing + Hunting" scenario in the fifth, sixth, seventh, and eighth columns considers a fixed annual flow of ecosystem services, while the discounting for the "Cattle Grazing + Hunting + NGD" scenario considers all periods between the introduction of NGD (short run impacts), and the period when the ecosystem reaches a new steady state (long-run impacts). Finally, the last column shows the estimated negative impact of introducing NGD.

The impact of NGD ranges between -\$51.703 and -\$60.416 million. In this sensitivity analysis, the amount of extra nitrogen available for plants in the soil layers closer to the surface is the most relevant feature. Although, the estimated impacts do not vary greatly. As mentioned in the first section of this supplementary section, the nitrogen restrictions mainly define how fast the ecosystem reaches a new steady state.

The fourth sensitivity analysis that we performed considers different WTP per household to maintain the population of sage grouse at the undisturbed steady-state. Table SI7 shows

the discounted value of hunting benefits, cattle grazing profits, sage grouse existence value, and the sum of all services for WTP varying between \$1 and \$14.

Each row of the table represents a different scenario. Unlike the previous sensitivity analyses, the hunting benefits and the cattle grazing profits, remain unchanged because the responses of all species are not affected and only the existence value is updated. The first column describes the WTP/household assumed and the second column describes the scenario.

The discounting for the "Cattle Grazing + Hunting" scenarios considers a fixed annual flow of ecosystem services, while the discounting for the "Cattle Grazing + Hunting + NGD" scenarios considers the flow of ecosystem services in all periods. The last column shows the estimated impact of NGD.

The impact of NGD ranges between -\$17.019 and -\$68.84 million and is fairly sensitive to the assumed WTP per household. It is important to keep in mind that every single household in the U.S. (except for Alaska and Hawaii households) are assumed to value the sage grouse living in the ARNG region, depending on the distance to it. Since the existence value considers such a large number of households, small changes in the WTP per household have big impacts in terms of the aggregated value.

References

- Allredge, A., Lipscomb, J., and Whicker, F. (1974). Forage intake rates of mule deer estimated with fallout cesium-137. *The Journal of Wildlife Management*, 38(3):152–156.
- Anderson, J. and Shumar, M. (1986). Impacts of black-tailed jackrabbits at peak population densities on sagebrush-steppe vegetation. *Journal of Range Management*, 39(2):152–156.
- Anthony, R. and Smith, N. (1977). Ecological relationships between mule deer and white-tailed deer in Southeastern Arizona. *Ecological Monographs*, 47(3):255–277.

- Ares, J. (1976). Dynamics of the root system of blue grama. *Journal of Range Management*, 29(3):208–213.
- Bakker, J. and Wilson, S. (2001). Competitive abilities of introduced and native grasses. *Plant Ecology*, 157:117–125.
- Berendse, F. and Aerts, R. (1987). Nitrogen-use-efficiency: A biologically meaningful definition? *Functional Ecology*, 1(3):293–296.
- Biodiversity Conservation Alliance (2005). The special values of the Great Divide. *National Wildlife Federation*.
- Brody, S. and Procter, R. (1932). Relation between basal metabolism and mature body weight in different species of mammals and birds. *University of Missouri Agricultural Experiment Station Research Bulletin*, 166:89–101.
- Brody, S., Procter, R., and Ashworth, U. (1934). Basal metabolism, endogenous nitrogen, creatinine, and neutral sulphur excretions as functions of body weight. *University of Missouri Agricultural Experiment Station Research Bulletin* 1, 166:89–101.
- Byers, J. (1997). *American Pronghorn: Social Adaptations and Ghosts of Predators Past*. University of Chicago Press, Chicago, IL.
- Chapin, F., Vitousek, P., and Van Cleve, K. (1986). The nature of nutrient limitation in plant communities. *The American Naturalist*, 127(1):48–58.
- Comerford, W., Kime, L., and Harper, J. (2013). Beef background production. Retrieved July 27, 2016, from http://extension.psu.edu/business/ag-alternatives/livestock/beef-and-dairy-cattle/beef-background-production/extension_publication_file.
- Dahl, P., Judge, J., Gallo, J., and England, A. (1993). Vertical distribution of biomass and moisture in a prairie grass canopy. *College of Engineering, Technical Reports*.

- Davies, K. and Bates, J. (2010). Vegetation characteristics of mountain and Wyoming big sagebrush plant communities in the Northern Great Basin. *Rangeland Ecology and Management*, 63(4):461–466.
- Dietz, D. (1972). Nutritive value of shrubs. In *Wildland Shrubs - Their Biology and Utilization*. U.S. Department of Agriculture Intermountain Forest and Range Experiment Station General Technical Report INT-1, Ogden, UT.
- Egoscue, H., Bittmenn, J., and Petrovich, J. (1970). Some fecundity and longevity records for captive small mammals. *Journal of Mammalogy*, 51(3):622–623.
- Fagerstone, K., Lavoie, G., and Griffith, R. (1980). Black-tailed jackrabbit diet and density on rangeland and near agricultural crops. *Journal of Range Management*, 33(3):229–233.
- Fagerstone, K. and Ramey, C. (1996). *Rodents and lagomorphs*. The Society of Range Management, Denver, CO.
- Finnoff, D. and Tschirhart, J. (2009). Plant competition and exclusion with optimizing individuals. *Journal of Theoretical Biology*, 261:227–237.
- Finnoff, D. and Tschirhart, J. (2011). Inserting ecological detail into economic analysis: Agricultural nutrient loading of an estuary fishery. *Sustainability*, 3:1688–1722.
- Fraser, D. (2004). *Factors influencing livestock behaviour and performance*. Forest Practices Branch, British Columbia Ministry of Forests, Rangeland Health Brochure 8, Victoria, BC.
- Free Map Tools (2018). How far is it between. Retrieved August 8, 2018, from <https://www.freemaptools.com/how-far-is-it-between.htm>.
- Hansen, R. (1972). Estimation of herbage intake from jackrabbit feces. *Journal of Range Management*, 25(6):468–471.
- Hansen, R. and Reid, L. (1975). Diet overlap of deer, elk, and cattle in Southern Colorado. *Journal of Range Management*, 28(1):43–47.

- Hart, R. and Ashby, M. (1998). Grazing intensities, vegetation, and heifer gains: 55 years on shortgrass. *Journal of Range Management*, 51(4):392–398.
- Hitchcock, A. and Chase, A. (1950). *Manual of the Grasses of the United States*. U.S. Govt. Print. Off., Washington, D.C., 2nd ed. edition.
- Hudson, R. and Nietfeld, M. (1985). Effect of forage depletion on the feeding rate of wapiti. *Journal of Range Management*, 38(1):80–82.
- Jiang, Z. and Hudson, R. (1992). Estimating forage intake and energy expenditures of free-ranging wapiti (*cervus elaphus*). *Canadian Journal of Zoology*, 70(4):675–679.
- Johnson, M. (1979). Foods of primary consumers on cold desert shrub-steppe of Southcentral Idaho. *Journal of Range Management*, 32(5):365–368.
- Johnson, R. and Anderson, J. (1984). Diets of black-tailed jackrabbits in relation to population density and vegetation. *Journal of Range Management*, 37(1):79–83.
- Jurik, T. and Kleibenstein, H. (2000). Canopy architecture, light extinction and self-shading of a prairie grass, *Andropogon gerardii*. *American Midland Naturalist*, 144(1):51–65.
- Kelsey, R., Nelson, A., Smith, G., and Peiper, R. (1973). Nutritive value of hay from nitrogen-fertilized blue gramma rangeland. *Journal of Range Management*, 26(4):292–294.
- Kleiber, M. (1975). *The fire of life: An introduction to animal energetics*. Robert E. Krieger Publishing Co., Huntington, NY, rev. edition.
- Köchy, M. and Wilson, S. (2000). Competitive effects of shrubs and grasses in prairie. *Oikos*, 91:385–395.
- Lambers, H., Chapin, F., and Pons, T. (2006). *Plant Physiological Ecology*. Springer, New York, NY, 2nd edition.

- Leu, M., Hanser, S., and Knick, S. (2008). The human footprint in the west: A large-scale analysis of anthropogenic impacts. *Ecological Applications*, 18(5):1119–1139.
- Loomis, J. (2000). Vertically summing public good demand curves: An empirical comparison of economic versus political jurisdictions. *Land Economics*, 76(2):312–321.
- Mackie, R., Kie, J., Pac, D., and Hamlin, K. (2003). Mule deer *odocoileus hemionus*. In Feldhamer, G. A., Thompson, B. C., and Chapman, J. A., editors, *Wild Mammals of North America: Biology, Management, and Conservation*, pages 889–905. The Johns Hopkins University Press, Baltimore, MD.
- Mackie, R., Pac, D., Hamlin, K., and Dusek, G. (1998). Ecology and management of mule deer and white-tailed deer in Montana. *Montana Department of Fish, Wildlife and Parks*.
- Miller, T., Burns, J., Munguia, P., Walters, E., Kneitel, J., Richards, P., Mouquet, N., and Buckley, H. (2005). A critical review of twenty years' use of the resource ratio theory. *The American Naturalist*, 165(4):439–448.
- Ngugi, K., Powell, J., Hinds, F., and Olson, R. (1992). Range animal diet composition in Southcentral Wyoming. *Journal of Range Management*, 45(6):542–545.
- Olsen, F. and Hansen, R. (1977). Food relations of wild free-roaming horses to livestock and big game, Red Desert, Wyoming. *Journal of Range Management*, 30(1):17–20.
- Pac, D., Mackie, R., and Jorgensen, H. (1991). Mule deer population organization, behavior, and dynamics in a Northern Rocky Mountain environment. *Montana Department of Fish, Wildlife and Parks, Final Report, Federal Aid in Wildlife Restoration Project W-120-R, Montana*.
- Pyle, W. and Crawford, J. (1996). Availability of foods of sage grouse chicks following prescribed fire in sagebrush- bitterbrush. *Journal of Range Management*, 49(4):320–324.

- Reich, P., Ellsworth, D., and Walters, D. (1998). Leaf structure (specific leaf area) modulates photosynthesis-nitrogen relations: Evidence from within and across species and functional groups. *Functional Ecology*, 12(6):948–958.
- Remington, T. and Braun, C. (1988). Carcass composition and energy reserves of sage grouse during winter. *The Condor*, 90(1):15–19.
- Richardson, L. and Loomis, J. (2009). The total economic value of threatened, endangered and rare species: An updated meta-analysis. *Ecological Economics*, 68:1535–1548.
- Sage Grouse initiative (2016). Conserve our Western roots. Retrieved June 17, 2016, from <http://www.sagegrouseinitiative.com/roots/>.
- Sala, O., Golluscio, R., Lauenroth, W., and Roset, P. (2012). Contrasting nutrient-capture strategies in shrubs and grasses of a Patagonian arid ecosystem. *Journal of Arid Environments*, 82:130–135.
- Savory, C. (1978). Food consumption of red grouse in relation to the age and productivity of heather. *The Journal of Animal Ecology*, 47(1):269–282.
- Severson, K. and May, M. (1967). Food preferences of antelope and domestic sheep in Wyoming’s Red Desert. *Journal of Range Management*, 20(1):21–25.
- Severson, K., May, M., and Hepworth, W. (1980). Food preferences, carrying capacities, and forage competition between antelope and domestic sheep in Wyoming’s Red Desert. *University of Wyoming Agricultural Experiment Station Bulletin*, SM 10.
- Smika, D., Haas, H., Rogler, G., and Lorenz, R. (1961). Chemical properties and moisture extraction in rangeland soils as influenced by nitrogen fertilization. *Journal of Range Management*, 14(4):213–216.
- Stewart, K., Bowyer, R., Dick, B., Johnson, B., and Kie, J. (2005). Density-dependent

- effects on physical condition and reproduction in North American elk: An experimental test. *Oecologia*, 143:85–93.
- Stinson, D., Hays, D., and Schroeder, M. (2004). Washington State recovery plan for the greater sage-grouse. *Washington Department of Fish and Wildlife*.
- Sturges, D. (1977). Soil water withdrawal and root characteristics of big sagebrush. *The American Midland Naturalist*, 98(2):257–274.
- Tilman, D. (1985). The resource-ratio hypothesis of plant succession. *The American Naturalist*, 125(6):827–852.
- Tilman, D., Wedin, D., and Knops, J. (1996). Productivity and sustainability influenced by biodiversity in grassland ecosystems. *Nature*, 379:718–720.
- U.S. Census Bureau Population Division (2018). Annual estimates of housing units for the United States, regions, Divisions, States, and Counties: April 1, 2010 to July 1, 2017. Retrieved July 12, 2018, from <https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk>.
- Walker, B., Kinzig, A., and Langridge, J. (1999). Plant attribute diversity, resilience, and ecosystem function: The nature and significance of dominant and minor species. *Ecosystems*, 2(2):95–113.
- Weaver, J. (1926). Root habits of native plants and how they indicate crop behavior. In Weaver, J. E., editor, *Root Development of Field Crops*, chapter IV. McGraw-Hill Book Company, New York, NY, 1st edition.
- WGFD (2014). Annual reports of big and trophy game harvest and annual reports of small and upland game harvest. Retrieved October 16, 2014, from <https://wgfd.wyo.gov/Hunting/Harvest-Reports/>.

- Whitaker, J. (1980). *The Audubon Society Field Guide to North American Mammals*. Alfred A. Knopf, New York, NY.
- Yoakum, J. (2004). Distribution and abundance. In O’Gara, B. W. and Yoakum, J. D., editors, *Pronghorn Ecology and Management*, pages 75–105. University Press of Colorado, Boulder, CO.
- Zablan, M. (1993). *Evaluation of sage grouse banding program in North Park, Colorado*. Ms, Colorado State University.
- Zachow, R. (1997). *Elk (Cervus elaphus)*. South Dakota Department of Game, Fish and Parks, Division of Wildlife, Pierre, SD.

Calibration Parameters

| Parameters and Variables | Plants | | | Herbivores | | | | |
|--|-----------------------|-----------------------|-----------------------|-----------------------|-------------------------|----------------------|----------------------|----------------------|
| | Grass | Shrub | Elk | Cattle | Jack-rabbit | Prong-horn | Mule Deer | Sage Grouse |
| Density (ind ha ⁻¹) | 115200 ¹ | 8000 ² | 0.0496 ³ | 0.0387 ⁴ | 3 ⁵ | 0.03 ⁶ | 0.09 ⁷ | 0.025 ⁸ |
| Biomass accumulation x_i or consumption $x_{i,j}$ (kg) | 0.01016 ⁹ | 0.05796 ¹⁰ | 2620 ¹¹ | 1325.54 [*] | 99.4(Gr) | 209 ¹³ | 639.8 ¹⁴ | 25 ¹⁵ |
| | | | | | 28.4(Sh) ¹² | | | |
| Gross energy content e_i (kcal kg ⁻¹) | 4200 ¹⁶ | 5068 ¹⁷ | | | | | | |
| Extinction parameter k_i | 0.3 ¹⁸ | 0.4 ¹⁹ | | | | | | |
| Average lifespan l_i (years) | 5 ²⁰ | 42 ²¹ | 14 ²² | 1 ²³ | 7 ²⁴ | 10 ²⁵ | 10 ²⁶ | 9 ²⁷ |
| Predation risk p_i | 0.0284 [*] | 0.0133 [*] | | | | | | |
| Leaf area s_i (m ² kg ⁻¹) | 10 ²⁸ | 7.1 ²⁹ | | | | | | |
| Minimum nitrogen requirement ϑ_i | 3.206 [*] | 2.637 [*] | | | | | | |
| Basal metabolism β_i (kcal year ⁻¹) | 3796 [*] | 13227 [*] | 1581212 ³⁰ | 1250554 ³¹ | 54388.2 ³² | 335584 ³³ | 568967 ³⁴ | 42110 ³⁵ |
| Average weight w_i (kg) | 0.0219 ³⁶ | 0.1246 ³⁷ | 315.5 ³⁸ | 273 ³⁹ | 3.2 ⁴⁰ | 46.4 ⁴¹ | 123.8 ⁴² | 1.5 ⁴³ |
| Respiration parameter r_i | 43646181 [*] | 4677586 [*] | 0.4607 [*] | 2.13013 [*] | 8.0533 [*] | 15.3652 [*] | 2.7799 [*] | 134.75 [*] |
| Parameter of the willingness to supply $g_{k,i}$ | | | 0.01119 [*] | 0.0073 [*] | 0.026 [*] (Gr) | 0.00326 [*] | 0.0299 [*] | 0.00032 [*] |
| | | | | | 0.044 [*] (Sh) | | | |
| Shading energy loss SEL _{i} or energy expenditure price $e_{k,i}$ (kcal kg ⁻¹) | 54428 [*] | 67768 [*] | 2992.51 [*] | 1374.31 [*] | 3277 [*] (Gr) | 1841.3 [*] | 3286.64 [*] | 1564.48 [*] |
| | | | | | 4431 [*] (Sh) | | | |

Table S11: The asterisk (*) indicates that the parameter/variable is estimated by assuming that the ecosystem is at steady state. The steady state that arises after cattle are introduced to the ecosystem is used to calibrate their parameters. The undisturbed steady-state is used for all other species.

¹From studies of Wyoming big sagebrush and mountain big sagebrush (*Artemisia tridentata*) communities in south east Oregon that contain the native grasses common to Wyoming: Idaho fescue (*Festuca idahoensis*), prairie junegrass (*Koeleria macrantha*), bluebunch wheatgrass (*Pseudoroegneria spicata*), Thurbers needlegrass (*Achnatherum thurberianum*), needle and thread (*Hesperostipa comata*), squirreltail (*Elymus elymoides*), and Sandberg bluegrass (*Poa secunda*). Davies and Bates (2010, p. 464) report grass densities of both communities and we use an average of 11.52 individual (ind) plants m^{-2} or 115200 ind ha^{-1} .

²See footnote 1. An average of Wyoming big sagebrush density (1.1 ind m^{-2}) and mountain big sagebrush (0.5 ind m^{-2}) was used to obtain 8,000 ind ha^{-2} (Davies and Bates, 2010, p. 464).

³Stewart et al. (2005) state a high and low population density of 4.51 elk km^{-2} - 5.41 elk km^{-2} . The mean value of approximately 4.96 elk km^{-2} is used here (0.0496 elk ha^{-1}).

⁴According to the EIS, there are 31 relevant BLM grazing allotments in the ARNG and the surrounding area, which allows for a total of 39,695 animal unit months (AUMs). Only a portion of this allotment is in the ARNG. To estimate the cattle density, we assume that the number of AUMs inside the ARNG is proportional to the acreage in the ARNG. This results in 21,135 AUMs inside the ARNG. Assuming each animal is allowed to graze for 5 months implies a total of 4,227 individual steers and heifers grazing inside the ARNG. Since there are 109,297 ha in the ARNG, the estimated cattle grazing density is 0.0387.

⁵Studies have reported jackrabbit densities between 0.02 ha^{-1} and 35 ha^{-1} (Anderson and Shumar, 1986; Fagerstone et al., 1980; Fagerstone and Ramey, 1996), where the highest density estimates are usually observed around agricultural lands. The density estimate used is 3 ha^{-1} .

⁶Yoakum (2004) reports a pronghorn density for Wyoming of 3.0 ind km^{-2} , or 0.03 ha^{-1} .

⁷BLM lands hold over 323,748.5 ha of crucial range for 85,000 mule deer within the great divide resource management area (Biodiversity Conservation Alliance, 2005). This translates to 0.2625 mule deer ha^{-1} .

⁸A study of the Hart Mountain National Pronghorn Refuge in Lake County, Oregon revealed a sage grouse density in the 1980s of 2.5 birds km^{-2} which is converted to 0.025 grouse ha^{-1} (Pyle and Crawford, 1996).

⁹Using data from footnote 1, the average biomass production of grasses over both communities was 300 kg ha^{-1} (Davies and Bates, 2010, p. 464). We assumed this was grazed with a moderate intensity as defined by cattle grazing and note that ungrazed blue gamma has $\frac{667}{397} = 1.68$ more standing biomass than grazed blue gamma (Hart and Ashby, 1998, p. 394). Applying this yields 504 kg ha^{-1} . Also, Hart and Ashby (1998) report blue gamma biomass of 667 kg ha^{-1} which is averaged with data from Davies and Bates (2010) to obtain 585.5 kg ha^{-1} . We convert to wet weight with a ratio of wet weight to dry weight ratio of 2 (Dahl et al., 1993) to obtain 1,171 kg ha^{-1} . Finally, dividing by the number of plants yields 0.01016 kg ind^{-1} .

¹⁰Severson and May (1967) report annual forage production for Wyoming big sagebrush to be 206.85 lb DW acre^{-1} . This is converted to (206.85 lb DW acre^{-1}) (2 WW DW $^{-1}$) (0.453592 kg lb^{-1}) (2.471 acre ha^{-1}) (ha (8000 ind) $^{-1}$) = 0.05796 kg WW ind^{-1} .

¹¹Estimates of daily forage intake for elk range from 7 kg days^{-1} (Fraser, 2004; Jiang and Hudson, 1992) to 9.5 kg days^{-1} (Hudson and Nietfeld, 1985). Using the average, annual forage intake is 3011 kg . Ngugi et al. (1992) study diet composition of grazing and browsing animals in South central Wyoming and report that elk diet consisted 84% to 90% of grass. We used the average of 87% to scale elk demand for grass down to 2620 kg years^{-1} .

¹²Hansen (1972) estimates an intake rate of 0.389 kg days^{-1} for jackrabbits. This is extrapolated to an intake of 141.985 kg years^{-1} . For shrub-steppe and mixed shrub-grass communities, diet composition of 70% grass and 20% shrub is used (Johnson, 1979; Johnson and Anderson, 1984). This is translated to an annual intake of 99.39 kg (of grasses) and 28.40 kg (of shrubs).

¹³Severson et al. (1980) report pronghorn daily forage intake rate to be 0.8 kg ind^{-1} , which is converted to 292 $\text{kg ind}^{-1} \text{ years}^{-1}$. Annual pronghorn diet consisted from 65% to 78% sagebrush in South central Wyoming and in the Red Desert (Olsen and Hansen, 1977; Severson et al., 1980). The average is used to scale down annual forage requirement to 209 kg .

¹⁴Allredge et al. (1974) report mean forage intake rate of 0.998 kg (45.36 $\text{kg})^{-1} \text{ day}^{-1}$ for Colorado mule

deer. Using the weight, 123.8 kg, total intake is calculated: 994.2 kg years⁻¹. See footnote 38. Shrubs have been documented to comprise between 46% and 82.7% of mule deer diets in various studies (Anthony and Smith, 1977; Hansen and Reid, 1975). The mean value of 64.35% is used to scale the forage requirement down to 639.8 kg year⁻¹.

¹⁵Savory (1978) studies food intake of red grouse in Scotland and reports that annual intake vary from 18 kg to 25 kg (both in terms of dry weight). The higher estimate is taken to be a reasonable approximation of the food intake of sage grouse.

¹⁶From Kelsey et al. (1973, p. 293).

¹⁷Dietz (1972) reports a gross energy content of 5.068 kcal g⁻¹ for sagebrush from South Dakota. This is converted to 5068 kcal kg⁻¹.

¹⁸The extinction coefficient is low for vertically inclined leaves (for example, 0.3-0.5 for grasses), but higher for a more horizontal leaf arrangement (Lambers et al., 2006, p. 26).

¹⁹See footnote 18. Light extinction for shrub formations is higher than for grasses. We use 0.4.

²⁰Perennials are assumed to have 5 years average longevity (Walker et al., 1999, p. 102).

²¹In a Wyoming big sagebrush community in Wyoming the plants ranged from 26 to 57 years of age. Average age reported of 42 years is used (Sturges, 1977).

²²The average lifespan for an elk is 14 to 16 years for males and 15 to 17 years for females (Zachow, 1997). The lower value for males of 14 years is used.

²³Ranchers employ a stocker operation where they acquire young adult steers or heifers and graze them for one season in a year before they are sent to market.

²⁴Egoscue et al. (1970) report that a captive black-tailed jackrabbit lived for 6 years and 9 months. In calibration, 7 years is used as lifespan in the wild.

²⁵Pronghorns have an estimated lifespan of 5 to 15 years (Byers, 1997); we used the average of 10 years.

²⁶Maximum age for female mule deer range from 12 to 14 years, while for males it is 8 years (Pac et al., 1991; Mackie et al., 1998, 2003). A life span of 10 years is used.

²⁷Greater sage grouse can survive at least 9 years in the wild (Zablan, 1993; Stinson et al., 2004).

²⁸Approximately the middle of the range for the inverse of g m⁻² (Jurik and Kleibenstein, 2000, p. 58).

²⁹Reich et al. (1998) report that mean specific leaf area for evergreen shrubs is 71 cm² g⁻¹, or 7.1 m² kg⁻¹.

³⁰Brody et al. (1934) obtained $M = 70.5\omega^{0.734}$ as the power function relationship between daily metabolic rate in kcal per day (M) and body weight in kg (ω) for mammals. Using a weight of 315.5 kg (footnote 38), total metabolic energy requirement is about 1,756,902 kcal year⁻¹. Because 90% of elk's diet is accounted for in the food web, the basal metabolism requirement is scaled down to 1,581,212 kcal year⁻¹.

³¹For mammals, resting metabolic rate in kcal days⁻¹ (M) is related to body weight (ω) in kg by the formula $M = 67.61\omega^{0.756}$ (Kleiber, 1975). Weights are given in footnote 39. Extrapolating to a 6 month season for both weights yields 857,063-1,532,784 kcal season⁻¹. The value used is 1,250,554 kcal season⁻¹.

³²Using the power function relationship and a jackrabbit weight of 3.2 kg (Fagerstone and Ramey, 1996), total metabolic energy requirement is 6,0431.32 kcal years⁻¹. See footnote 30. This is scaled down to 54388.19 kcal years⁻¹ because only 90% of a jackrabbit's diet is accounted for in the food web.

³³Using a weight of 315.5 kg in the power function, total metabolic energy requirement is about 430,235 kcal years⁻¹. See footnotes 30 and 38. Because 78% of pronghorn's diet is accounted for, the basal metabolism requirement is scaled down to 335,584 kcal years⁻¹.

³⁴Using the power function and the average mule deer weight 123.8 kg, the metabolic energy requirement is about 884,176 kcal years⁻¹. See footnotes 30 and 38. Because 64.35% of a deer's diet is accounted for in the food web, the basal metabolism requirement is scaled down to 568,967 kcal years⁻¹.

³⁵Brody and Procter (1932) obtained $M = 89\omega^{0.64}$ as the power function relationship between daily metabolic rate in kcal day⁻¹ (M) and body weight in kg (ω) for wild birds. Using the weight of an adult female sage grouse of 1.5 kg (Remington and Braun, 1988), total metabolic energy requirement of 42,109.62 kcal years⁻¹ is calculated.

³⁶If the biomass accumulation represents only the 46.5% of the total weight, the other 53.5% of comes from

Estimated Nitrogen Uptake of Grass and Shrubs

| Soil layer | Available Nitrogen (kg) | Grass' proportion of nitrogen uptake ($\gamma_{Gr,i}$) | Shrub's proportion of nitrogen uptake ($\gamma_{Sh,i}$) |
|-----------------|-------------------------|--|---|
| Surface | | | |
| 1 st | 0-0.15 | $N_1^* = 2.45 \times 10^8$ | 0.56 |
| 2 nd | 0.15-0.3 | $N_2^* = 1.59 \times 10^8$ | 0.24 |
| 3 rd | 0.3-0.46 | $N_3 = 1.06 \times 10^8$ | 0.09 |
| 4 th | 0.46-0.61 | $N_4 = 7.83 \times 10^7$ | 0.04 |
| 5 th | 0.61-0.91 | $N_5 = 1.09 \times 10^8$ | 0.07 |
| 6 th | 0.91-1.22 | $N_6 = 6.54 \times 10^7$ | 0 |
| 7 th | 1.22-1.52 | $N_7 = 5.35 \times 10^7$ | 0 |
| 8 th | 1.52-1.83 | $N_8 = 5.16 \times 10^7$ | 0 |

Figure SI1: The diagram depicts the root structure of blue grama (*Bouteloua gracilis*) (Weaver, 1926) and a drawing of the plant (Hitchcock and Chase, 1950). The diagram also depicts the root structure of the big sage brush (*Artemisia tridentata*) (Sage Grouse initiative, 2016). The total nitrogen available in each soil layer comes from Smika et al. (1961). See the appendix for further details.

the weight of the roots (Bakker and Wilson, 2001).

³⁷See footnote 36.

³⁸Weight is an average of the ranges of male and female weights from Whitaker (1980).

³⁹Weights of stocked cattle vary. We use typical weights of 273 kg per stocked feeder calf and 589 kg market weight at the end of the stocking season (Comerford et al., 2013).

⁴⁰Jackrabbit weight is taken from Fagerstone and Ramey (1996).

⁴¹See footnote 38.

⁴²See footnote 38.

⁴³Remington and Braun (1988).

Density Distribution of Grass' Roots

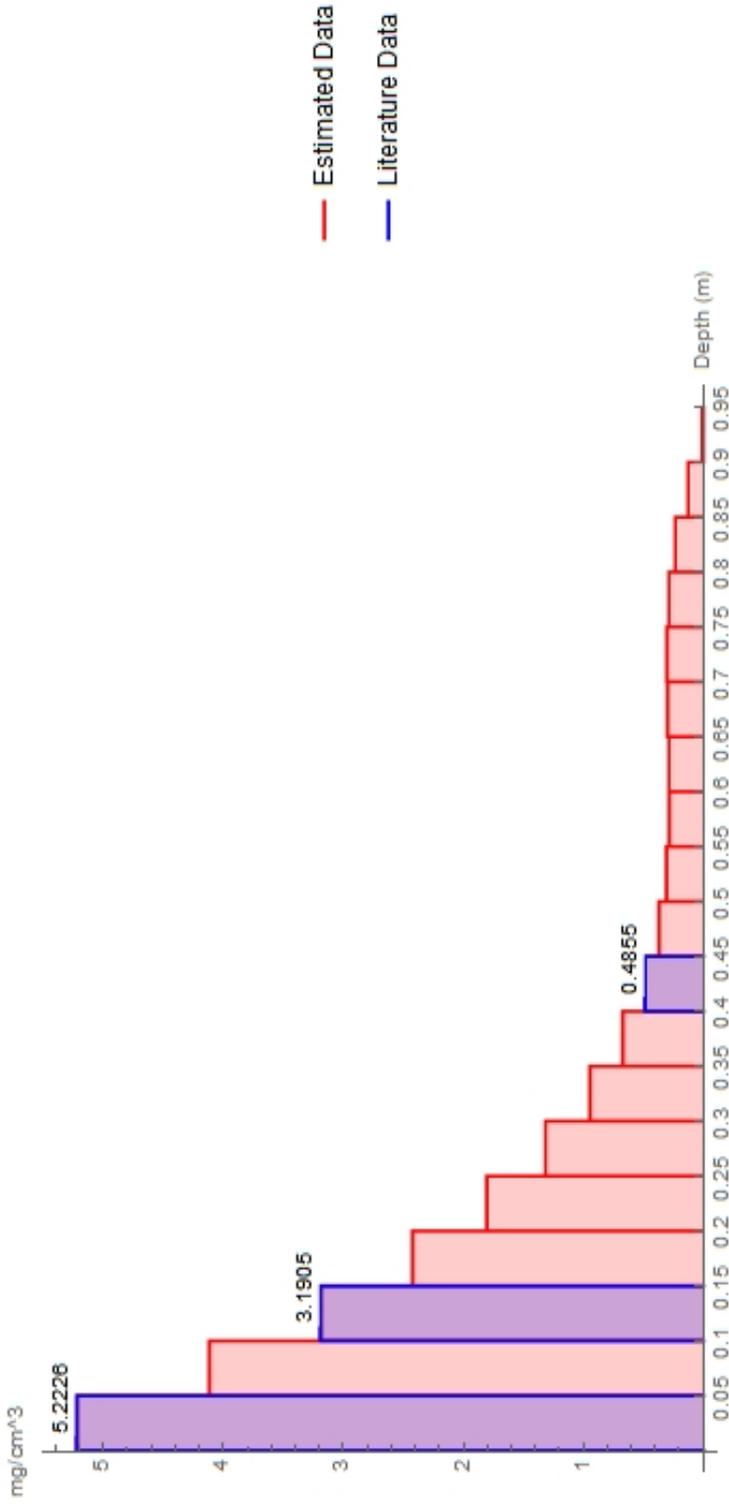


Figure SI2: Ares (1976, p. 211) estimated the blue grama's dry weight of root material (mg/cm^3) from core sections in two different samples taken on May 15, 1973 and August 9, 1973. The average of both samples is depicted above the "original data" bars. The graph also shows our extrapolation of root weight kg/cm^3 of grass plants for the intervals that were not reported. The position with respect to the horizontal axis of each bar represents the range of a soil segment and its height shows the roots weight within said segment.

Weight Distribution of Shrubs' Roots

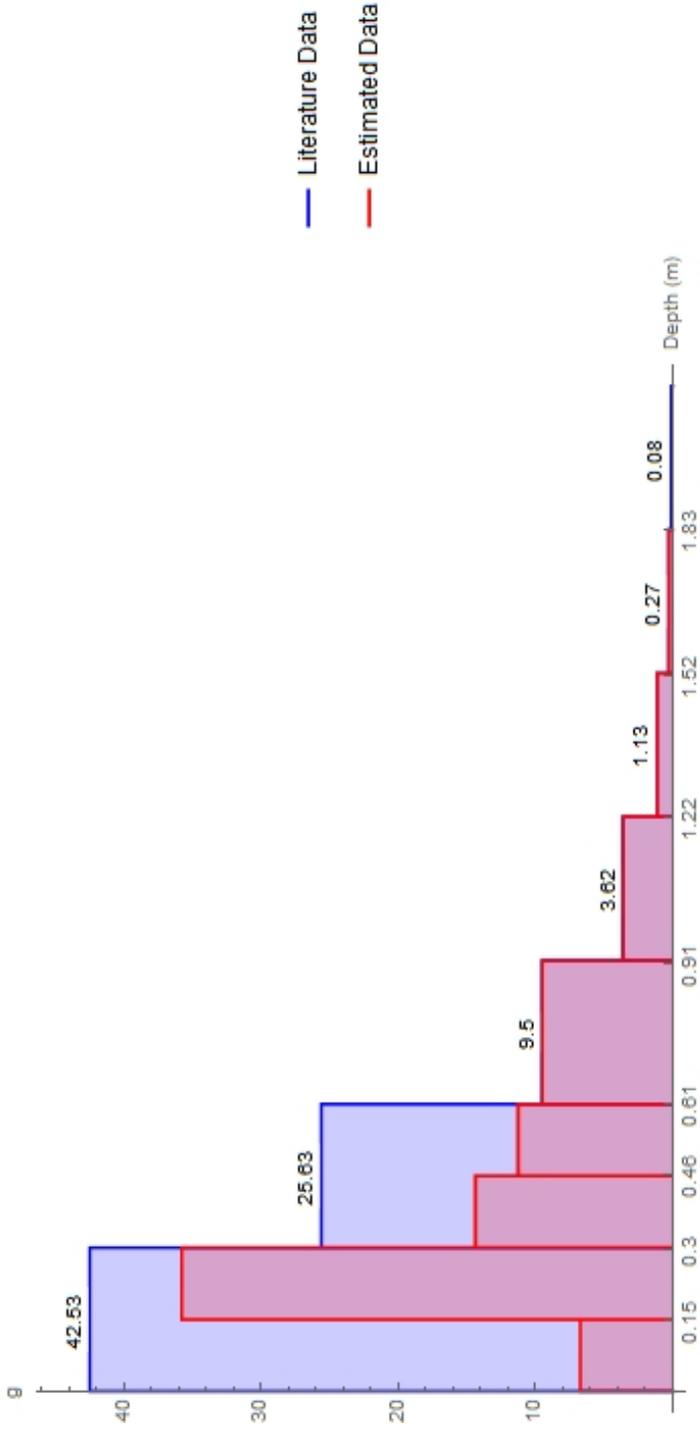


Figure SI3: Sturges (1977, p. 272) estimated the total weight of the portion of big sagebrushes root system less than 3 mm in diameter at 3 experimental sites (near the bottom, midway and crest of a north-facing slope). The average of the three sites is depicted above the “original data” bars. The graph shows our estimation for layers 1-4 (0-0.61 m) of root weight of shrub plants. The position with respect to the horizontal axis of each bar represents the range of a soil segment and its height shows the roots weight within said segment.

Distribution of Nitrogen in the Soil

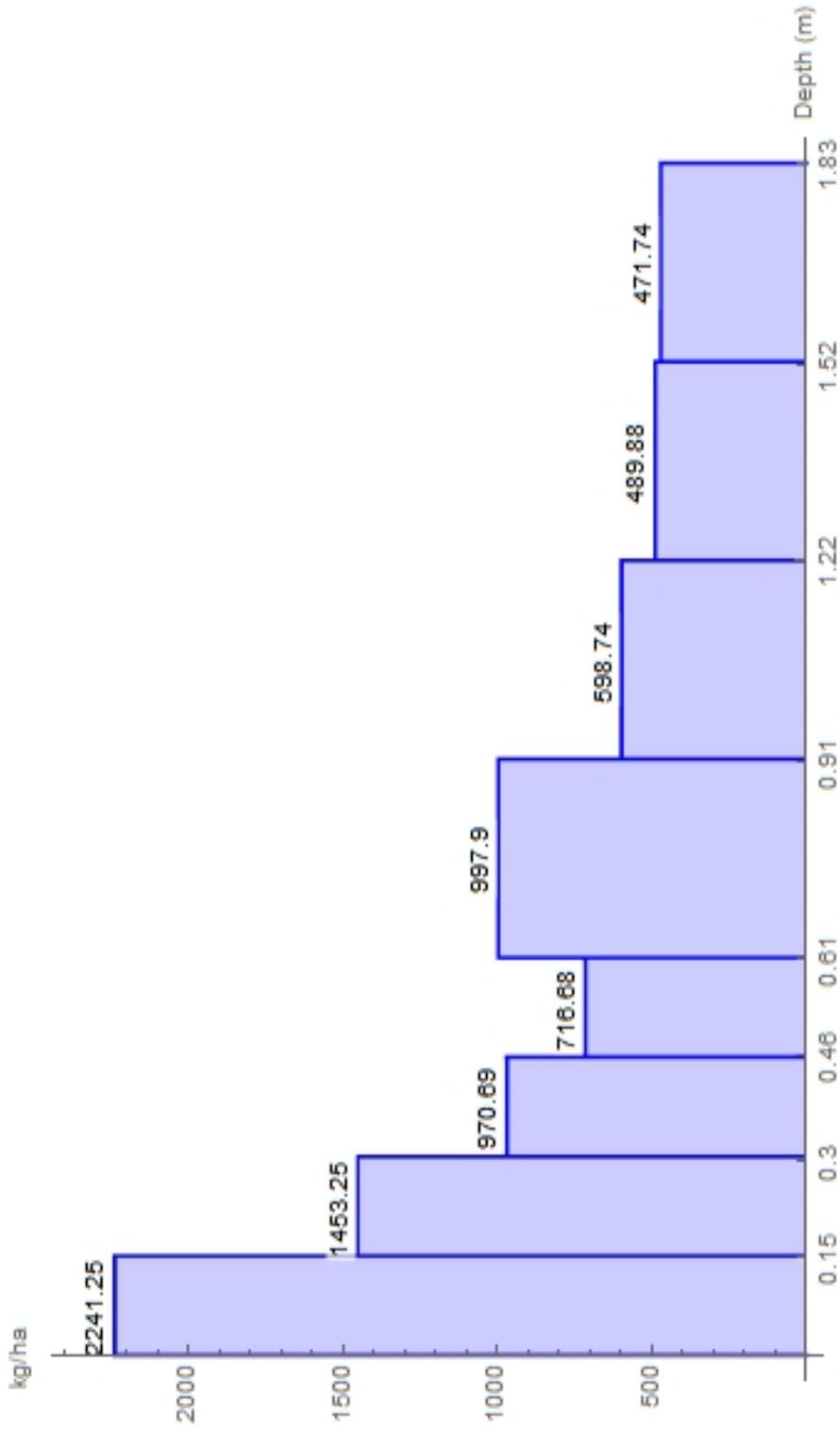


Figure SI4: Smika et al. (1961, p. 214) evaluated the effects of fertilization of native rangeland at the Northern Great Plains Field Station, Mandan, North Dakota in 1951. The soil nitrogen (ammonium nitrate) per ha of unfertilized plots of native grass is depicted above the bars. Each bar represents one of the soil layers we used in the model, 8 in total; its position with respect to the horizontal axis represents the range of the layer and its height shows the nitrogen contained in the layer.

Elk, Pronghorn, and Mule Deer Harvested inside the ARNG in 2014

| Concept | Elk | Pronghorn | Mule Deer |
|-----------------------------|-------|-----------|-----------|
| Total Harvest in the Units | 1,818 | 280 | 819 |
| Total Unit Area inside ARNG | 32.7% | 17.9% | 34.1% |
| Total Harvested in ARNG | 595 | 50 | 279 |
| Equilibrium Population | 5,421 | 3,279 | 9,837 |
| Percentage Harvested | 11.0% | 1.5% | 2.8% |
| Average Success Rate | 47.7% | 53.1% | 9.1% |

Table SI2: Estimation using the data from harvest reports (WGFD, 2014). The hunting areas (or units) intersect with the ARNG region but none falls entirely within it. We calculated the percentage of each unit that falls inside the ARNG region, and then assumed that the same percentage of elk, pronghorn, and mule deer from the total animals hunted were harvested inside the ARNG region.

Payouts and Nash Equilibria for Non-Cooperative Game between the BLM and WGF

| | | Cattle Grazing Density (BLM) | | | | | | | | | | | | | | | |
|-------------------------|--------|------------------------------|-----------------------|---------------|---------------|---------------|----------------|---------------|----------------|---------------------|-----------------------|----------------|----------------|-----------------------|-----------------------|---------------|----------------------|
| | | 0.025 | | 0.026 | | 0.027 | | 0.028 | | 0.029 | | 0.03 | | 0.031 | | 0.032 | |
| Hunt Rate (WGFD) | 0.2261 | 1.887 9.4 | 2.665 13.95 | 1.894 9.54 | 2.771 14.2 | 1.902 9.68 | 2.878 14.46 | 1.91 9.84 | 2.985 14.73 | 1.919 10. | 3.091 15.01 | 1.927 10.17 | 3.198 15.29 | 1.937 10.35 | 3.304 15.59 | 1.95 10.59 | 3.161 15.7 |
| | 0.2262 | 1.887 9.4 | 2.665 13.95 | 1.895 9.54 | 2.771 14.2 | 1.902 9.68 | 2.878 14.46 | 1.91 9.84 | 2.985 14.73 | 1.919 10. | 3.091 15.01 | 1.928 10.17 | 3.198 15.29 | 1.937 10.35 | 3.304 15.59 | 1.95 10.59 | 3.161 <u>15.7</u> |
| | 0.2263 | 1.887 9.4 | 2.665 13.95 | 1.895 9.54 | 2.771 14.2 | 1.903 9.68 | 2.878 14.47 | 1.911 9.84 | 2.985 14.73 | 1.919 10. | 3.091 15.01 | 1.928 10.17 | 3.198 15.29 | 1.937 10.35 | 3.304 15.59 | 0.0. | 0.0. |
| | 0.2264 | 1.888 9.4 | 2.665 13.95 | 1.895 9.54 | 2.771 14.2 | 1.903 9.68 | 2.878 14.47 | 1.911 9.84 | 2.985 14.73 | 1.919 10. | 3.091 15.01 | 0.0. | 0.0. | 0.0. | 0.0. | 0.0. | 0.0. |
| | 0.2265 | 1.888 9.4 | 2.665 13.95 | 0.0. | 0.0. | 0.0. | 0.0. | 0.0. | 0.0. | 0.0. | 0.0. | 0.0. | 0.0. | 0.0. | 0.0. | 0.0. | 0.0. |

Table SI3: The table shows the annual value of ecosystem services at the post-development steady-state for different combinations of pronghorn hunting and cattle grazing densities in the context of a non-cooperative game between the BLM and the WGF. Rows (columns) represent hunting rates (cattle grazing densities) indirectly chosen by the WGF (BLM). Each cell contains the values (million dollars) of the net benefits of hunting (top left), profits of cattle ranching (top right); existence value of sage grouse (lower left); and total value of ecosystem services per year (lower right). Bold values indicate the best responses of WGF (BLM) to the actions of the BLM (WGF); the underlined value marks the social optimum; shaded cells are the Nash Equilibrium; and cells of only zeros represent combinations that violate the population constraint.

Per household benefit gradients for sage grouse existence value: Percent of local WTP as a function of distance from habitat

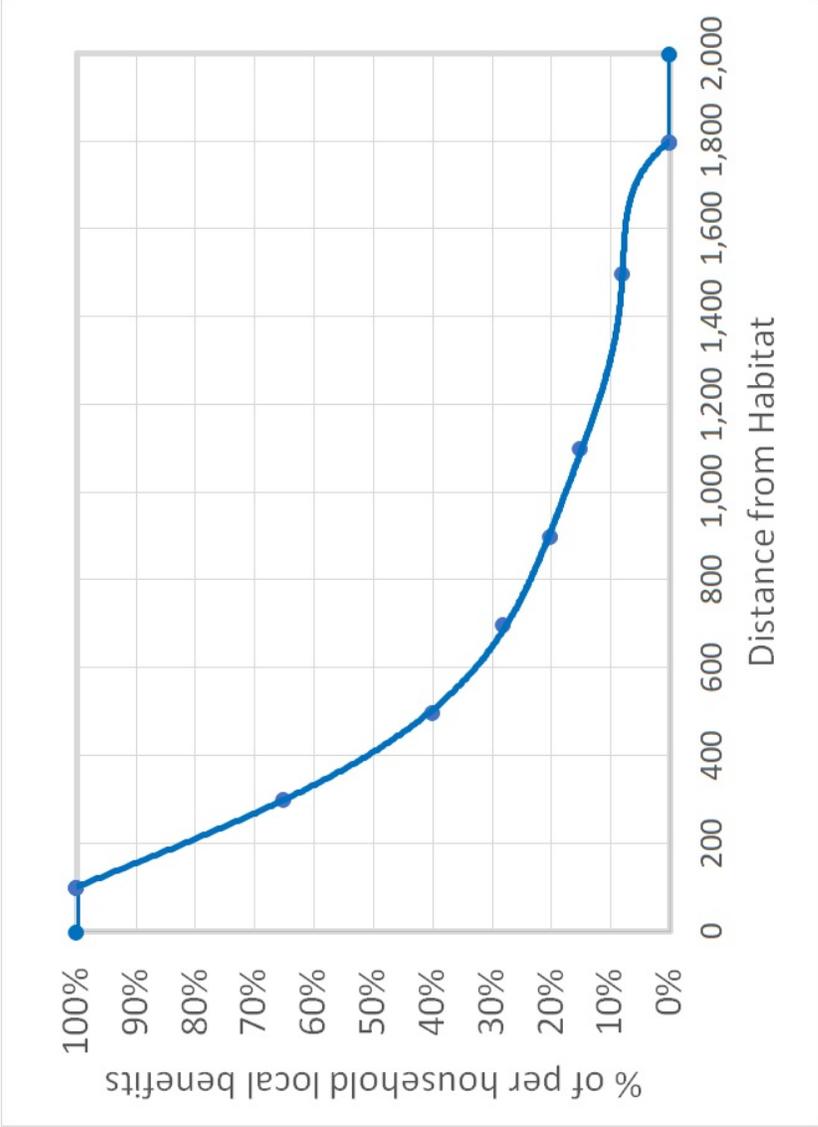


Figure SI5: In the spirit of Loomis (2000, p. 318), we assumed that the WTP of households of maintaining a stable population of sage grouse decreases with distance from habitat. The horizontal axis show the distance in miles to the ARNG region and the vertical axis shows what percentage of the local benefits in the Carbon County are perceived in counties further away.

Sensitivity Analysis: One-Time Shocks on Populations

| One-time negative shock on the population of | Reduction size (%) | Total Discounted Value (\$M) | | | |
|--|--------------------|------------------------------|-------------------------|--------------------------------|------------------------|
| | | Profits of Cattle Grazing | Net Benefits of Hunting | Existence Value of Sage Grouse | All Ecosystem Services |
| No Species | 0 | 0 | 0 | 264.18 | 264.18 |
| | 1 | 0 | 0 | 263.251 | 263.251 |
| | 10 | 0 | 0 | 254.822 | 254.822 |
| | 50 | 0 | 0 | 226.119 | 226.119 |
| Only Animals | 1 | 0 | 0 | 263.974 | 263.974 |
| | 10 | 0 | 0 | 262.167 | 262.167 |
| | 50 | 0 | 0 | 254.526 | 254.526 |
| Only Grass-eaters | 1 | 0 | 0 | 264.074 | 264.074 |
| | 10 | 0 | 0 | 263.087 | 263.087 |
| | 50 | 0 | 0 | 260.666 | 260.666 |
| | 1 | 0 | 0 | 264.042 | 264.042 |
| Only Shrub-eaters | 10 | 0 | 0 | 262.862 | 262.862 |
| | 50 | 0 | 0 | 256.334 | 256.334 |
| | 1 | 0 | 0 | 263.457 | 263.457 |
| Only Plants | 10 | 0 | 0 | 256.906 | 256.906 |
| | 50 | 0 | 0 | 235.867 | 235.867 |
| | 1 | 0 | 0 | 264.113 | 264.113 |
| Only Elk | 10 | 0 | 0 | 263.486 | 263.486 |
| | 50 | 0 | 0 | 260.232 | 260.232 |
| | 75 | 0 | 0 | 259.32 | 259.32 |
| | 1 | 0 | 0 | 264.006 | 264.006 |
| Only Sage Grouse | 10 | 0 | 0 | 262.486 | 262.486 |
| | 50 | 0 | 0 | 254.071 | 254.071 |
| | 75 | 0 | 0 | 238.99 | 238.99 |
| | 1 | 0 | 0 | 264.243 | 264.243 |
| Only Mule Deer | 10 | 0 | 0 | 264.827 | 264.827 |
| | 50 | 0 | 0 | 268.104 | 268.104 |
| | 75 | 0 | 0 | 275.388 | 275.388 |

Table SI4: The table shows the discounted value of cattle ranching profits, existence value of sage grouse, and total services for different population shock scenarios. The light-shaded cells show the minimum value in each column, while the dark-shaded cells show the maximum value.

Sensitivity Analysis: Sets of Species Affected by NGD

| Species | Sensitivity to NGD | | | Total Discounted Value (\$M) | | | | IMPACT |
|-----------------------------|----------------------|----------------------|------------------|------------------------------|----------------------------|-----------------------------------|---------------------------|---------|
| | DA3 1,500-1,000 m | DA2 1,000 - 500 m | DA1 500 - 0 m | Profits of Cattle Grazing | Net Benefits of Hunting | Existence Value of Sage Grouse | All Ecosystem Services | |
| Undisturbed | | | | | | | | |
| Elk | 0 | 0 | 0 | 55.07 | 56.56 | 435.2 | 546.82 | 0 |
| Sage Grouse | 0 | 0 | 0 | | | | | |
| Mule Deer | 0 | 0 | 0 | | | | | |
| Baseline | | | | | | | | |
| Elk | 0.2 | 0.5 | 0.8 | 49.057 | 49.539 | 389.833 | 488.429 | -58.396 |
| Sage Grouse | 0.25 | 0.55 | 0.85 | | | | | |
| Mule Deer | 0.7 | 0.8 | 0.9 | | | | | |
| Very low sensitivity to NGD | | | | | | | | |
| Elk | 0.2 | 0.2 | 0.2 | 57.879 | 56.582 | 432.487 | 546.949 | 0.124 |
| Sage Grouse | 0.2 | 0.2 | 0.2 | | | | | |
| Mule Deer | 0.2 | 0.2 | 0.2 | | | | | |
| Low sensitivity to NGD | | | | | | | | |
| Elk | 0.2 | 0.5 | 0.8 | 59.957 | 52.451 | 376.582 | 488.989 | -57.836 |
| Sage Grouse | 0.2 | 0.5 | 0.8 | | | | | |
| Mule Deer | 0.2 | 0.5 | 0.8 | | | | | |
| Moderate sensitivity to NGD | | | | | | | | |
| Elk | 0.25 | 0.55 | 0.85 | 60.339 | 52.453 | 376.343 | 489.136 | -57.689 |
| Sage Grouse | 0.25 | 0.55 | 0.85 | | | | | |
| Mule Deer | 0.25 | 0.55 | 0.85 | | | | | |
| High sensitivity to NGD | | | | | | | | |
| Elk | 0.7 | 0.8 | 0.9 | 60.004 | 48.065 | 357.082 | 465.151 | -81.674 |
| Sage Grouse | 0.7 | 0.8 | 0.9 | | | | | |
| Mule Deer | 0.7 | 0.8 | 0.9 | | | | | |

Table SI5: The table shows the discounted value of hunting benefits, cattle ranching profits, existence value of sage grouse, and the sum of all services for different combinations of species affected by NGD. The light-shaded cells show the minimum value in each column, while the dark-shaded cells show the maximum value.

Sensitivity Analysis: Nitrogen Availability and Uptake Capacity

| Additional nitrogen in the soil (%) before any disturbance | Nitrogen-uptake ratio of grass to shrub | | Scenario | Total Discounted Value (\$M) | | | | |
|--|---|-----------|--------------------------------|------------------------------|--------------------------|--------------------------------|------------------------|---------|
| | 1st layer | 2nd layer | | Profits of Cattle Grazing | Net Benefits of Hunting | Existence Value of Sage Grouse | All Ecosystem Services | IMPACT |
| | 1 | 23 | | 1.7 | Cattle Grazing + Hunting | 55.073 | 56.555 | 435.196 |
| | | | Cattle Grazing + Hunting + NGD | 49.057 | 49.539 | 389.833 | 488.429 | |
| 0.5 | 23 | 1.7 | Cattle Grazing + Hunting | 52.232 | 56.214 | 422.171 | 530.616 | -56.534 |
| | | | Cattle Grazing + Hunting + NGD | 46.488 | 49.272 | 378.322 | 474.082 | |
| 0.1 | 23 | 1.7 | Cattle Grazing + Hunting | 50.466 | 55.944 | 412.209 | 518.619 | -55.125 |
| | | | Cattle Grazing + Hunting + NGD | 44.901 | 49.061 | 369.532 | 463.494 | |
| 1.5 | 23 | 1.7 | Cattle Grazing + Hunting | 59.155 | 56.905 | 449.059 | 565.118 | -60.416 |
| | | | Cattle Grazing + Hunting + NGD | 52.76 | 49.811 | 402.131 | 504.702 | |
| 1 | 25 | 1.7 | Cattle Grazing + Hunting | 55.073 | 56.555 | 435.195 | 546.823 | -58.396 |
| | | | Cattle Grazing + Hunting + NGD | 49.057 | 49.539 | 389.832 | 488.427 | |
| 1 | 21 | 1.7 | Cattle Grazing + Hunting | 55.073 | 56.555 | 435.196 | 546.825 | -58.396 |
| | | | Cattle Grazing + Hunting + NGD | 49.057 | 49.539 | 389.833 | 488.429 | |
| 1 | 23 | 1.8 | Cattle Grazing + Hunting | 60.751 | 56.544 | 408.058 | 525.353 | -54.869 |
| | | | Cattle Grazing + Hunting + NGD | 51.961 | 49.573 | 368.95 | 470.484 | |
| 1 | 23 | 1.6 | Cattle Grazing + Hunting | 41.2 | 55.586 | 388.87 | 485.656 | -51.703 |
| | | | Cattle Grazing + Hunting + NGD | 37.791 | 48.863 | 347.299 | 433.954 | |

Table SI6: The table shows the discounted value of hunting benefits, cattle ranching profits, existence value of sage grouse, and the sum of all services for different nitrogen uptake ratios in the soil layers and nitrogen availability. The light-shaded cells show the minimum value in each column, while the dark-shaded cells show the maximum value.

Sensitivity Analysis: Sage Grouse WTP/Household

| Sage-grouse WTP/household | Scenario | Total Discounted Value (\$M) | | | | | IMPACT |
|---------------------------|--------------------------------|------------------------------|-------------------------|--------------------------------|------------------------|--|---------|
| | | Profits of Cattle Grazing | Net Benefits of Hunting | Existence Value of Sage Grouse | All Ecosystem Services | | |
| 11.38 | Cattle Grazing + Hunting | 55.073 | 56.555 | 435.196 | 546.825 | | -58.396 |
| | Cattle Grazing + Hunting + NGD | 49.057 | 49.539 | 389.833 | 488.429 | | |
| | Cattle Grazing + Hunting + NGD | 55.073 | 56.555 | 38.242 | 149.871 | | |
| 1 | Cattle Grazing + Hunting + NGD | 49.057 | 49.539 | 34.256 | 132.852 | | -17.019 |
| | Cattle Grazing + Hunting | 55.073 | 56.555 | 305.938 | 417.566 | | |
| | Cattle Grazing + Hunting + NGD | 49.057 | 49.539 | 274.048 | 372.644 | | |
| 8 | Cattle Grazing + Hunting | 55.073 | 56.555 | 535.391 | 647.019 | | -68.84 |
| | Cattle Grazing + Hunting + NGD | 49.057 | 49.539 | 479.583 | 578.179 | | |
| | Cattle Grazing + Hunting + NGD | 55.073 | 56.555 | | | | |

Table SI7: The table shows the discounted value of hunting benefits, cattle ranching profits, existence value of sage grouse, and the sum of all services for different WTP/household to maintain the population of sage grouse stable at the undisturbed steady-state. The light-shaded cells show the highest impact, while the dark-shaded cells show the lowest impact.