Measuring the Wind Power Potential Outside of Conservation Areas in Wyoming

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Signature(s)

Abstract

The U.S. Department of Energy has set a nationwide goal of producing 20% of electricity using wind power by 2030. Kiesecker et al. (2011) explored the capacity to meet this goal while focusing wind farm placement on lands already disturbed by development with the intention of habitat loss mitigation. However, the study used only wind speed to determine site suitability, which may have led to an incorrect estimate of electricity generation capacity. The objective of this paper is to implement a site suitability model in Wyoming that takes into account other important criteria, including slope, land cover, wind speed, and proximity to roads. We seek to determine whether it is feasible for the state to achieve the DOE 20% goal without allowing development in conservation areas. Site suitability across the state was modeled using physical and infrastructural data from a variety of sources. A binary constraint layer and a layer of evaluation criteria were multiplied to create a suitability index map. Conservation zones were determined using data on the locations of managed lands from the Wyoming Geographic Information Science Center, as well as sage grouse core area data from the Wyoming Fish and Game Department. Conservation zones were restricted from development and the power generation capacity of the state was calculated for the suitable lands that remained. Results indicate that 291.74 GW of power could be produced on lands outside of conservation zones. These results demonstrate that Wyoming has more than twenty times the land required to meet the DOE goal even without building on conservation areas. This may be an overestimate, as the lands designated as conservation zones were limited and probably did not completely represent environmentally significant areas. Future research could focus on better defining areas of high conservation importance.

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I. Introduction

The vast majority--over 70%--of electricity in the United States is produced using fossil fuels such as coal, natural gas, and oil (International Energy Agency). But with increasing concern about the environmental consequences of fossil fuels and their long-term sustainability, domestic renewable energy sources have grown in popularity. Wind power in particular has grown rapidly—by more than 30% annually in the last decade—and in 2011 the nation's wind farms generated 55,700 gigawatt hours (gWh), or almost 1% of the nation's supply of electricity (International Energy Agency). In 2008 the Department of Energy released a report titled "20% by 2030" that called for the generation of 20% of America's electricity via wind by 2030. This was a recommendation and not legally binding, but several states have adopted similar renewable energy portfolio standards, which are policies requiring that a minimum percentage of a state's power be obtained using renewable energy. This legal commitment to increased renewable energy may portend future growth of the wind industry as states strive to meet policy requirements (DOE 2009).

Most states have some wind energy development: utility-scale wind projects stand in at least 37 states (AWEA 2010). But with an annual energy potential of 747,000 gWh, Wyoming has the seventh highest potential of any state to capture the wind to generate electricity (AWEA). From 1999 to 2011, the electricity production capacity of Wyoming's wind industry increased by a factor of almost 20 (from 640 gWh to 12,400 gWh annually) , and the expansion might be expected to continue, given the DOE push for increased wind development (DOE). Wyoming has excellent conditions for wind development, with nearly the lowest population density of any state (U.S. Census Bureau) and an abundance of open land. In addition, 48% of lands in the state are federally owned and managed by the Bureau of Land Management (BLM). Since 2009, the BLM in Wyoming has been active in promoting the development of wind energy projects on federal lands in an effort to meet the renewable energy goals legislated by the Energy Policy Act of 2005 (U.S. BLM).

Much of wind power's appeal comes from its environmentally-friendly image; unlike fossil fuels, turbines release no greenhouse gases or other forms of air pollution in the process of electricity generation. But though they are widely considered to be a "green" energy source, wind turbines can have a negative impact on the environment (Fielding 2006, Kiesecker et al. 2011, Lucas et al. 2008, Osborn et al. 2000). The spinning blades of turbines have been directly linked to bat and bird fatalities (Lucas et al. 2008, Osborn et al. 2000, Kuvlesky et al. 2007). Although the public has expressed concern about this impact on wildlife, the potential long-term effects of large wind farms on birds and bats are not well understood (Manville 2009).

However, the negative impacts of wind turbines aren't limited to fatal collisions. Commercial wind turbines tend to be built together in large arrays to compensate for the relatively low production capacity of each individual turbine. A greater area of land is required to generate the same amount of power from wind as can be produced using other methods.[1] Consequently, wind is a form of energy production with a comparatively large terrestrial footprint. As such, its contribution to habitat loss and fragmentation as a result of insufficiently discriminate wind farm siting can pose a significant problem for conservation (McDonald et al. 2009).

Among the most pressing concerns about the environmental impact of wind power in Wyoming is its potential effect on the greater sage grouse, a ground-dwelling bird species of high conservation interest. Although it has not been formally listed as endangered, and though

[1] Wind requires about 50 times as much area/GW as nuclear, one of the most compact forms of energy production (McDonald 2009).

management is currently recommended at the state level, the U.S. Fish and Wildlife Service has stated that the species warrants protection under the Endangered Species Act (USFWS 2011). Sage grouse are dependent on large, connected tracts of sagebrush ecosystem to maintain stable populations. Combined effects of habitat loss, fragmentation, and disturbance have lead to the disappearance of sage grouse from 50% of their former range and an estimated drop in population from 16 million to between 200,000 and 500,000 in only a century (Broder 2010); any additional habitat loss comes at a very high cost. The situation has the potential to worsen as development of wind energy moves forward, because the best sites for wind power generation often overlap with key sage grouse habitat areas (Becker et al. 2009). The birds tend to be negatively affected by tall structures such as turbines and transmission towers and avoid them accordingly, a behavior that may stem from an evolutionary instinct to avoid perching predatory birds (Lammers & Collopy 2007, Pruett et al. 2009). Therefore, construction of wind farms has the potential to result in further fragmentation and degradation of habitat quality that could put even greater pressure on a species that is already vulnerable.

In response to the threats facing sage grouse, since 2008 Wyoming's government has designated sections of both public and private land as "Sage Grouse Core Areas" and has issued limitations on the development that is allowed within those areas (Streater, 2011). No new development may occur in core areas unless it is demonstrated that sage grouse populations will not be affected.

Despite reservations, wind energy remains an appealing alternative to fossil fuels, especially if wind farms sites are selected to avoid sprawl into environmentally sensitive areas (McDonald et al., 2009). Kiesecker et al. (2011) introduced a potential strategy for reducing the heavy areal impacts of wind farms. Prompted by the DOE goal of producing 20% of the nation's electricity using wind by 2030, the authors identified the states that would be able to produce 20% of their own energy demand using wind power while avoiding construction on land that was previously undisturbed (i.e. lands not yet impacted by agriculture, gas, or oil developments). They found that nine states would be unable to meet the DOE goal by installing wind turbines only on disturbed land. However, several states demonstrated a capacity to produce a surplus of wind energy on land that was already disturbed. The total surplus energy from these states was sufficiently large that lower capacity states could import it to meet their own requirements. With such cooperation, the nationwide 20% goal was found to be achievable without any state needing to build on undisturbed land. Wyoming was one of the states with the potential to produce a surplus, and it was estimated that Wyoming would be able to generate more than five times the energy necessary to meet its own 20% goal even while excluding undisturbed lands.

The "disturbed lands first" approach has the potential to be extremely valuable in guiding renewable energy development in the future. However, one limitation of the study is that it used wind speed as the only factor in determining which lands were suitable for wind energy production. This may cause their model to incorrectly estimate the amount of suitable land and thus the state's electricity production potential. Although wind speeds are of central importance to whether a turbine will be profitable in a given location, many other factors affect the suitability of a site for wind power.

A number of studies have sought to determine the best locations for installing wind turbines by establishing a measurable set of criteria necessary for optimal placement and using the criteria to evaluate potential sites. Common criteria used in suitability analyses include proximity to settlements, protected areas, and infrastructure; and wind potential, slope, and land cover conditions. Geographic Information Systems (GIS) has been central to such site suitability studies because of its capacity for the integration, analysis, and display of this spatially-rooted information.

Several approaches have been used in determining the appropriate siting criteria and implementing suitability analyses. Baban and Parry (2001) surveyed 64 public and private organizations in the UK, including local bodies of government and wind companies, in order to discover which criteria people on the ground were using to select suitable turbine sites. This information was used to create a list of constraints based on access and costs for construction, topography, wind speed, and land use, as well as the social implications of noise pollution, visual impact, and health and safety. Sites were evaluated against each of the criteria on an index scale of 0 to 10, the criteria were weighted according to their relative importance, and a map of suitable sites was produced.

Alternatively, Lejeune et al. (2008) used a research team to develop a list of areas of recreational, historical, or biological value to serve as the criteria. One of three constraint levels was applied to each area: “sensitive,” “highly sensitive,” or “exclusion,” depending on the impact that turbine installation was expected to have in the area. The criteria were aggregated, and the highest constraint level that applied to each cell was assigned to it to qualitatively determine the suitability of that location.

Other authors have adopted the criteria used by previous studies. Aydin et al. (2010) created a list of six environmental objectives that they determined a suitable site must fulfill (e.g. “Acceptable in terms of noise,” or “Acceptable in terms of bird habitat). They then borrowed a set of minimum distance criteria—using distances from towns, airports, and ecologically important areas—from the work of others and from current legislation to use as quantitative proxies for determining whether their objectives had been met. A fuzzy decision-making approach was applied to the criteria, and the results were aggregated to determine how well each location (represented by cells) satisfied the suitability criteria as a whole.

Many of these studies share a basic framework: they used a decision-making system alongside GIS to combine their geographic data with the priorities of people in order to determine site suitability. Using a similar framework, in this paper we seek to implement a site suitability model in order to determine which locations in Wyoming will most likely be targeted for wind energy development. An examination of the literature on turbine site suitability revealed that a paper by Tegou et al. was best situated to guide our project in terms of both subject matter and ease of execution. Their study used eight criteria to evaluate the suitability of turbines sites: visual impact, land value, slope, land cover, wind potential, distance from road network and transmission lines, and electricity demand. Each of these was classified and graded internally on a scale from 0 to 1. Pair-wise comparisons were used determine the relative weights of the criteria, and the weighted map of evaluation criteria was multiplied with a map of constraints (areas where building was prohibited) to arrive at a final suitability map. The authors of this study were uncommonly explicit about the details of their methodology, making it relatively easy to replicate.

In addition to identifying suitable sites in Wyoming, we also attempt to integrate Kiesecker's idea of building on developed land first. We examine whether Wyoming could produce 20% of its electricity with wind on the land that our model identifies as suitable, but with the ecologically significant conservation zones removed from consideration. Finally, we discuss the outlook for future wind development in Wyoming and the potential for export of surplus energy to other states.

II. Methodology

We attempted to improve the model developed by Kiesecker et al. (2011) in two ways: by using a more sophisticated model for site suitability that utilizes other factors in addition to wind potential and by establishing the framework for a more detailed conservation layer. Our revised model consisted of three stages. First we created an economic suitability model to identify desirable turbine locations throughout the state. Then we created a layer of "conservation zones" – areas of conservation value that would be jeopardized by the construction of wind turbines. Finally, we estimated the total potential wind power that could be generated in areas we determined to be suitable for wind development, both with and without the conservation areas as a restriction to wind development. All analysis was conducted using ArcGIS 10.

Our suitability map was the product of a raster overlay using an evaluation layer and a constraint layer. The process of calculating suitability index values for each cell is represented by the equation below:

$$\mathbf{SI = (\sum w_i * x_i) * c_j}$$

In order to create the constraint layer, constraining variables (c_{j-n}) are assigned a value for each cell using binary classification. This divides the map into areas that are either suitable (=1) or unsuitable (=0). A set of criteria (x_{i-n}) with assigned index values ranging from 0 to 10 are added to create the evaluation layer assigns each cell a value between 0 and 10 based on its suitability for wind development, with ten being most suitable. Pair-wise comparisons are used to determine the weights (w_{i-n}) that are applied to the variables in the evaluation layer. The weighted evaluation layer is then multiplied with the constraint layer to produce a final suitability layer. A cell rated as "suitable" in the constraint layer is thus assigned its value from the evaluation layer in the final suitability index, while a cell rated "unsuitable" in the constraint layer is assigned a value of zero regardless of its score in the evaluation layer. The methodology for the site suitability portion of our model was based on that used by Tegou et al. (2010) in their study of potential wind power locations on the island of Lesvos, Greece. Notable diversions from their methodology are described in the discussion section of this paper. A diagram of this process can be found in Appendix 1.

Evaluation layer – The evaluation layer consisted of four variables: proximity to roads, slope, land cover, and wind potential. Unless otherwise noted, variables are graded on a suitability scale from 0 to 10, with larger numbers being more suitable for wind energy development.

Road data was obtained from the Wyoming Geographic Information Science Center. Tegou et al. applied multiple ring buffers for every 100 meters to a maximum distance of 2500 meters from roads. Areas beyond this were considered unsuitable for wind development. We attempted to replicate this, but ArcMap was unable to process the multiple-ring buffers despite repeated attempts. We therefore simplified the technical demands on the program by treating roads as a constraint layer; all cells within 2500 meters of a road are given a score of 10, while those further away were given a score of 0.

Slope data was derived from an elevation file of Wyoming with a resolution of 30 meters, which we obtained from the United States Geological Service’s Seamless Data Viewer. We used the slope tool to measure slope in each cell, with values ranging from 0% to approximately 750%. We then reclassified the slopes according to the grading used by Tegou et al. in which flat areas are most suitable with a score of 10. The grading value decreases until the slope reaches 25%, at which point it is classified as unsuitable regardless of scores for other variables in the evaluation layer.

Land cover data was obtained from the USGS Northwest GAP Analysis Program, and included 91 land cover types. These 91 land cover types were graded on a scale from 0-10 based on their potential for wind development. In general, areas covered by grasses or scrubby plants were rated more highly than forests, both because construction is easier and because taller trees can slow wind speed and cause turbulence (Tegou et al., 2010). Wetlands, urban areas, and other unsuitable land cover types were classified as unsuitable regardless of scores for other variables in the evaluation layer. In order to assign land cover types grading values consistent with the Tegou model, we classified each Wyoming land cover type into one of nine land cover classes, depending on the cover type represented in Tegou et al. (2010) that it matched most closely (Table 1).

Table 1. *Grading values for land cover.*

Land Cover Class	Grading value
Bare Land	10
Low scrubland	10
Dense scrubland	9
Cropland	9
Pine Forest	1
Deciduous forest	1
Wetlands	(Constraint)
Urban Land	(Constraint)
Other	(Constraint)

Wind potential data came from a National Renewable Energy Laboratory dataset that classifies areas into seven wind power classes, each representing a given range of wind speeds. We reclassified the data based on the relationship between wind speed and grading value used by Tegou et al. (Table 2).

Table 2. *Grading values for wind potential.*

Wind Power Class	Wind speeds (m/s)	Grading value
1	0 - 5.6	1
2	5.6 – 6.4	1
3	6.4 – 7.0	6
4	7.0 – 7.5	7
5	7.5 – 8.0	8
6	8.0 – 8.8	9
7	8.8+	10

Maps of each evaluation variable can be found in Appendix 2. We overlaid the four evaluation variables to produce our evaluation layer. Grading values of cells for each evaluation variable were multiplied by the weight of that variable, and were then summed with the values of corresponding cells from different variables to produce an evaluation score.

Table 3. *Weighting for Evaluation Layer*

Variable	Weight
Slope	0.06
Proximity to Roads	0.22
Land Cover	0.31
Wind Class	0.41

This weighting was based on that created by Tegou et al. (2010) using the Analytic Hierarchy Process and was modified to account for differences in variables and methodology. The four variables used in our evaluation layer – slope, proximity to roads, land cover, and wind potential – accounted for 67% of the weighting used in the Greek model, with the remaining percentage accounted for by variables excluded in our study. We adjusted the weights of the four variables in our study to sum to 1 while maintaining their balance relative to one another. This weighting produced the map shown in Figure 1.

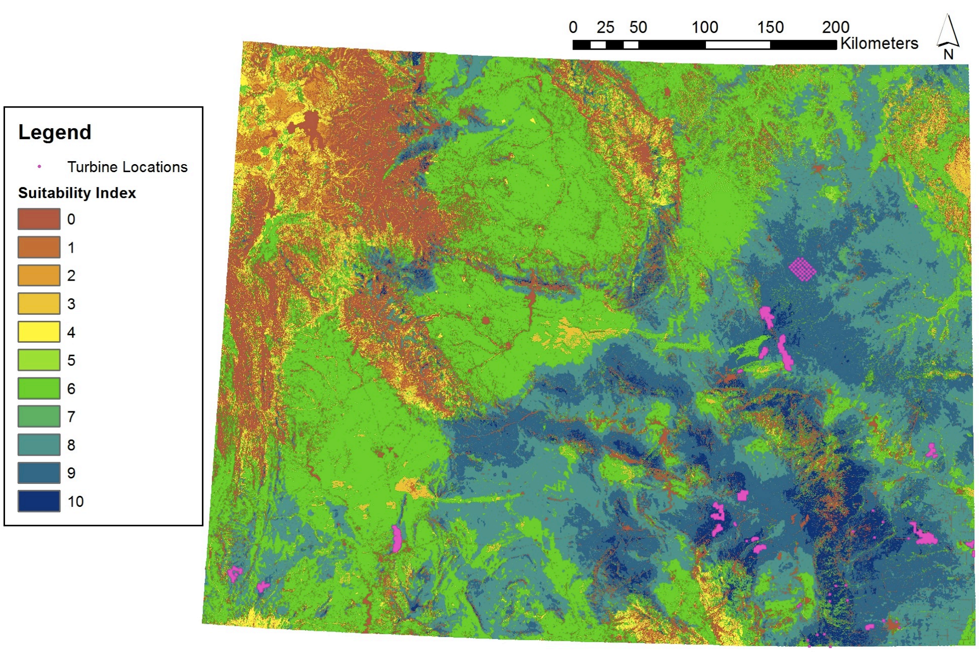

Figure 1. *Evaluation layer, created through a weighted overlay of slope, land cover, road proximity, and wind potential layers.*

Constraint Layer – Our constraint layer consisted of four criteria: specific types of land cover, steep slopes, proximity to airports, and proximity to settlements. Wetlands, floodplains, open water, scree fields, urban areas, and other clearly unsuitable types of land cover were rated as unsuitable. Cells with slopes above 25% were rated as unsuitable. A 500m buffer was created around all municipal boundaries and city locations to represent the concerns about noise, visual impact, and "NIMBY" opposition, and all areas within that buffer were treated as constraints. We also constrained areas around airports with buffers for safety reasons. We found a range of buffer distances used in related literature. Various sources used 2500m (Aydin et al., 2010), 3000m (Sliz-Szliniarz and Vogt, 2011; Acker et all, 2007), and 5000m (Lejeune and Feltz, 2008). We decided to use 3000 m for the purposes of our study because it was the most common in the relevant literature and it most accurately reflected distances that already exist between turbines and airports in Wyoming. Maps of each constraint variable can be found in Appendix 3, and the complete constraint map is shown in Figure 2.

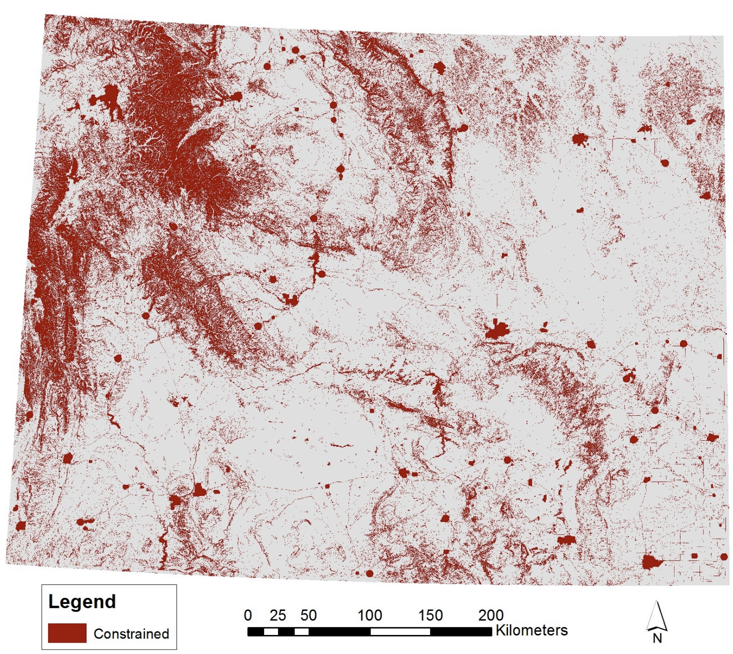

Figure 2. *Constraint layer created by combining steep slopes, restricted land cover types, areas around airports and areas around cities/towns.*

We developed our economic suitability map by multiplying the constraint layer with the evaluation layer. The resulting map (Figure 3) provides an index for suitability across the state.

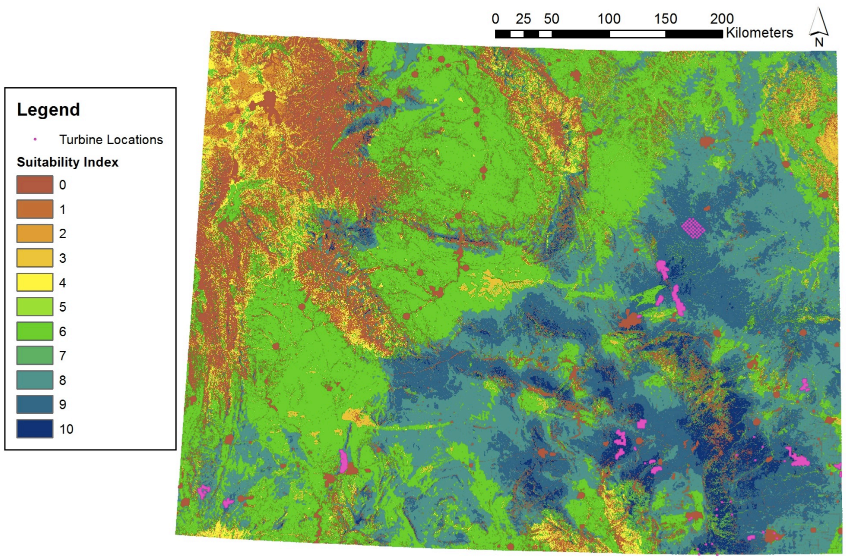

Figure 3. *Economic suitability map for Wyoming, showing locations of existing and planned turbines in pink.*

There is a strong correlation between areas that our suitability index scores highly and the locations of current and planned turbines. (See Table 4.)

Table 4. *Area and number of turbines in each index score.*

Index Score	Area (km^2)	% of State	Turbines	% of Turbines	Turbines/100km^2
0	47294.8	18.7	29	1.7	0.06
1	2411.4	1.0	0	0.0	0.00
2	2048.0	0.8	0	0.0	0.00
3	9631.4	3.8	0	0.0	0.00
4	7162.0	2.8	0	0.0	0.00
5	1703.1	0.7	1	0.1	0.06
6	82062.1	32.4	54	3.2	0.07
7	2351.9	0.9	7	0.4	0.30
8	56225.2	22.2	290	17.0	0.52
9	35919.2	14.2	893	52.4	2.49
10	6675.5	2.6	431	25.3	6.46
Total	253484.6	100.0	1705	100	0.06

The turbine density in areas rated 10 in our suitability index is 100 times greater than the statewide average. Turbines are most dense in the areas rated 8, 9, and 10, with over 95% of all of Wyoming's turbines falling into those areas although they encompass only 39% of the state's area.

Because of this, we consider all areas rated 8, 9, or 10 "desirable" and all layers rated 7 or below "undesirable". The resulting map is shown in Figure 4.

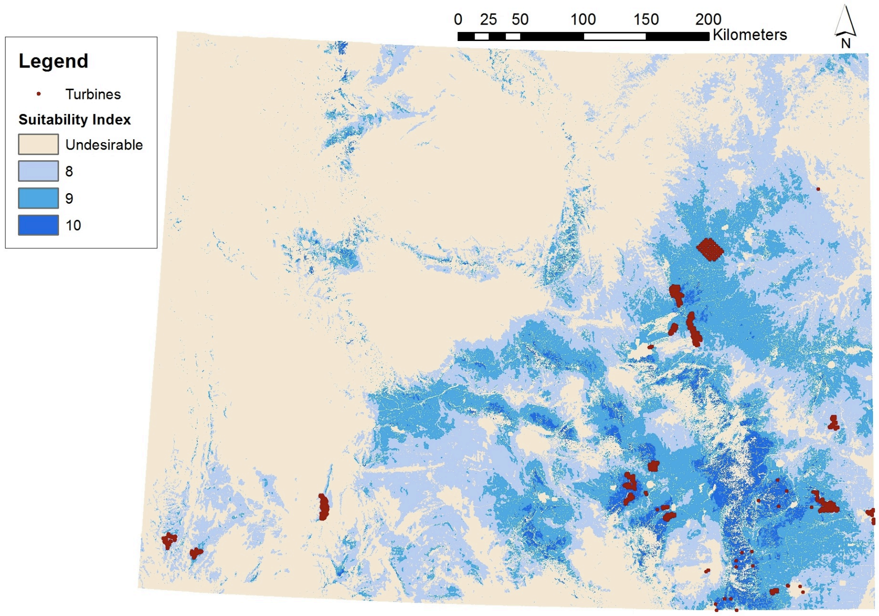

Figure 4. *Areas identified by our model as desirable and undesirable. Note that almost all of the existing and planned turbines fall within areas our model identifies as desirable.*

Conservation Zones – Our conservation zones attempt to identify areas that should be protected from wind development for conservation reasons. Whereas Kiesecker et al (2011) used all "undisturbed lands" (including rangelands) in this category, we chose to use only areas that have been specifically designated as having particular conservation value. Our conservation layer was made up of "managed lands"—a collection of National Forests, National Grasslands, Wildlife Refuges, and similar such protected lands—and sage grouse core habitat areas. We obtained a dataset of managed lands from the Wyoming Geographic Information Science Center and edited it to exclude the Wind River Indian Reservation, which was created for reasons unrelated to biological concerns. The sage grouse core habitat dataset outlines the sage grouse core areas delineated under Governor Matthew Mead in 2011 and was obtained from the Wyoming Game and Fish Department. Maps of the individual layers that make up the "conservation zones" layer can be found in Appendix 4. The complete conservation zones layer is shown in Figure 6.

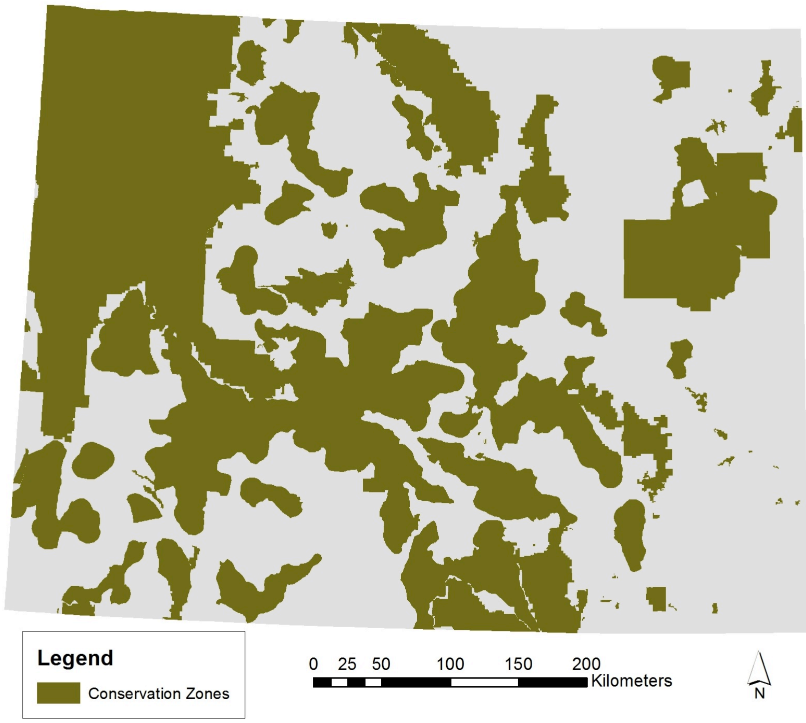

Figure 6. *Conservation zones composed of managed lands and Sage grouse core areas.*

Estimate of Wind Power Capacity

The final step of our study was to compare the total wind capacity of Wyoming to its wind capacity when conservation zones are removed from consideration for potential development. We based our methodology for this stage on that used by Kiesecker et al. (2011), who assume that turbines are constructed with a nameplate capacity and at a density that would have a maximum output capacity of 11.24 MW/km^2. We determined the area of land rated 8, 9, or 10 (deemed "desirable") on our suitability scale that fell within each wind class and multiplied the area by 11.24 and by the appropriate capacity factor (Table 6). We performed these calculations both with and without our conservation zones dataset used as a constraint for wind development.

Table 6. *Capacity Factor by Wind Power Class. (Areas in Wind Power Classes 1 and 2 are judged to be unsuitable for wind power generation.)*

Wind Power Class	Capacity Factor
3	38%
4	43%
5	46%
6	49%
7	53%

III. Results

When we don't remove conservation zones from potential development, areas rated 8, 9, or 10 in our index make up 98,820 km^2, or about 39% of Wyoming's area. 56,225 km^2 (22.2%) is rated 8; 35,919 km^2 (14.2%) is rated 9; and 6676 km^2 (2.6%) is rated 10. We estimate the total wind power production potential on these lands at 459.52 GW. However, when we limit potential development to areas outside of what we designate as "conservation zones", areas rated 8, 9, or 10 make up only 62,502 km^2, or about 24.7% of Wyoming's area (Figure 7). This is a decrease of about 36.8% from the suitable area without restrictions. 35,024 km^2 (13.8%) is rated 8; 22,645 km^2 (8.9%) is rated 9; and 4,834 km^2 (1.9%) is rated 10. We estimate the total wind power potential on these lands at 291.74 GW, a decrease of about 36.5% from our estimate without restrictions.

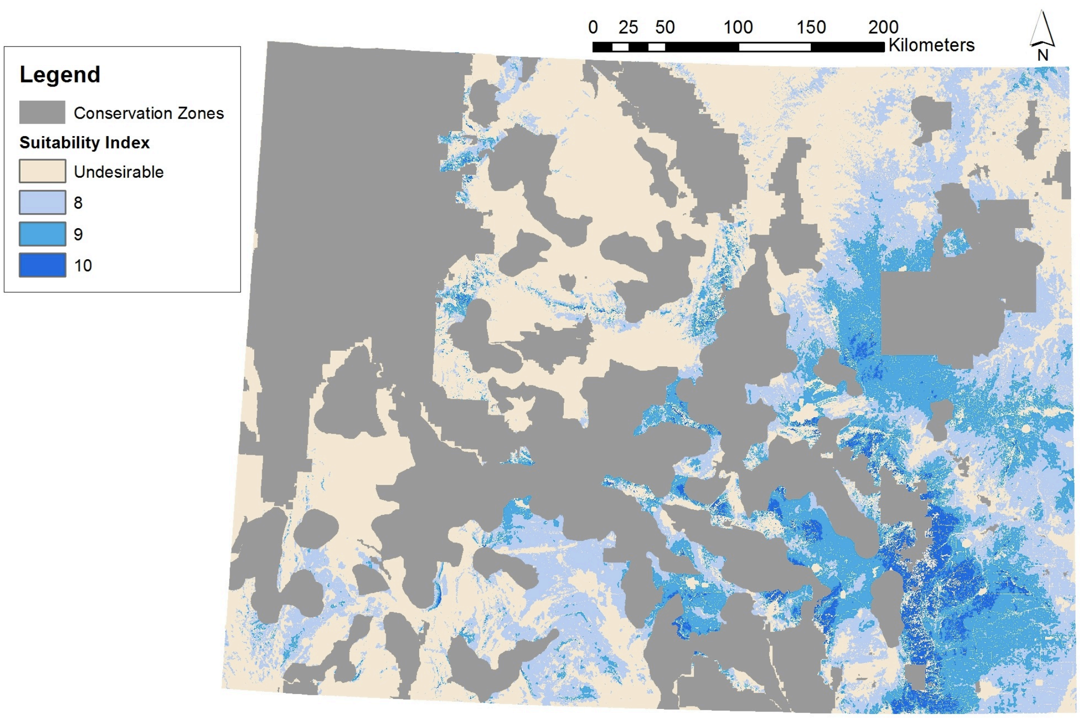

***Figure** 7. Suitability map with conservation zones restricted.*

Even with conservation-based restrictions in place, our model estimates that Wyoming has enough wind power potential to meet its DOE goal of 12.77 GW of wind power generation more than twenty times over.

***Sensitivity Analysis* –** We used a sensitivity analysis in order to test the stability of the suitability model. Our intent was to determine whether small variations in the weighting of the variables in our evaluation map would significantly alter our output. We based our methodology for the sensitivity analysis off of that described by Jacek Malczewski (1999). Along with our base map (our original suitability map) we created eight other maps, each with the weighting for one of the four variables (land cover, roads, slope, and wind potential) either increased or decreased by 3%. In order to compensate for this change, 1% was either removed from or added to the weight of each of the other three variables. We then determined the area within each of the top three index scores (the areas we deem desirable for turbine development) and compared these areas to the area of each index score in our base layer to measure the magnitude of changes produced by shifts in weighting. The results of the sensitivity analysis are in Table 5.

Table 7. *Results of sensitivity analysis. The area (km^2) of land in each of the top index classes is listed for each scenario, along with the percent change from the area determined in our base scenario.*

Index Value	Base (km^2)	LC - 3 (km^2)	LC + 3 (km^2)	Rd - 3 (km^2)	Rd + 3 (km^2)	Slp - 3 (km^2)	Slp + 3 (km^2)	W - 3 (km^2)	W + 3 (km^2)
10	6675.5	6447.9 (-3.4%)	6675.5 (+0.0%)	6447.9 (-3.4%)	6677.8 (+0.0%)	6677.8 (+0.0%)	6126.3 (-8.2%)	6447.9 (-3.4%)	6677.8 (+0.0%)
9	35919.2	33212.1 (-7.5%)	35925.4 (+0.0%)	33212.1 (-7.5%)	35927.3 (+0.0%)	38076.9 (+6.0%)	33097.3 (-7.9%)	36148.3 (+0.6%)	32982.3 (-8.2%)
8	56225.2	59115.7 (+5.1%)	56258.2 (+0.1%)	59178.2 (+5.3%)	56191.6 (-0.1%)	54028.2 (-3.9%)	59550.0 (+5.9%)	56111.9 (-0.2%)	59247.8 (+5.4%)
8 – 10	98819.9	98775.7 (+0.0%)	98859.1 (+0.0%)	98838.2 (+0.0%)	98796.7 (+0.0%)	98782.9 (+0.0%)	98773.6 (+0.0%)	98708.1 (-0.1%)	98907.9 (+0.1%)

Within the areas that fell into the top three index scores, the largest shifts in output occurred when the weighting of the slope variable was increased by 3%. Lands rated 10 and 9 decreased, but lands rated 8 increased by almost 6%. Out of the 1,614 turbines in areas rated 8 or above in our suitability analysis, only 56 (3.5%) were located in areas that changed index scores when the weighting of the slope variable was increased by 3%. Figure 8 marks identifies the areas rated 8, 9, or 10 that changed suitability index scores under this scenario.

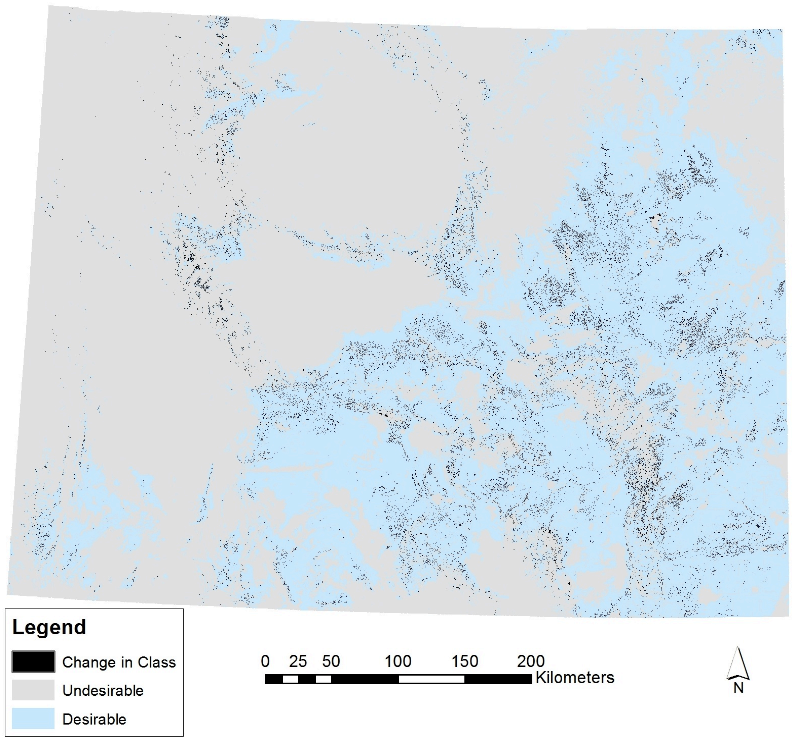

Figure 8. *Areas within the top three index classes that changed index scores from our base scenario when the weighting of slope was increased by 3%.*

Despite variability within the top three suitability index scores, there was very little change between the areas we identified as "desirable" (suitability scores of 8, 9, or 10) and areas we identified as "undesirable" (suitability scores of 7 or below). The largest changes between these areas occurred when the weighting for wind potential was increased or decreased by 3%, but even in these cases the amount of land rated "suitable" changed by less than 0.1% from our base map. For the purposes of our study, the suitability index model is very stable. However, it is worth noting that because our model rounds suitability index scores to the nearest integer, some small variation that results from weighting shifts may not show up. Increasing the precision of the model would probably reveal more variation as a result of altered weighting scenarios.

IV. Discussion

Our estimate for Wyoming's wind energy production potential if conservation concerns are taken into consideration is more than four times higher than the estimate provided by Kiesecker et al. (2011). This is mostly because our model allows for wind development on lands classified as "undisturbed" by Kiesecker et al. as long as such land is not identified as having specific conservation value. Kiesecker et al. classified all rangeland as "undisturbed", thus placing it off-limits to wind development.

For this and other reasons discussed in more detail below, our model probably overestimates the amount of land that can be developed for wind power without threatening conservation goals (Kiesecker et al. probably underestimate such land). Despite these shortcomings, our estimate of Wyoming's wind energy potential (291.74 GW) is large enough in relation to the DOE's goal (12.77 GW) to make it clear that Wyoming can generate 20% of its energy via wind and still be left with a substantial surplus, all without putting conservation interests at risk.

Although these findings are promising, the immediate future of wind development in Wyoming is limited for several reasons. Much of the industry's growth in the last ten years can be attributed to generous federal aid programs, all of which will have expired by the end of 2012 (Cardwell 2012, U.S. Treasury). Additionally, although Wyoming has great potential for energy production, it has one of the lowest population densities in the country. It could be an important exporter of wind energy, but only if the infrastructure and market were in place to transport and accept the energy it produces. Two transmission line projects have recently been granted accelerated permitting by the Obama Administration (DOE 2011). One of these, the TransWest Express Transmission Project, would connect Wyoming to the market in southern California, Nevada, and Arizona, which would bode well for a state whose production potential has mainly been limited by lack of transmission lines. However, in an effort to benefit its own economy, California has recently passed legislation limiting the amount of renewable energy from outside the state that can be used to fulfill its portfolio standard (van der Voo 2011). Similar limits on imported energy by other neighbors could significantly decrease the potential for expansion in Wyoming's wind industry.

There are several considerations that do not feature in our model due to issues with data availability, time constraints, or impracticality of implementation.

Economic Suitability Index – Our site suitability index fails to take into account several factors that may influence the location of turbines: land value, landowner cooperatives, visual impact, electricity demand, and proximity to transmission lines. The primary reason that we didn't use land value as a variable is that we were unable to acquire the parcel data that would have been necessary (Tegou et al. estimated land value based on another model, but we decided that this was outside the scope of our project). However, ignoring land value does not seem to present a serious problem for our model. Given that most of the land being acquired for wind turbines is either unused or is used for pastoral or agricultural purposes; and given that wind turbine installation does not preclude continued agriculture, very little land is removed from use when turbines are installed. Out of all the literature about using GIS models to identify suitable turbine locations, the paper by Tegou et al. is the only one that included land value as a variable. Even in that study, land value was assigned the weakest weight of the eight evaluation variables (only 0.025). So although our model might be improved with land value included as a variable, its absence is not likely to have a serious effect on the accuracy of our economic suitability index.

Another influence on the cost of obtaining private land may be the recent emergence of landowner cooperatives, in which groups of landowners in highly suitable areas organize to drive up land prices for wind developers (Barringer, 2008). However, the difficulty of modeling this led to its exclusion from our suitability index. We are unaware of any studies that have attempted to model the impact of landowner cooperatives. Janke (2010) incorporated population density into his suitability analysis for wind farms in Colorado, but this was unrelated to cooperatives.

We only partially address the significance of visual impact on site suitability. We included a 500m buffer around all towns and municipal boundaries, but this does not wholly address issues of visual impact. For example, it doesn't take into account public opposition that might arise from when turbines affect scenic views. Tegou et al. (2010) provide a methodology for determining visual impact, but it would require heavy modification before being relevant to Wyoming (shorelines and archeological sites play a large role in their visual impact model).

Another significant omission from this analysis is transmission lines. Proximity to transmission lines was used as a variable by Tegou et al. (2010) but we omitted it from our model for several reasons. The only transmission line data we were able to acquire is from 2004, and more than 90% of Wyoming's turbines have been planned or built since then. On top of that, the transmission data does not identify which lines have enough capacity to take on additional power. This means that many of the lines included in the dataset may not be able to carry any additional energy generated by wind turbines.

When we included the transmission line data in our model we found that it weakened the relationship between suitability index score and current and planned turbines. We did this by creating multiple ring buffers around the transmission lines included in the data. Rings closest to the transmission lines were assigned a value of ten (most suitable), with this value decreasing for cells further from the transmission lines out to 2000 meters. Cells beyond 2000 meters were assigned a value of zero. We used a dataset of existing and planned turbines to assess the validity of incorporating the transmission lines into our suitability model. We determined the density of turbines in each value on our index to produce the data shown in Table 8 and Figure 9.

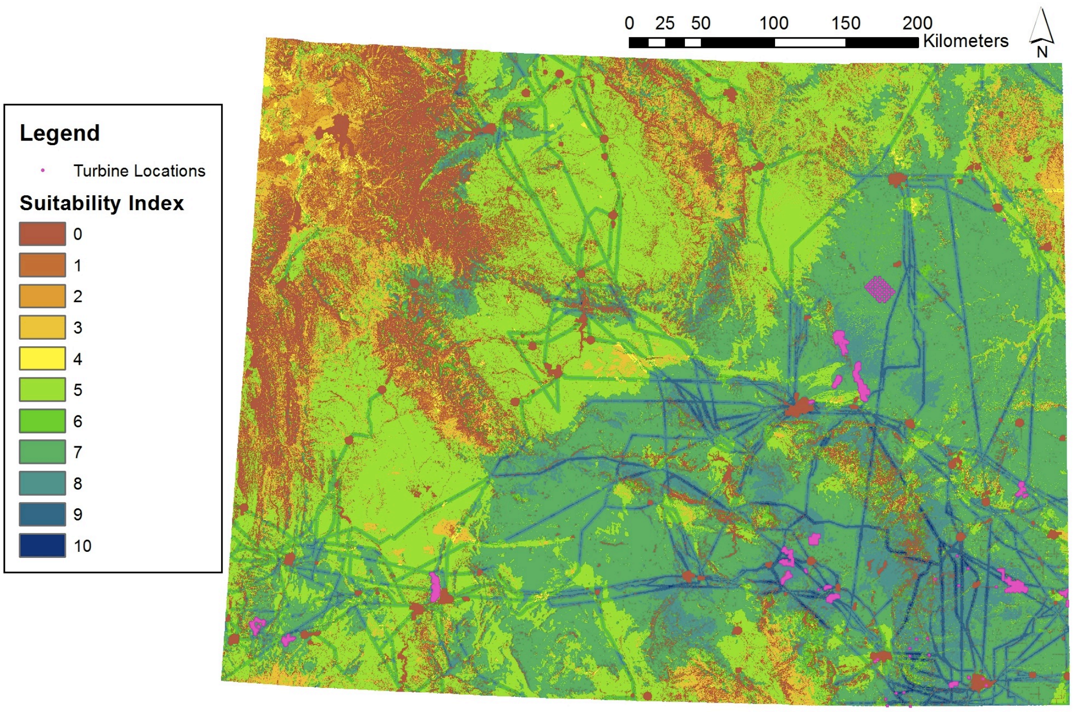

Figure 9. *Suitability model with transmission lines included as a variable. For comparison,* *see Figure 3 on p. 15.*

Index Score	Area (km^2) w/ Trans.	Area (km^2) w/o Trans.	Turbines w/ Trans.	Turbines w/o Trans.	Turbines/100km^2 w/ Trans.	Turbines/100km^2 w/o Trans.
0	47294.8	47294.8	29	29	0.06	0.06
1	2411.2	2411.4	0	0	0.00	0.00
2	2048.2	2048.0	0	0	0.00	0.00
3	14362.5	9631.4	0	0	0.00	0.00
4	2893.1	7162.0	0	0	0.00	0.00
5	70534.3	1703.1	28	1	0.04	0.06
6	10744.7	82062.1	25	54	0.23	0.07
7	67378.8	2351.9	543	7	0.81	0.30
8	25172.1	56225.2	782	290	3.11	0.52
9	7046.4	35919.2	283	893	4.02	2.49
10	358.5	6675.5	15	431	4.18	6.46

Table 8. *Areas, number of turbines, and turbine density in each index score when transmission lines are included as a variable (white) and when they are not included (gray). Note that density of turbines is skewed more heavily towards higher index values when transmission lines are not included in the suitability model.*

Most turbines are located in cells with high index values. However, few are located in the best possible areas, and a substantial number are in relatively low-rated areas. There is a stronger relationship between index score and turbine density. But when we remove the transmission lines as an evaluation variable, both the distribution of turbines and turbine density skew much further towards the highest values than when transmission lines were included.

Additionally, we recognize that over time, new transmission lines will be built to make suitable areas accessible and existing transmission lines will reach capacity. Because of this, we hypothesize that although transmission lines may serve as an excellent predictor for where turbines can be constructed in the short term (within a few years), over the timescale that is considered here – up through 2030 – a dataset created in 2004 will lose relevance.

Conservation Zones – Our study also operates under a very narrow definition of "conservation zones". We include national and state parks, wilderness areas, and government-managed wildlife protection areas. But with the exception of a few small parcels owned by The Nature Conservancy and the sage grouse core areas, private land with conservation value is not identified in our dataset of "conservation zones".

Due to data limitations we were unable to identify habitat valuable to bald eagles, golden eagles, and ferruginous hawks. The only data that featured nesting areas for these species was clipped to represent only locations with wind speeds rated Class 4 and above by the NREL. Almost all of the areas with an index value of 8 are in Class 3 wind regions, and so are about 15% of existing and planned turbines. It was inadvisable to ignore these areas in our biological assessment. We consequently abandoned the eagle and hawk habitat because the data was incomplete for the scope of our study area. Identifying such areas and including them in our "conservation zones" dataset would further limit the amount of land available for wind development.

We also included sage grouse core areas in our conservation zone dataset. However, the designation of these core areas was not influenced solely by biological considerations; public policy concerns also played a major role. As a result, the core areas are not a representation of the ideal conservation strategy, and it should be understood that biological concerns might call for larger zones in which wind development is not permitted. These limitations to our identification of "conservation zones" suggest that our model probably overestimates the amount of land that can be developed for wind power without adverse conservation effects.

Using designated conservation zones in models may be a productive approach for determining the amount of electricity that can be generated via wind power without damaging environmental interests. It maximizes potential for wind development while minimizing resulting environmental damage. However, our methodology for "conservation zones" as laid out in this paper should be viewed as a suggested framework for assessing the impacts of conservation policies rather than as a suggestion of future policies restricting development. We do not advocate restricting only the conservation zones we identify in this study, and we encourage future researchers to model habitat for species for which data is not currently available. Such data would be a valuable addition to our model.

***Energy Production Capacity* –** There are also shortcomings in how we estimate Wyoming's total capacity for wind energy production (both with and without conservation concerns taken into account). Our methodology assumes that turbines are constructed at the maximum practical density in all suitable locations. While this works as a theoretical model, it is highly unlikely to occur in reality for two reasons. First, most turbines are constructed as a part of wind farms rather than as individuals. Our model doesn't screen out areas that are too small to build economically viable wind farms, so some small areas that are identified as "desirable" are in fact very unlikely to be developed. Second, it is very unlikely that turbines will be constructed at maximum practical density throughout extremely large areas, even areas of contiguous suitable locations. There is an upper limit to the size of a wind farm as well as a lower limit. As a result, Wyoming's actual total capacity for wind energy production is probably substantially lower than what we identify in our study. Kiesecker et al. did not address this when estimating statewide wind energy potential, but they did search for large contiguous blocks of undeveloped land in order to determine which states could generate 20% of their electricity through wind power. Perhaps a similar approach could be utilized for determining statewide electricity generation potential.

V. Conclusions

This study implemented a site suitability model in order to determine which locations in Wyoming were most suitable for wind energy development, and attempted to integrate it with the strategy of targeting wind projects on previously developed land. We examined whether Wyoming could fulfill a U.S. Department of Energy goal to produce 20% of its electricity with wind power on the land that is found to be suitable, while removing ecologically significant conservation zones from consideration. The results show that 291.74 GW of power could be produced in Wyoming on lands outside of conservation zones. This is more than twenty times the amount needed to fulfill the Department of Energy's 20% by 2030 goal. The amount of land and power reported could be an overestimate, given that the lands designated as conservation zones in this study were limited and most likely did not represent all areas meriting environmental protection. We recommend that future research focus on better defining areas of high conservation importance.

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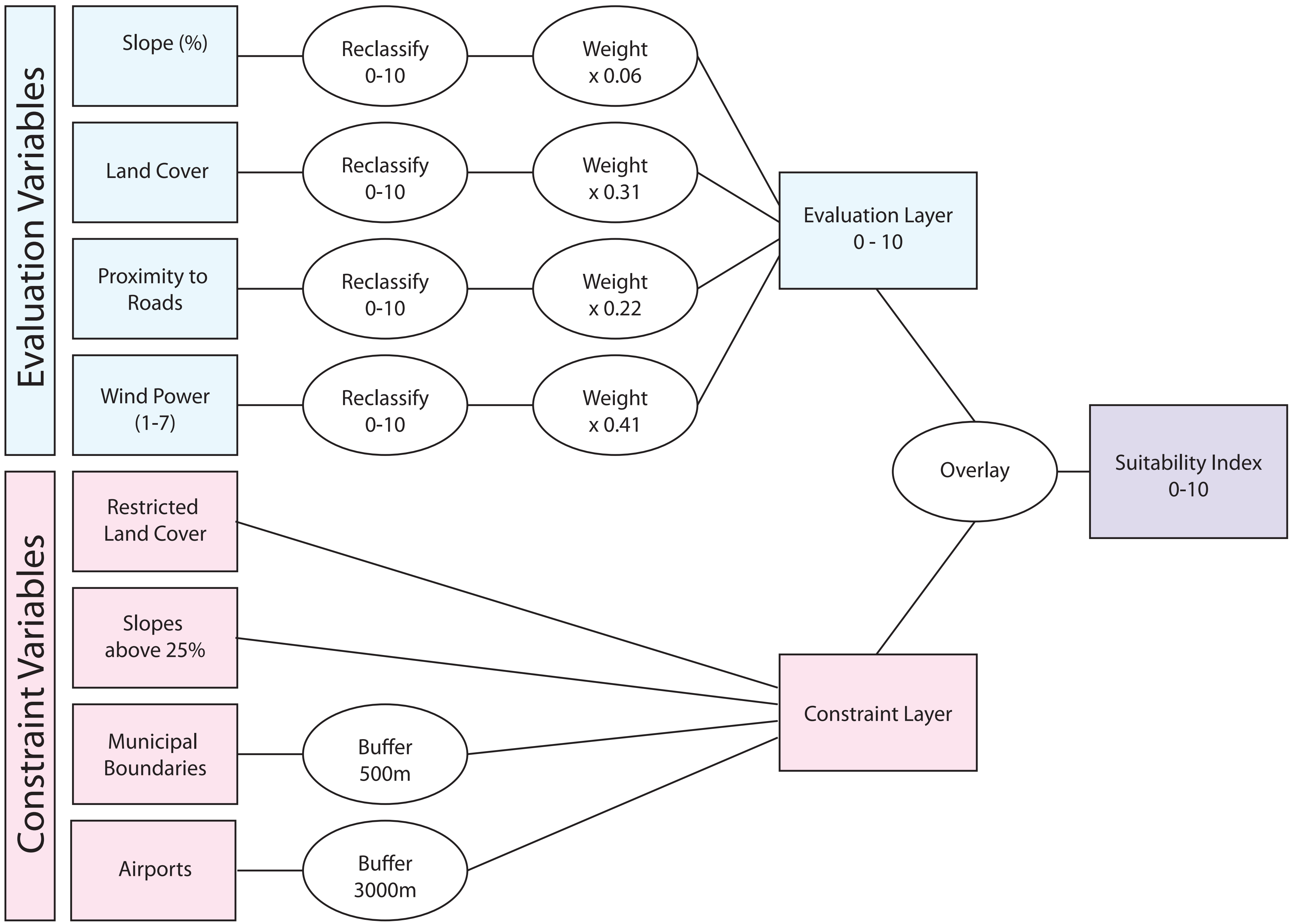
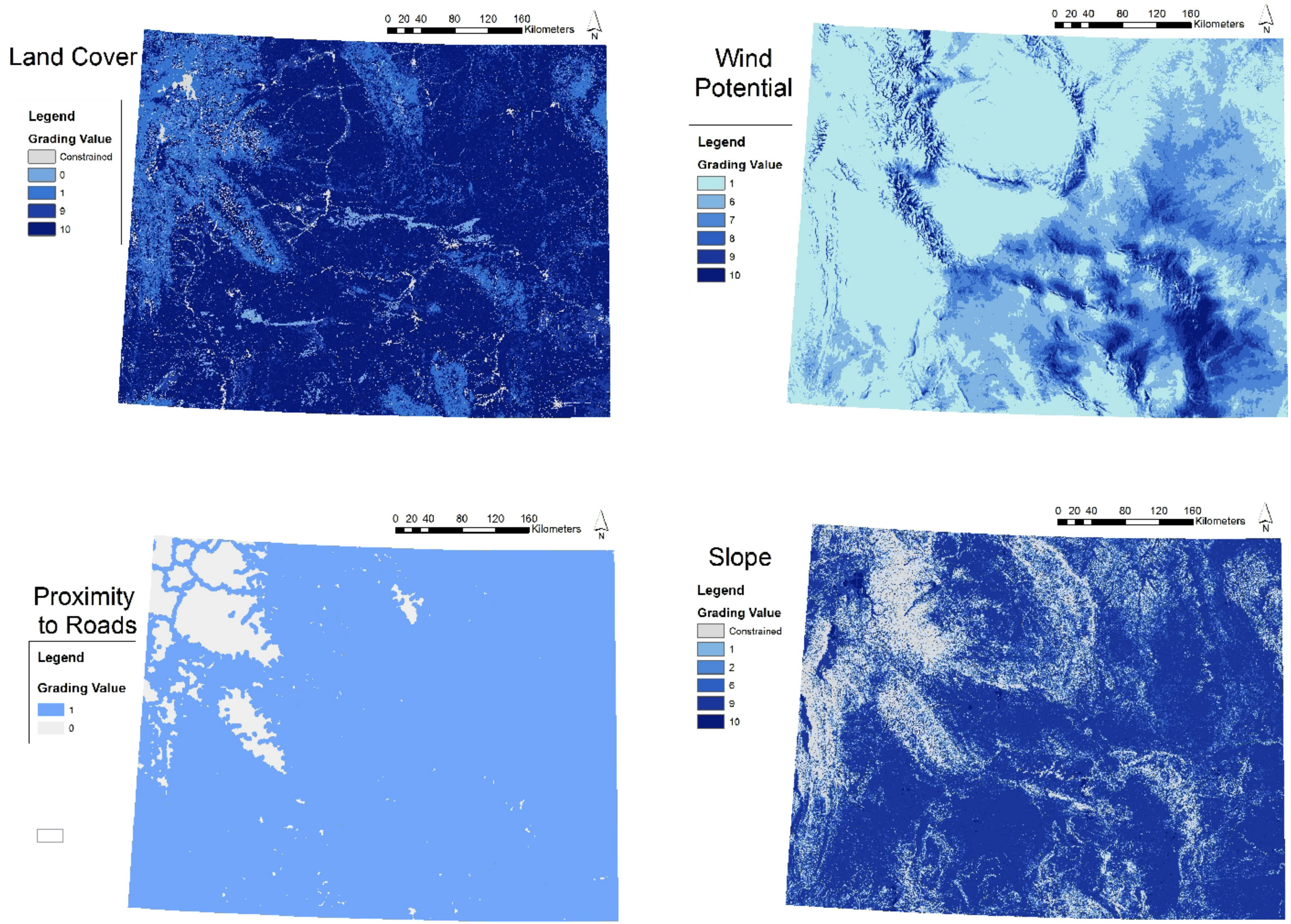
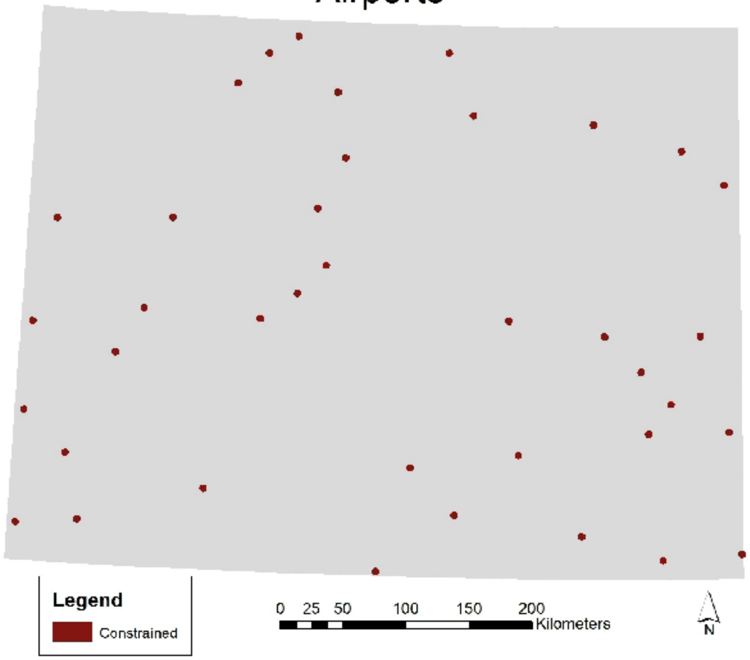


Appendix 1: Model for Site Suitability Index



Appendix 2: Evaluation Layers

Airports



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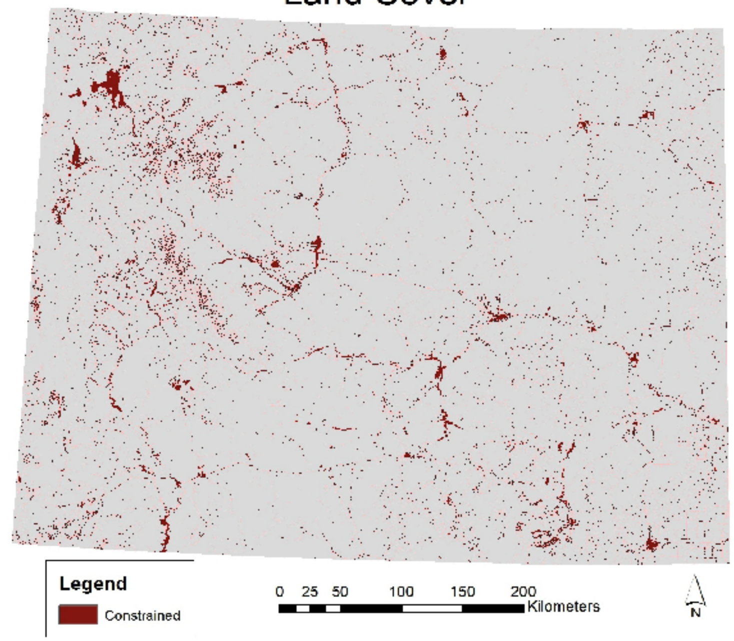
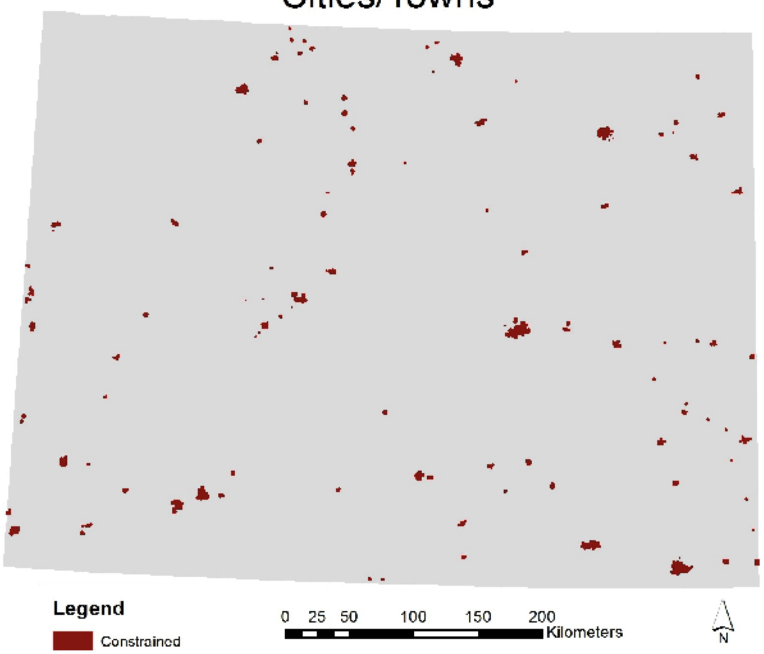
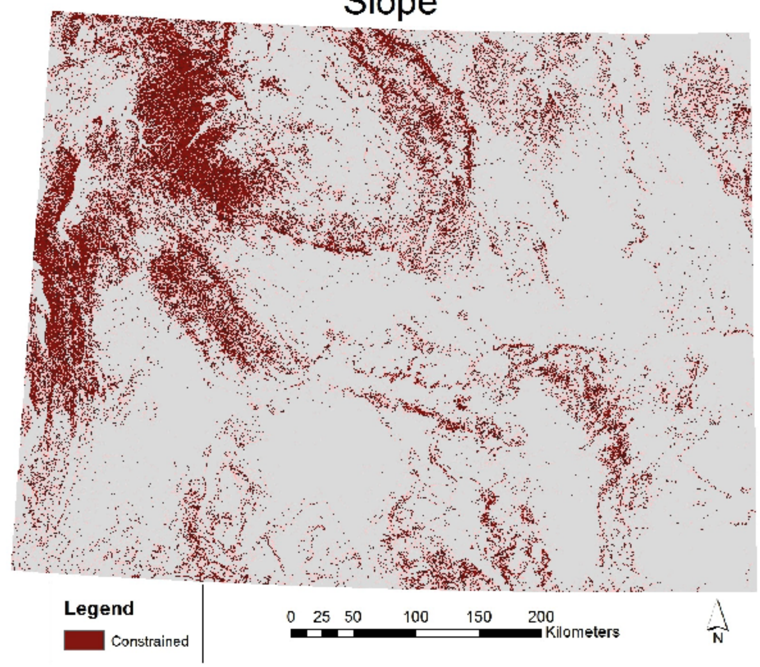


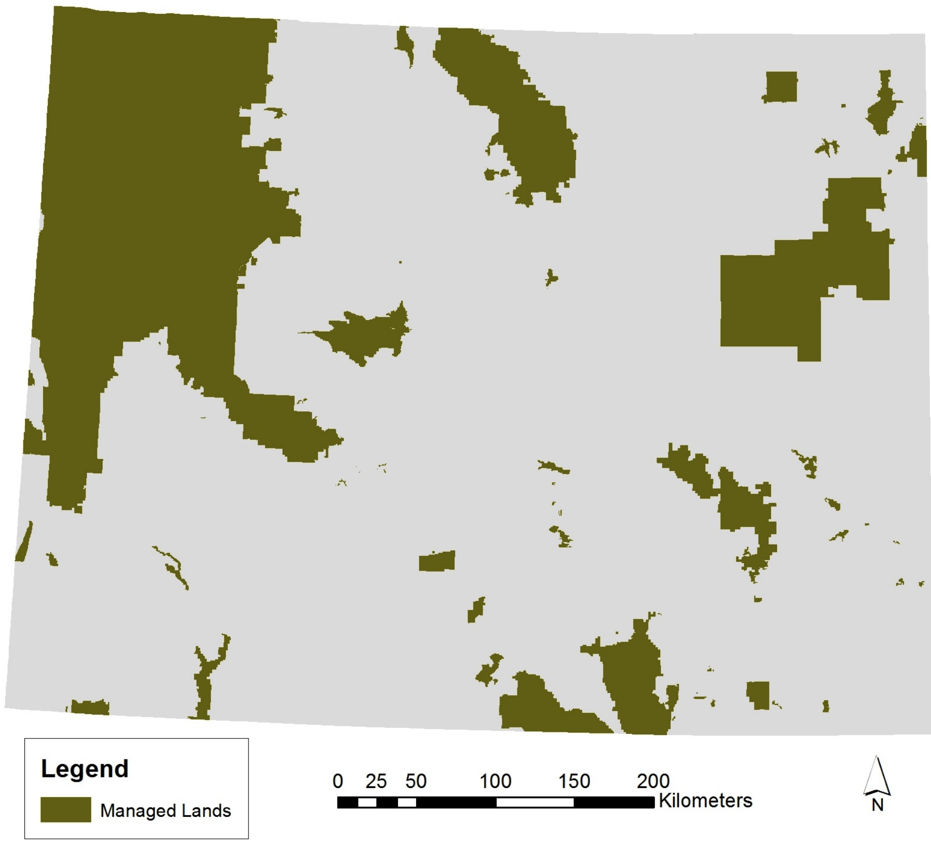
Cities/Towns

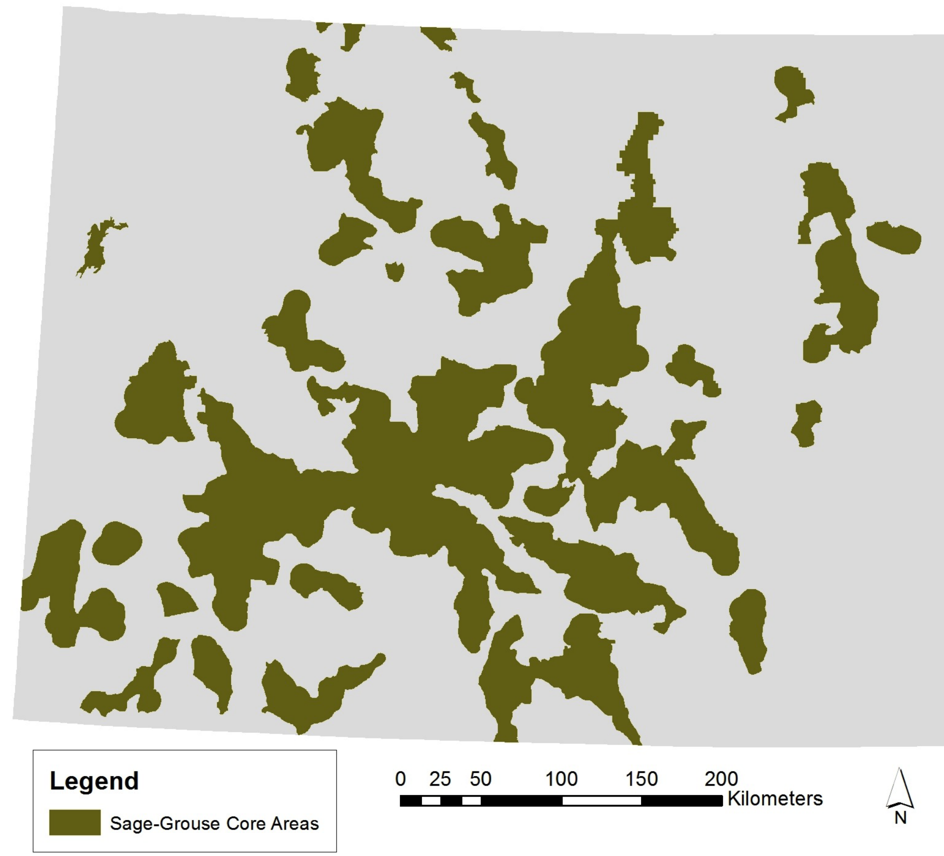


Slope



Appendix 3: Constraint Layers





Appendix 4: Conservation Layers