Spatial tradeoff between economic goods and ecosystem services: A case of the oil and gas industry

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Abstract

In land management / land use decisions understanding the interdependence between development and conservation is crucial. We develop a Net Resource Assessment (NetRA) which accounts for energy development and ecosystem service impacts. The NetRA is used to estimate the Net Resource Value (NRV) which is the expected present value from energy development minus the total economic costs (explicit and implicit). We apply the NetRA in the Mancos shale formation for oil and gas development in the Piceance Basin of Colorado, and integrate the impacts on mule deer and aquatic species habitat. Our findings demonstrate that a spatial tradeoff between energy development and ecosystem services can be modeled into a useable policy tool. We evaluate the use of this tool under three energy development scenarios to demonstrate the economic outcomes of energy development.

Highlights:
1 Introduction

In January of 2021 executive order 13990 and 14008 overturned executive order 13766 from 2017 that expeditated environmental review and approvals for high priority projects. Prior to these executive orders a court ruling in 2019 halted oil and gas leases on 300,000 acres of public land in Wyoming as the sale of leases “did not sufficiently consider climate change.” The court’s decision placed a pause on sales and leases and ordered the Bureau of Land Management (BLM) to redo its environmental assessments (Duncombe, J. (2019). These are examples of how federal leasing rules can create conflicts between energy resource development and ecosystem service protection causing delays in administering leasing programs.

In a review of the regulatory support for the balanced development of federal public lands, Burke (2020) details changes in practice at a regional scale between political administrations that define the implementation of efficient energy leasing regulations at the federal level. She describes the impact of three administrations approaches to efficient leasing practice and the inefficiencies that can arise as a result.

Exploration and management of energy development is site specific where the resources could have co-located and spillover effects on ecosystem services. Energy development accumulates over sites and time to have variable impacts on ecosystem services in a region. The objective of federal land agencies is to support energy development while maintaining ecosystem services across a range of potential regional landscapes. Similarly, this is the objective described by Burke (2020) during the Obama administration, but interpreted in ways that were different than the previous administration. The Obama Administration introduced a set of oil and natural gas leasing reforms that downscaled management decision making (see executive order 13514). The same dynamic has recurred during the Trump administration through upscaling the management
decision making to a regional scale. Each time an extensive review is required, reforms to promote a successful, efficient land leasing program occur.

Agencies and the many stakeholders involved in federal land development need accurate information for effective stewardship regarding development and preservation decisions. These types of decisions affect the quantity and value of marketed goods such as energy resources, and the provisioning of nonmarket ecosystem services (Wossink and Swinton 2007). Imbalance can alter local and regional economic growth over time. To balance competing interests a land management program needs a scalable estimate of the risks and returns derived from the in-place energy and environmental resources.

This paper provides an analysis of energy development on public lands over space and time and the impact these decisions have upon ecosystem services. Applying a production possibilities framework, we assess the opportunity costs of differing energy production levels on social benefits (i.e. minimizing the social costs) of co-located ecosystem services. We investigate the balancing of local tradeoffs in a gridded landscape of public land that is due to the joint production of energy resources (i.e. oil and natural gas) and the cumulative impact on ecosystem services (i.e. mule deer and aquatic species) that occur over the lifecycle of regional resource development. Because energy development affects the values associated with ecosystem services, current leasing and development decisions have become a focus of societal choices for regional growth paths. Hence public land use decisions require a practical, empirical approach. Currently, there is considerable uncertainty associated with the expected joint output over the lifetime of development and its subsequent realization.

We employ a system dynamics model of interrelated stock and flow variables with feedback loops. Spatiotemporal production of two nonrenewable energy resources (oil and natural
gas) and two co-located ecosystem services (mule deer population and aquatic species). The spatiotemporal model generates specific patterns of development on a land grid of $i, i = 0, \ldots, I$ cells assessing the impacts of energy development upon ecosystem services. Energy development scenarios depend on the landscape location, leasing schedule, and social cost considerations that can be producer friendly with minimal regard for ecosystem services to scenarios that are more environmentally friendly. The selection of the $i$ cells contained in the different scenarios reveal that over time there can be patterns of energy production for $i$ having a smaller impact on ecosystem services. Because energy development involves land cover and subsurface disturbances, there is an opportunity cost to producers to conserve the in-situ direct and indirect use ecosystem services. We seek to maximize the joint output of the co-located energy resources and ecosystem services under differing development policies and levels of nonmarket valuation for the ecosystem services, to demonstrate the use of the system dynamics tool. The empirical demonstration is undertaken as a dynamic decision problem for a land steward or resource manager for cumulative energy production in the Piceance Basin, Colorado.

2 Materials and Methods

The basis for our approach is that each outcome for $i$ can be represented as a point inside or along a production possibility frontier (PPF) of the value of the marketable energy resources and ecosystem services (Wossink and Swinton 2007). Transformation to a PPF enables an evaluation of the tradeoffs of alternative development scenarios by stakeholders as outcomes of potential total economic value.

2.1 Economic Theory for the model

The foundation for the model is the joint production of two nonrenewable (energy resources) and two renewable (ecosystem services) natural resources. Joint production yields a
net resource value (NRV) that is used to assess the spatiotemporal tradeoffs for each regional development pattern in $i$. The $NRV$ is the expected present value of the economic benefit from the extraction of an energy resource minus the total cost of production, which is the aggregation of the development, production, and social costs (Bernknopf et al. 2019). In deriving social cost we estimate consumer surplus from a meta-analysis function approach for the two ecosystem services utilizing publicly available data$^1$ for recreational use values for ecosystem services. The $NRV$ can then be estimated at local (public land lease) and regional (energy basin) scales to compare development outcomes (scenarios) from a range of exploration and development plans.

A production possibility set contains a range of regional energy production plans that represent a portfolio of lands on a grid $i = 0, ..., I$, with varying outputs of both energy development and ecosystem services. Determining when and where to produce energy resources indicates whether the leasing program is within (less efficient) or along (most efficient) the production possibilities frontier for the region $i$. A decision for each $i$ controls the quantities to produce of these energy resource along with the length of time to produce. This decision creates impacts upon ecosystem services, using our meta-analysis equation to estimate ecosystem benefit impacts, an NRV is then calculated for each scenario.

Previous literature has analyzed the joint production of marketable commodities and nonmarket ecosystem services in an agricultural setting (Wossink and Swinton 2007, Sauer and Wossink 2013, Forney et al. 2012) and in multiple land use regional analysis (Nelson et al. 2009). The joint production and cost minimization of traditional agricultural marketed outputs and the provision of ecosystem services of a farm is derived by Wossink and Swinton (2007). In this study, a PPF provides an approach for maximizing agricultural production that utilize biophysical

$^1$ http://revaluation.forestry.oregonstate.edu/
functions of the ecosystem as inputs. They found that production relationships between agricultural output and non-marketed ecosystem services may be complementary, competitive, or substitutive. Ecosystem services share production inputs, such as land with production relationships. They demonstrated how complementary relationships lead to costless voluntary provisioning of ecosystem services that are inputs to marketed farm products, and competitive production relationships lead to the provision of ecosystem services at lower costs than when they are direct substitutes for farm products or when they are produced outside of agriculture with no marketed complement and the same ecosystem production technology. More recently, Sauer and Wossink (2013) derived the marginal cost of inputs by developing an empirical transformation function incorporating multiple outputs and inputs, in a spatially explicit empirical model in which land heterogeneity affects output. They develop a transformation function is developed that represents the output producible from a given set of inputs and existing conditions in the feasible production set. The transformation function reflects the maximum amount of outputs producible from a given input vector and external conditions. They demonstrate that calculating the marginal cost of providing ecosystem services based on separate evaluations can lead to misleading results.

Forney et al. (2012) measure the tradeoff between crop output and potable groundwater supplies in a region of Iowa. The joint outputs are corn, soybeans, and a regional decline in groundwater quality. In this application they demonstrated that the spatiotemporal application of nutrients to corn and soybean crops affect groundwater quality unevenly across Northeast Iowa. Groundwater contamination increases over time in areas of corn production and remotely in other parts of the region where near surface soils and geology are more permeable. A reordering of the landscape to plant corn that uses significant amounts of Nitrogen fertilizer in areas with less permeable geology and soybeans, that use much smaller quantities of Nitrogen, in more permeable
areas demonstrated that corn and soybean could be sustained while impacts to groundwater quality could be avoided.

Nelson et al. (2008) evaluated a set of land uses and land covers in a bounded area for nine land uses in the Willamette River Basin, OR. A land use pattern is the basis for the biological and economic models they developed. An efficiency frontier is developed for terrestrial vertebrate conservation and economic returns in an example to maximize the joint output of land uses. Along the efficiency frontier, land-use patterns can generate a maximum economic return finding that land-use changes that increase biologic conservation have minimal impact on economic development. To achieve each regional outcome, one or more of the land covers are affected and achievement of a balanced set of land uses along efficiency can be costly as preferences move toward more conservation of land.

All of these previous approaches and models contain aspects of land use development, resource development and subsequent impacts on ecosystem services. However, they are loosely tied to an explicit planning process that affects public lands at multiple scales and they do not assess the impact of energy development over long-term decision making.

We develop a model that employs a multi-use resource manager seeking to maximize the joint output of energy resources and ecosystem services over a long-term planning horizon. The PPF found Figure 1 displays alternative outputs of the production set and a production possibilities frontier for energy development and ecosystem services. Each point in Figure 1 represents different policy and management decisions that consider the extent of the region being developed, the density of producing facilities (i.e. well platforms) and the intensity of the rate energy development. Any point on the PPF is an efficient outcome for production of the co-located resources while any point on the interior of the curve is an inefficient production decision.
For example, point C has very little ecosystem services with large energy development decisions while point F has very little energy development with ecosystem service protection. Allocative efficiency would be when the marketplace for the energy resources and ecosystem services are both in equilibrium and on the PPF line, which could be represented as either point A or B depending upon societal preferences.

An important input into obtaining allocative efficiency is the price of each energy resource along with the price of other complementary or substitutary energy resources. In addition, it is important to understand the external impacts that energy development may have upon co-located ecosystem services. Further, point D is inferior (i.e. inefficient) because increases in both nonrenewable and renewable resources can be achieved with a change in the leasing pattern thus increasing social wellbeing by moving to either point F or C.

As an example of the interdependence between energy development and ecosystem services, energy development requires a road network that alters ecosystem services. This commonly leads to fragmentation of the ecosystem (Northrup et al., 2015; Buchanan et al., 2014; Wilbert et al., 2008) which can negatively impact wildlife species. In addition, rainfall and snowpack runoff from this road network can lead to increased sediment loading within the
watershed which has the potential to impact aquatic species (Ewert, 2015; Hausle, 1973). As such we include the external impacts of energy resource development into the model to calculate the social (implicit) costs of extraction and not just private (explicit) costs. Figure 2 displays the Marginal Private Costs (MPC) of energy development and the external impact upon ecosystem services as the Marginal Social Cost (MSC). As can be seen in the left panel of Figure 2, the MSC is above the MPC displaying a negative production externality for energy resources. If $Q^*$ of energy resources is developed the private costs would be $P^*$ while the true social costs are $P^1$. Incorporating social costs into the production decision leads to an efficiency point that includes private and social benefits and or costs of energy resource development.

The right panel of Figure 2 displays how we quantified the impacts upon ecosystem services from energy development. Starting at a level of ecosystem services represented as $Q^*$ would provide marginal benefits, quantified as consumer surplus, represented as the area under the marginal benefit curve and to the left of the $Q^*$ line. As energy development occurs ecosystem services are impacted resulting in a new level of $Q^1$ creating a loss in consumer surplus as displayed in Figure 2. As ecosystem services are lost, we model this loss not as a one-time loss, rather as a
permanent loss, meaning that this loss in consumer surplus results in each subsequent period in the modeling time frame. If further development occurs a further loss is observed represented as $Q^2$ in Figure 2. This creates a dynamic effect for the consumer surplus calculation in quantifying the loss in ecosystem services.

The incorporation of external costs into the production decision is done under three energy development scenarios (new well development, well development protecting mule deer, no new development) as a demonstration. Quantification of the consumer surplus loss from Figure 2 is accomplished through a meta-analysis regression previously developed (see Bernknopf et al., 2019). In addition to these three development scenarios we incorporate three ecosystem service levels of value by calculating the number of hunting and fishing days for the Piceance Basin, the state of Colorado and the general populous of Colorado (U.S. Fish and Wildlife Service, 2014). These three levels of value are employed in order to show the difference in social costs using direct use values only (i.e. Piceance Basin hunting and fishing days) and working up to non-use values for just the hunters (i.e. all hunting and fishing days for Colorado) and the entire population of the state. While this method is not perfect, as the Rosenberger data set only incorporates studies for direct use values, we employ these scenarios to demonstrate how production outcomes could be altered based upon the incorporation of different levels of ecosystem service values.

2.2 Model Development

While the economic theory of optimal control serves as a necessary function in natural resources research, the complexity of certain scenarios (such as the spatial heterogeneity of energy development and ecosystem services) requires approaches that are beyond the scope of the theoretical economics framework (Venables 2014).
A decision to lease and develop a natural resource asset is based on the Net Present Value (\(NPV\)) of a series of cash flows produced from oil and natural gas wells (\(R\)) in \(i\) at a discount rate \(r\). The combination of inputs and outputs represents the revenue (value) created over the lifetime of the energy project and can be evaluated by calculating its \(NPV\). By adding ecosystem services as an input to production, we create a new component of value for development \(i\) (Wossink and Swinton 2007, Fenichel and Abbott, 2014). By incorporating the value of the ecosystem services the cash flows are affected negatively as a social cost (\(SC\)), which is relevant to an investment decision. Since we combine direct and indirect use assets, we label the combination to have an \(NRV\). \(NRV\) is \(NPV\) consistent and can be considered a reliable tool for investment decisions because it correctly measures value creation (Marchioni and Magni, 2018).

The \(NRV\) for the region is:

\[
NRV = \sum_{i=1}^{I} \sum_{t=0}^{T} \frac{1}{(1 + r)^t} \times (R_{it} - PC_{it} - EC_{it})
\]

(1)

Where \(i = 1, \ldots, I\) and \(t = 0, \ldots, T\) are indices for the land grid and time in years, respectively, \(r\) is the discount rate, \(R_{it}\) is the revenue from crude oil and natural gas in \(i\) for \(t\) years, \(PC_{it}\) is the private cost of production in \(i\) for \(t\) years and \(EC_{it}\) is the ecological social cost in \(i\) for \(t\) years.

Decomposing equation 1 into its three components \(R_{it}, PC_{it}\) and \(EC_{it}\), yields:

\[
R_{it} = P_{(G)it} \times \left[ k \times q_{(G)i15} + \sum_{t=0}^{L} (n_{it} \times q_{(G)it}) \right]
\]

\[
+ P_{(O)it} \times \left[ k \times q_{(O)i15} + \sum_{t=0}^{L} (n_{it} \times q_{(O)it}) \right]
\]

(2)
Where \( n \) is the number of new wells in \( i \) for \( t \) years, \( k \) is the number of legacy wells in 2017, \( L \) is the lifespan of a well, \( P_{(G)lt} \) and \( P_{(O)lt} \) are the prices of gas and oil respectively from EIA (2019)\(^2\), and \( q_{(G)lt} \) and \( q_{(O)lt} \) are the quantities of crude oil and natural gas produced. Further decomposition of the revenue term involves estimation of \( q_{(O)lt} \) and \( q_{(G)lt} \):

\[
q_{(O)lt} = q_{(G)lt} \times OGR_t \tag{3}
\]

\[
q_{(G)lt} = \frac{q_{(G)0}}{(1+bdm)^m} \tag{4}
\]

Where \( q_{(G)lt} \) is the current natural gas production rate, \( q_{(G)0} \) is the initial production rate (start of production), which was set to 2,509.426 thousand standard cubic feet per day (Mscf/d), \( b \) is the curvature of the line, 1.189361 degrees (\(^\circ\)), \( d \) is the nominal decline rate and is a constant equal to 2.402775, \( m \) is the cumulative time, in days, since the start of production until the final period of production, and \( OGR_t \) is the oil to gas ratio found from historical production between 2000 and 2017.

\[
PC = Tax + Acq + Com + Roy + Pad + Inv + Road + Wat + Sand \tag{5}
\]

Equation 5 presents the private costs incurred in resource development. \( TAX_{lt} \) is the cost of taxes in \( i \) for \( t \) years, calculated as \( Tax = R \times 0.875 \times 0.058636 \), \( ACQ_{lt} \) is the acquisition and leasing cost in \( i \) in year \( t \), \( Com_{lt} \) is the completion cost in \( i \) in year \( t \), \( Roy_{lt} \) is the royalty of 12.5\% per year, \( Pad_{lt} \) is the pad cost in \( i \) in year \( t \), calculated as \( Pad = C_{pp} \times \Delta pad \), \( C_{pp} \) is the cost per pad, \( \Delta pad \) is the added pad, \( Inv_{lt} \) is the investment in \( i \) in year \( t \), calculated as \( Inv = C_{vd} + C_{hd} \),

\(^2\)https://www.eia.gov/todayinenergy/detail/detail.php?id=38112
\( C_{vd} \) is the vertical drilling cost, calculated as \( C_{vd} = \Delta \text{well} \times l_d \times P_{dc} \) where \( \Delta \text{well} \) is the added well, \( l_d \) is the formation depth, \( P_{dc} \) is the drilling cost rate, \( C_{hd} \) is the horizontal drilling cost, calculated as \( C_{hd} = \Delta \text{well} \times D_{lin} \times P_{dc} \), and \( D_{lin} \) is the linear distance, \( \text{Road}_{it} \) is the road cost in \( i \) in year \( t \), calculated as \( \text{Road} = P_{rc} \times l_r \), where \( P_{rc} \) is the road cost rate, \( l_r \) is the total road length, \( \text{Wat}_{it} \) is the cost of water in \( i \) in year \( t \), calculated as \( \text{Wat} = P_w \times V_{wu} \), where \( P_w \) is the water rate, \( V_{wu} \) is the total volume of water used, and \( \text{Sand}_{it} \) is the cost of sand in \( i \) in year \( t \), calculated as \( \text{Sand} = P_s \times Wgts \), where \( P_s \) is the sand price, and \( Wgts \) is the total sand used.

\[
EC_{it} = C_{mit} + C_{fit}
\]  

Equation 6 presents the social costs of energy development, modeled as a loss in consumer surplus from Ecosystem Services. \( EC_{it} \) is the ecological cost in \( i \) in year \( t \), \( C_{mit} \) is the mule deer cost in \( i \) in year \( t \), and \( C_{fit} \) is the aquatic species cost (Brook trout) in \( i \) in year \( t \). Derivations for \( C_{mit} \) and \( C_{fit} \) can be found in Bernknopf et al., (2019).

Differing policy objectives provide the scenarios of analysis of land use for a range of different risks that arise and affect co-located ecosystem services in the region during economic development. A scenario investment choice is weighted by preferences for benefits from economic development and the associated social costs of changes to ecosystem services. Model treatments include two types of extraction and two ecosystem services (intensive margin) and are leased to developers over the areal extent of a region composed of private and public lands (extensive margin). The land cover in the region is altered over space and time. We evaluate the local and regional economic impacts of the land cover changes in seeking a balance between conventional oil and shale gas development and the impacts to co-located ecosystem services as displayed in Figure 3 to produce the NRV.
3 Results and Discussion

Figure 4 presents the historical development of cells and wells in the Piceance Basin, CO from 2000 to 2017. This historic information was utilized to calibrate the NetRA in order to run the three policy scenarios. As can be seen in Figure 4, growth in energy development occurred from 2004 till 2010 after which the basin experienced a leveling off in development of both wells and cells. Figure 5 displays the location of wells in the basin as of 2019 along with the location of mule deer habitat. This information is utilized in the policy scenarios as we can bound where development is or isn’t allowed based upon an ecosystem constraint (i.e. mule deer). Figure 6 displays the quantity of energy resources that were produced from 2000 to 2017. Similar to Figure 4 the basin experienced growth in energy development beginning in 2004 and peaking in 2011. Since 2011 the quantity of energy produced in the region has decreased.
Figure 4: Historical development - number of wells and number of grid cells developed over time (data source: COGCC (2019)).

Figure 5: Historical development - location of wells (left) and mule deer range (right). Wells are developed irrespective of mule deer concentration. Data source: COGCC (2019).
3.1 Results of the three policy scenarios

The NetRA produces estimates of value to the energy development sector and the social value of ecosystem services. As more development occurs ecosystem services are adversely impacted causing the social value to decrease. Results from model runs are broken into three policy scenarios. First, development is allowed to occur in the basing without account for its impact upon ecosystem services. This new development allows for new wells to be added, we assume a constant addition of 2 wells added to each developed cell over a 20-year time horizon. Second, development occurs at the rate of 2 wells for each cell but with a targeted approach to protect mule deer habitat. Third, no new development is allowed in the basin, wells can be added to existing pads, but new cells cannot be developed, effectively capping development in the region for a 20 year model run. This final scenario displays an extreme ecosystem service protection approach.
Table 1 displays the private resource value for oil and gas development, the social resource value (i.e. ecosystem services) and the NRV for each policy scenario. Within each policy scenario there are three treatments to demonstrate the impacts of development on ecosystem service valuation. While the Rosenberger data set is compiled of economic use values run the three policy scenarios under three levels of ecosystem service values. The first treatment, labeled Piceance Hunt and Fish, values changes to mule deer and aquatic species using 15% of the total hunting and fishing days for the state of Colorado as the Piceance basin represents roughly 15% of the states land mass. Total hunting and fishing days for the state were obtained from the U.S. fish and wildlife Service recreation survey in 2011 (U.S. Fish and Wildlife Service, 2014). The second

<table>
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<th>Treatment</th>
<th>Private Resource Value</th>
<th>Social Resource Value</th>
<th>Net Resource Value</th>
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<td><strong>New Development</strong></td>
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<td>Colorado Populous</td>
<td>$32.988</td>
<td>$30.989</td>
<td>$63.977</td>
</tr>
<tr>
<td><strong>No New Development</strong></td>
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<td></td>
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<td>Piceance Hunt and Fish</td>
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Values are in billions of U.S. dollars
consumer surplus. While not perfect, this gives provides insight into the effects oil and gas development could have on nonuse values such as bequest, option, or existence values. As the unit of consumer surplus impact increases from the basin level to the state’s population, the social resource value will decrease as the impacts to consumer surplus become larger.

The first scenario observes the highest NRV when the ecosystem service is valued using the basin level of hunting and fishing. As expected, the NRV decreases as the unit of account increases for the loss in consumer surplus. The second development scenario observes the same trend. However, comparing these first two scenarios brings up an interesting result. The NRV in larger for each treatment within this second scenario and two of the three treatments are larger than the first treatment within the first scenario. The final policy scenario protects mule deer habitat by allowing new wells on existing pads, but no new cells can be developed. Due to this restriction of no new development, we observe the lowest NRV’s for this scenario.

4 Conclusion

Exploration and development of energy resources could have spillover impacts upon co-located ecosystem services. Understanding these impacts is crucial to developing a long-term land management decision process. Our developed model allows for an analysis of energy resource development and the subsequent impacts upon co-located ecosystem services. This can aid federal land agencies in supporting energy development while maintaining ecosystem services across landscapes.

Running the developed model under three different policy scenarios provides insight into how differing land management decisions can impact the NRV. We draw three conclusions from this research. First, energy resources and ecosystem services can be quantified to create a
net resource value. This is an important step in supporting energy development while maintaining ecosystem services. Quantifying energy resources and ecosystem services into a resource value to create a net resource value is necessary and can be accomplished. Second, we found the NRV to be the largest when development occurs, but it is done in a targeted approach to protect ecosystem services. As displayed in Table 1, not only did the NRV for this policy scenario increase due to a smaller loss to ecosystem services (social resource value) the private resource value also increased. This was brought on as energy development costs were decreased in this scenario as development was not allowed in critical Mule Deer habitat. Third, placing an ecosystem service restriction, as the third policy scenario does, lowers the NRV. It is possible to protect ecosystem services without this large restriction and increase both private and social resource values.

This analysis resulted in our recognition that estimating the quantity of energy resources and ecosystem services is not the final answer to a decision, rather it is how that information can be used to evaluate alternative plans by examining tradeoffs to energy resources and ecosystem services. As we have shown resource development can occur while keeping an eye on the provisioning of ecosystem services. In order to understand the outcomes of alternative choices, it is necessary for land use decision managers to know both the private and social value of resources. The developed NetRA is a step in that direction as private and social values are integrated together into one modeling framework.
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References


