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Review

State of knowledge about energy development impacts on North American rangelands: An integrative approach

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ABSTRACT

To reduce dependence on foreign oil reserves, there has been a push in North America to develop alternative domestic energy resources. Relatively undeveloped renewable energy resources include biofuels and wind and solar energy, many of which occur predominantly on rangelands. Rangelands are also key areas for natural gas development from shales and tight sand formations. Accordingly, policies aimed at greater energy independence are likely to affect the delivery of crucial ecosystem services provided by rangelands. Assessing and dealing with the biophysical and socio-economic effects of energy development on rangeland ecosystems require an integrative and systematic approach that is predicated on a broad understanding of diverse issues related to energy development. In this article, we present a road map for developing an integrative assessment of energy development on rangelands in North America. We summarize current knowledge of socio-economic and biophysical aspects of rangeland based energy development, and we identify knowledge gaps and monitoring indicators to fill these knowledge gaps.

Contents

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1. Introduction

Energy security is essential for sustainable development because it provides the means for resolving many of the challenges facing humanity, including water and food shortages and poverty. Twentieth century agriculture was characterized by abundant, low cost energy derived from fossil fuels. To reduce dependence on foreign fossil fuel reserves, there has been a focus on developing more diverse sources of energy. In the United States of America this led to the Energy Policy Act of 2005 directing the Department of Energy to develop an Unconventional Strategic Fuels Program (RFF, 2005).

In North America, many untapped energy resources, including renewable sources (biofuels, wind and solar) and natural gas resources are associated with rangelands (Fig. 1), which cover much of the continent west of the 95th meridian (Havstad et al., 2007). Developing such energy resources will inevitably impact rangelands and the ecosystem services they provide. Comprehensively evaluating such effects is hindered by the complex interactions among biophysical and socio-economic factors that affect the functionality of ecosystems and the inconsistent use of concepts and terms by diverse scientific disciplines to describe complex social-ecological systems (Ostrom, 2009).

The Sustainable Rangeland Roundtable (SRR) developed the Integrated Social, Economic and Ecological Conceptual (ISEEC) framework to disentangle the complexity of interactions affecting the delivery and use of rangeland based ecosystem services (Fox et al., 2009). This framework provided a useful tool for systematically identifying interactions that influence the integrity of rangelands used for biofuels production and the indicators used to compare the effects of developing renewable energy and natural gas resources on rangelands (Kreuter et al., 2012).

This article consists of five parts. In the first section we describe the ISEEC framework in the context of energy development on rangelands. In the second and third sections we discuss key aspects of the socio-economic and biophysical subsystems of the ISEEC framework, respectively, with the latter section focusing on biofuels, wind energy and natural gas. Solar energy is not addressed because it is being developed almost exclusively in the arid southwest where rangeland vegetation productivity is low. In the fourth section, we discuss aspects of energy development on rangelands in Canada and Mexico. In the last section, we identify knowledge gaps that provide guidance for future research and indicators to comprehensively assess the effects of energy development on ecosystems services provided by North American rangelands.

2. Application of the ISEEC framework for energy development on rangelands

The ISEEC framework is a tool for systematically exploring complex interactions among biophysical and socio-economic elements of rangeland ecosystems. The state of the system is categorized by its biophysical condition and natural capital and its socio-economic capital and human condition, while biophysical processes determine the ability of rangelands to deliver ecosystem services and socio-economic processes create the context in which ecosystem services are used (Fig. 2). These processes act on the biophysical and socio-economic states at time t_0 to produce different states at a time t_1. Interactions occur through delivery and utilization of extractable goods, in situ delivery and use of services, and external effects of human activities.

Expanding detail within the framework enables us to focus on key linkages pertaining to development of alternative energy

Fig. 1. Three energy options derived from rangelands near Abilene, Texas (Photo provided by R. James Ansley).

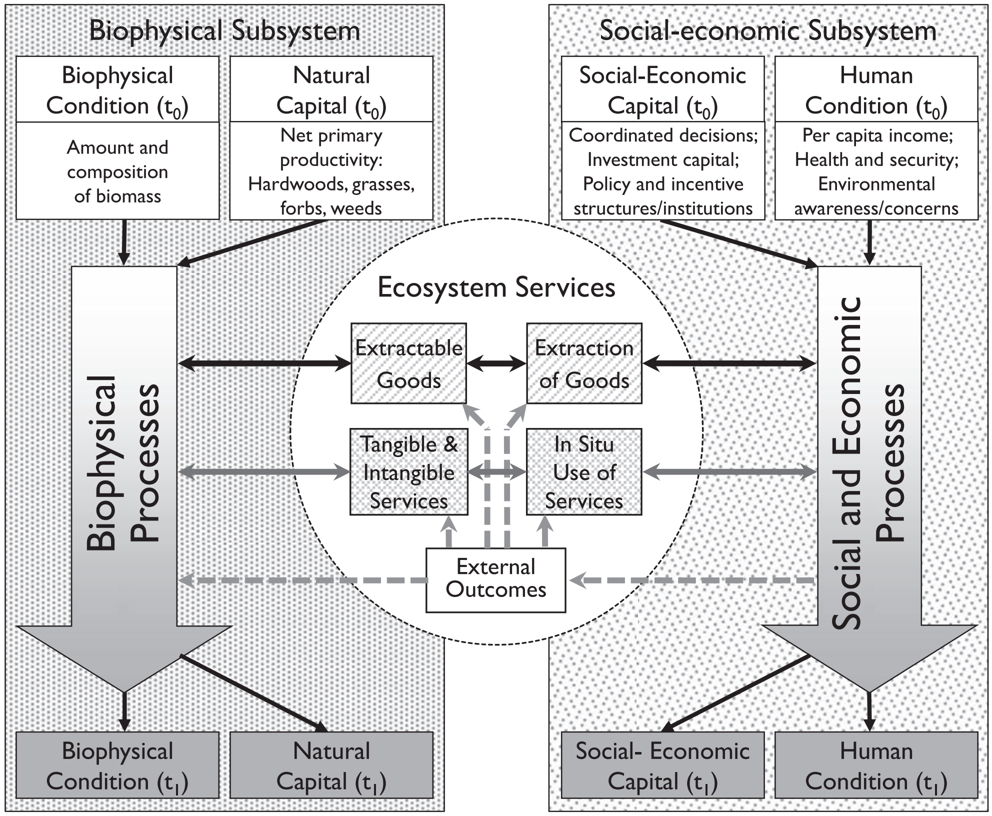

Fig. 2. Integrated Social, economic and Ecological Conceptual (ISEEC) framework of social-ecological linkages affecting the delivery and use of ecosystem goods and services on rangeland ecosystems (after Fox et al., 2009).

sources on rangelands (Fig. 3). Link [1] and [2] represent the biophysical processes that produce extractable goods (provisioning services) and in situ services (regulating and cultural services, respectively).

Demand for energy sources and other goods and services provided by rangelands is driven by numerous factors. In the case of alternative energy, these factors include attitudes toward energy development, which are influenced by cultural norms, education, and legal systems [A1 & A2]. These produce laws, regulations and incentives for alternative energy development [B] and affect demand for energy [C], which together influence alternative energy development [D]. In turn, these factors lead to public and private investments in novel energy production capacity [E], which increases capacity for alternative energy production [F].

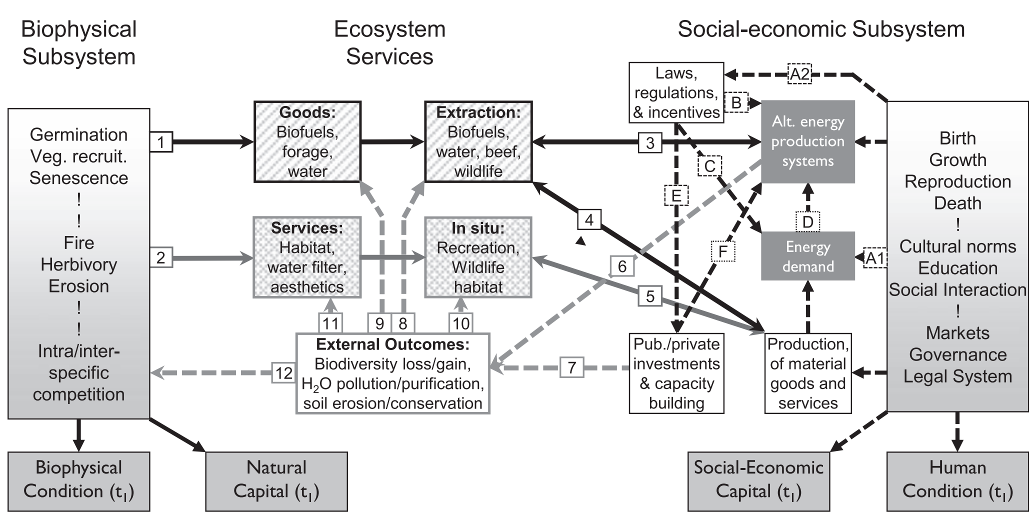

Fig. 3. Influences of biofuels (or other unconventional energy) production on linkages between biophysical and socio-economic subsystems of rangeland ecosystems. Black solid arrows relate to the provision and use of extractable ecosystem goods; solid grey arrows related to the provision and use of in situ ecosystem services; black dashed arrows represent linkages within the social-economic subsystem that influence the demand for and supply of alternative energy; and the grey dashed lines represent the feedback effects of developing alternative energy sources on rangelands and mitigation efforts.

Drivers for development of alternative energy influence rangelands through extraction of biofuels (or vegetation impacts due to infrastructure, such as wind turbines, oil and gas well pads, roads, and transmission lines) [3] and extraction of other goods, such as forage [4]. In situ use of ecosystem services is represented by link [5], which is influenced by social factors affecting development of facilities that enhance use of these services (e.g., tourism facilities).

The feedback effects within the rangeland energy production system are represented by external outcomes (soil erosion, water pollution, green house gas emissions, biodiversity loss, etc.) of using ecosystem goods for energy production [6]. This can be negatively or positively affected by private and public investments in energy acquisition infrastructure or effective mitigation measures, respectively [7]. These feedback effects can influence use and delivery of extractable goods ([8] and [9], respectively), in situ ecosystem services on rangelands ([10] and [11], respectively) and biophysical processes that lead to provision of these goods and services [12]. In the following two sections we discuss elements of the socio-economic and biophysical subsystems, respectively, of energy development on rangelands focusing on biofuels, unconventional oil and gas and wind energy.

3. Aspects of the socio-economic subsystems of energy development

3.1. Public attitudes and behaviors relating to energy development and ecosystems

Data from a study of energy resources and natural environments in Texas were used to examine public attitudes and behaviors towards oil and gas development in environmentally sensitive areas. Echoing findings from similar research in the Barnett Shale (Theodori, 2012, 2013), the study revealed Texas residents generally dislike problematic social and/or environmental issues they perceive to accompany oil and gas development more than economic and/or service related issues. Moreover, the results of the study indicated that perception of the oil and gas industry is associated with survey respondents' views about governmental regulations limiting oil and gas exploration and production in environmentally sensitive settings. Those who had a more negative perception of oil and gas related socio-environmental issues were significantly more likely to support stronger governmental regulations for oil and gas exploration and production on the continental shelf and in coastal wetlands, desert ecosystems, and hardwood forests. Lastly, the data suggested that perception of socio-environmental issues is a key explanatory factor of actions taken in response to development of oil and gas in environmentally sensitive areas. Individuals holding more negative views on these issues were more likely than their counterparts with less negative views to have contacted a local elected official or governmental agency to complain about oil and/or gas drilling or production on environmentally-sensitive lands and to have attended a public meeting to oppose exploration and/or production of oil and/or gas in such areas. Based upon these results, we propose that energy industry representatives, community leaders, governmental and regulatory agency personnel, and other stakeholders recognize that the public's negative perception of potential socio-environmental consequences of oil and gas development in environmentally-sensitive areas is strongly and consistently associated with pro-environmental attitudes and behaviors.

4. Aspects of the biophysical subsystems of energy development

4.1. Implications of biofuels production on rangeland resources

Woody plants growing on rangelands in the Southern Great Plains region of the USA, such as honey mesquite (*Prosopis glandulosa*) and juniper species (*Juniperus ashei* and *J. pinchotii*), may have significant potential as bioenergy feedstock. Reasons include a large standing biomass; they grow predominantly on land that is not well suited for food or fiber production and, therefore, do not impact food markets; they do not require fertilization, irrigation, or cultivation; the wood has low moisture content thus eliminating drying costs; and some species like mesquite have significant regrowth potential following harvest. Many mesquite and juniper areas in the Southern Great Plains have 22–45 Mg/ha (10–20 dry tons/ac) standing mass (Ansley et al., 2010). Recent research on mesquite determined that the best long-term option is to harvest only above ground biomass and allow regrowth for subsequent harvests every 10–12 years (Park et al., 2012). However, when offered the option of committing mesquite on their land for future biofuel harvesting, most ranchers preferred whole plant extraction so they would not need to contend with regrowth even though extraction of whole plants is a much less economical option for bioenergy production because it increases feedstock transport costs over time as land areas with sufficient biomass for harvesting become increasingly more distant to the processing facility (Cho et al., 2014).

Other ecological and economic benefits after woody plant harvest include greater grass production and diversity, increased soil stability and potentially greater livestock production. All of these responses result from the temporary (or permanent) removal of the woody overstory. In addition, strategic harvesting along brush sculpting lines has potential to improve wildlife habitat and, therefore, increase recreational hunting income (Ansley et al., 2013). The periodic harvesting of brush for bioenergy also removes the need for expensive or risky brush management treatments (herbicide application, mechanical grubbing, or prescribed fire) that are essential for livestock managers to grow sufficient grass as forage for their animals.

There are many challenges to sustainable and reliable production of this feedstock, however. These include variation in plant distribution, density and growth forms; lower annual growth rates than traditional woody energy crops; lack of efficient harvest technology for multi-stemmed growth forms; and relatively high harvesting and transportation costs. Whereas wood chips could possibly be used in bioelectricity generation by co-firing with coal or bio-gas (Chen et al., 2013), conversion of rangeland wood chips to ethanol does not appear to be viable. Recent studies comparing the economic and greenhouse gas (GHG) performances of honey mesquite as a cellulosic feedstock relative to dryland and irrigated sweet sorghum and dryland switchgrass found that mesquite may be suitable as a complementary feedstock to meet total biomass feedstock demand (Park et al., 2012; Wang et al., 2014). Mixing woody biofuel patches with rangeland patches that can support highly productive grass species, such as switchgrass (*Panicum virgatum*), may be the most viable option for the future. Mesquite was superior to all other feedstocks in GHG offset and use efficiencies when land use change effects were taken into account, and the grass community, soil stability, and alternate uses (cattle grazing, wildlife hunting) would be enhanced by periodic brush harvesting (Wang et al., 2014).

4.2. Wind energy development effects on wildlife conservation

The advantages of wind energy facilities are that they are driven by a persistent energy source and emit no direct pollutants. Accordingly, this clean energy source has become increasingly popular and has enjoyed significant subsidies to encourage development of wind farms throughout North America and in other countries. However, wind energy development presents substantial challenges in wildlife management (Arnett et al., 2007; NAS, 2007; Loss et al., 2015). These challenges result from the large size and dense placement of wind turbines and from infrastructure, such as roads and transmission lines, required to support wind farms and deliver electricity to the national electricity grid.

Wind energy facilities can lead to wildlife habitat degradation and collision related fatalities of bats and birds, especially raptors that soar along ridges where wind turbines are frequently placed (Kunz et al., 2007; Curry, 2009). For example, the Lower Gulf Coast of Texas, which is characterized by high native species diversity and valuable nature tourism and recreational hunting, has been identified as a region where wind energy development negatively impacts migratory birds and bats. One possible solution in such areas is to locate wind turbines on croplands that are less frequented by birds and bats rather than on native rangelands. A potentially greater impact is associated infrastructure because it can result in extensive habitat fragmentation and can provide avenues for invasion by exotic species (Kuvlesky et al., 2007). Other effects of wind energy development include diminished aesthetic quality of the landscape, elevated noise, shadow flicker, and electromagnetic interference (Krohn and Damborg, 1999).

Wind energy development has not always been accompanied by adequate assessments of wildlife impacts, and impact assessments that have been conducted often lacked scientific rigor. While environmental impacts of such developments can be spatially disbursed, associated environmental and social costs may be disproportionately borne by communities located near wind turbines. The National Academy of Sciences report on the environmental impacts of wind energy projects stated, given projected substantial increases in wind turbines in coming decades, there is a need for better analysis of cumulative effects of wind turbines on the fatalities of birds and bats (NAS, 2007). Similarly, a report from the Wildlife Society concluded there is a lack of information upon which to base decisions regarding siting of wind energy facilities, their impacts on wildlife, and possible mitigation strategies (Arnett et al., 2007). Recognizing the lack of comprehensive and rigorous impact assessments, the National Research Council's Committee on Environmental Impacts of Wind-Energy Projects provided a framework for evaluating the benefits and risks of wind energy projects and recommended that federal, state and local agencies use a coordinated approach for evaluating planning, regulation, and location of wind energy projects (Loss et al., 2015).

4.3. Oil and gas production and water interactions in rangelands

Unconventional fossil fuel development, particularly natural gas and oil from shales and tight sandstones, has grown rapidly across rangelands in the USA and Canada. Tens of thousands of horizontally drilled, hydraulically fractured wells have been developed in the last few years alone (EPA , 2015).

Water issues associated with horizontal drilling and hydraulic fracturing can be grouped into three broad categories: water requirements for extraction and processing, potential water contamination, and wastewater disposal. Between 2010 and 2013, the average amount of water used to hydraulically fracture a well in the USA was 9.2 million L (Jackson et al., 2015). Most wells were drilled in water limited rangeland ecosystems of the central and western USA, with ground water supplying a substantial amount of the requirements (Nicot and Scanlon, 2012).

The intense water requirements for unconventional oil and natural gas wells must be placed in the context of energy return on the water investment. Unconventional oil and gas wells use more water than conventional wells do per unit energy. However, because the amount of energy returned can be large, the average water intensity for extraction and processing of hydraulically fractured natural gas wells (15 L H_20/GJ energy returned) is only half as much as for coal production (27 L/GJ), one third as much as for nuclear production (47 L/GJ), one seventh that of oil sands production (110 H_20/GJ), and one sixteenth that of oil shale production (240 L/GJ) (Jackson et al., 2014). In contrast, the water footprint is higher than for conventional natural gas and far higher than for renewables such as wind power and solar photovoltaics, which require very little water. How the water footprint of unconventional oil and gas production is viewed depends greatly on the fuel and system to which it is compared.

The footprint of unconventional oil and gas production in rangelands is more visible through land use issues, where there is little difference between conventional and unconventional wells. Both conventional and unconventional oil and gas production require land for building well pads, roads, and pipelines, which fragments habitats (Brittingham et al., 2014). Wildlife ranges and behavior can also be influenced by extensive truck traffic; typically 1000 or more truck trips are associated with a single well that is horizontally drilled and hydraulically fractured. The average number of well pads per well is increasing across the US, which helps reduce the land footprint, but does not eliminate this concern completely.

5. Energy development implications of for rangelands in Canada and Mexico

5.1. Energy development effects on British Columbia grasslands

An increasingly evident effect of using fossil fuels as a primary energy source is global temperature rise. In turn, rising global temperatures are expected to create more frequent and severe drought, which will affect forage production, intensify desertification, and reduce carrying capacity of rangelands for livestock (Antle, 1996). Fluctuating climate conditions and increased drought result in greater variation and lower forage yield, respectively, while higher temperatures and intensified solar radiation reduce animal performance. Together these effects lead to a reduction in livestock production, which poses challenges for food security and to livelihoods of livestock dependent communities (Carlyle et al., 2014; Cox et al., 2015; Nardone et al., 2010).

According to Wang et al. (2012), the general climate prediction for British Columbia is warmer and wetter winters and warmer and drier summers. Drier summers would occur from the combined effect of reduced precipitation and increased evaporation in some areas, resulting in an increased water deficit. British Columbia ranchers are already noticing effects of climate change; more than 63% of 239 rancher survey respondents believed that human activities are increasing the rate at which global climate changes occur, and 60% of 231 respondents have adapted their management because of climate change (Cox et al., 2015). The expected impact of climate change varies regionally; four year warming experiments in the southern interior grasslands of British Columbia resulted in a 15% reduction in forage biomass (Carlyle et al., 2014). Therefore, increase in variation in temperature and precipitation and the probability of extreme weather events will likely contribute to increased agricultural risk and vulnerability (Cox et al., 2015).

There are few examples of adaptive range management strategies specific to climate change, which can be partially attributed to an inadequate perception of climate change as a risk to livelihoods (Cox et al., 2015). Carbon sequestration reduces GHGs while improved grazing practices may be a strategy for increasing carbon sequestration (Conant et al., 2001; Ingram et al., 2008; Ziter and MacDougall, 2013), and therefore a viable option for climate change mitigation. If increased levels of soil carbon can be rewarded through carbon crediting programs, this could facilitate ranchers obtaining economic benefits from improved management practices.

5.2. Restoration of rangelands disturbed by energy development in Alberta

Alberta's Energy industry has disturbed rangelands since the early 1900s. In 1963 Alberta became the first Canadian province to enact legislation specifically focused on land reclamation. Following the passage of this legislation the primary goal for reclaiming affected areas was to re-contour land and stabilize soil by seeding agronomic or native species. More recently there has been growing awareness of disturbance impacts on biodiversity and health of Alberta's remaining native prairies and the need to develop practices that restore native plant communities.

To address this concern, a variety of range science tools were developed between 1998 and 2014 from a geospatial grassland vegetation inventory to the Range Plant Community Guides (ASRD/ESRD, 2003–2014) and Recovery Strategies for Industrial Development in Dry Mixed Grass (GSL, 2013), to multi-stakeholder groups such as the Foothills Restoration Forum and the 2010 Grassland Reclamation Criteria for Wellsites and Associated Facilities (ESRD, 2013). These Tools were created by collating knowledge and experience of agrologists, landowners, reclamation practitioners and the energy industry, along with data from long-term site monitoring and research on disturbance trajectories. When these range science tools are applied in combination, minimal disturbance techniques become standard practices for the oil and gas industry. However, risks to restoration success are abundant. Reclamation criteria thresholds need to be tested, long term monitoring continued, and tools like the recovery strategies for the other natural subregions must be completed, implemented, and maintained.

Facilities needed for oil and gas production create numerous impacts on rangelands, including admixing of soil horizons, soil compaction, alteration of soil thermal regime and pH, loss of organic matter and vegetation cover, reduced microbial abundance and diversity, and invasion by non native plant species. Although many energy developments are relatively small, they can contribute substantially to habitat fragmentation due to their sheer number and the network of roads that they require. Over 30 years of research has demonstrated that reclamation of rangelands impacted by oil and gas developments is possible when the reclamation process begins prior to construction. Careful consideration must be give to siting infrastructure to avoid sensitive areas and using construction techniques that minimize soil compaction by vehicles and equipment. Research found areas where older pipelines were installed using more invasive construction techniques were less likely than areas affected by more recently constructed pipelines to return to pre-disturbance soil and plant community conditions.

Microsites and organic amendments aid in conservation of soil water, nutrients, and temperature regimes; microsites increase native species survival and abundance while some mulches enhance grass and forb emergence but excessive mulch rates inhibit some species by limiting transmitted light penetration while providing the success of others species, such as fescue. Selection of appropriate plant species and revegetation methods based on site conditions leads to establishment of a diversity and abundance of native species that facilitate the restoration of grassland environmental services. The diversity of a native seed mix is not as important as type of species included. Transplanting seedlings, in particular forbs, and native sod are effective revegetation methods for species that are difficult to establish from seed; native sod can also introduce species that are not commercially available. Natural recovery is a viable revegetation technique on small disturbances where there are no issues with undesirable plants. Active management of non-native plant species, at least in the first five years, is necessary on most sites for successful grassland restoration. Mycorrhizal associations have been identified for most native grassland species. Key plant species are still often missing from reclaimed communities and these mycorrhizal associations may help us develop methods for effective establishment of these species.

5.3. Impacts of oil and gas developments in the rangelands of Northern Mexico

Multiple use and sustainable yield have been used as natural resource management guidelines on rangelands in Mexico. However, energy reform legislation has created privileges for mining and oil and shale gas extraction, which are being promoted as activities making best use of the land. While the energy reform legislation is expected to provide economic benefits for those with access to the mineral resources, questions about the broader impacts of hydrologic fracturing and other mining techniques on Mexican landscapes remain unanswered. This is critical because Mexico has been ranked sixth globally in potential unconventional oil and gas production, having rich deposits located in five geological basins: Chihuahua, Sabinas-Burro-Picacho, Burgos, Tampico-Mizantla, and Veracruz.

Due to its promotion of mineral extraction as the preferred land use, energy reform legislation in Mexico will negatively impact property rights (Villamil, 2014), land management and rangeland based goods and services demanded by society, including food, fiber, fuel, and fun. Anticipated effects of this new legislation include biota modification, soil disturbance, air and water contamination, seismic events, land and water grabbing, and socio-economic problems (Jalife-Rahme, 2014). Mining activities are frequently inconsistent with the policy of harmonious multiple use and sustainable development of rangelands. If the ecological effects of increasing hydraulic fracturing and other mining techniques are not rigorously addressed, there is significant risk of substantial deterioration of several ecosystem services, including carbon sequestration, biodiversity maintenance, and aquifer recharge (Souther et al., 2014). Such effects would create significant problems in protected natural areas, important conservation areas for birds, and terrestrial priority conservation regions. Other impacts would include intensified use of ground water resources and air and water pollution, which exacerbate climate change and negatively impact wildlife and humans.

6. Knowledge gaps and future research needs

The preceding discussion demonstrates the impetus for domestic energy development to address energy security in North America and identifies numerous uncertainties and potential social-ecological harms related to such developments. There remain significant knowledge gaps to comprehensively assess the impacts and benefits of energy development on rangelands throughout the world. Filling these gaps requires a systematic and integrative approach. The ISEEC framework facilitates the adoption of such an approach to filling these knowledge gaps. In the following discussion, we identify knowledge gaps related to each of the preceding subsections and specify how they relate to the linkages in Fig. 3.

Knowledge gaps regarding human perceptions of energy development: While we know that perception is a key factor in explaining attitudes toward and actions taken in response to development of oil and natural gas, we lack knowledge about factors that underlie the formation of perceptions about oil and gas development and about the energy industry. This knowledge gap relates to linkage [A1] and [A2] in Fig. 3.

Knowledge gaps regarding biofuels development: Development of energy from rangeland based biofuels faces three technological challenges including development of efficient harvesting systems to accommodate multi-stemmed and variable growth forms; development of technology for effective use of woody biomass, including use as wood chips co-fired with coal, torrefaction or biogas; and coordinated harvest and utilization of woody and grass based (mainly switchgrass) biomass systems. Improvement of GIS based remote determination of biomass distribution and integration of woody plant distribution and potential grass production sites with transportation networks to lower transport costs will also be important. These relate to linkages [B], [E] and [F]. Identifying ecological effects of repeated harvesting of re-sprouting woody plants also needs to be clarified. These gaps relate to linkages [3], [4], and [6] through [12].

Knowledge gaps regarding wind energy effects: There is a lack of cumulative impact assessments for wind farm developments in North America, and assessments of the best and worst placement of turbine sites that will minimize impacts on birds and bats. For example, does siting of turbines on croplands rather than rangelands reduce this impact? This knowledge gap also relates to linkages [3], [4] and [6] through [12].

Knowledge gaps regarding effects of oil and gas development on water resources: Data are needed to identify effects of using various sources of water (surface versus ground water and fresh water versus brackish water) for hydraulic fracturing on surface vegetation and water availability for communities where water is being withdrawn. Few studies have been conducted to determine how unconventional oil and gas development affects the ranges, abundances, and behaviors of wildlife because pre-development baseline measurements of wildlife are rare. These knowledge gaps relate to linkages [2] and [5] through [12].

Knowledge gaps regarding rangeland related carbon emission and rangeland management effects on carbon sequestration: There is a substantial lack of knowledge about range management effects on soil carbon sequestration. We do not have a good understanding of the emission of GHGs associated with unconventional oil and gas and other forms of energy production on rangelands. These knowledge gaps relate to feedback linkages [7] through [12].

Knowledge gaps regarding tools to restore oil and gas impacted rangelands: Long-term evaluations are lacking about the comparative efficacy of various reclamation techniques for different disturbance types. There is a lack of knowledge about the comparative reclamation efficacy of native species and cultivars or ecovars or microbiological responses to various reclamation techniques. These gaps relate to the feedback linkages [7] through [12].

Knowledge gaps about energy development impacts in Mexico: In Mexico, other uncertainties relating to unconventional oil and gas development include the broader effects of energy reform legislation, which enables energy development to take priority over other land uses and to seize land and water for hydraulic fracturing. This leads to uncertain landscape disturbances and conflicts between traditional and unconventional land uses, violation of the rights of people and communities to determine use of their natural resources, and difficulties in enforcing environmental laws. These

Table 1
Indicators for monitoring changes in biophysical-social-economic linkages affecting ecosystem goods and services in energy development on rangelands.

Linkage[a]	Description	Indicator [b]
1, 2	Plant composition Plant biomass	[12] Spatial extent of vegetation communities [14] Fragmentation of rangeland plant communities [20] Population status and geographic range of rangeland dependent species [21] Above ground plant biomass
3, 4	Biofuel utilization Other rangeland goods utilization	[27] Value of forage harvested from rangeland by livestock [28] Value of production of non-livestock rangeland products [32] Return on investment in livestock, wildlife, water, biofuel, etc.
5	Rangeland services utilization	[32] Return on investment in hunting, recreation, etc. [33] Area of rangelands under conservation ownership
6	Direct biofuel harvesting impacts	[01] Soil area with significantly diminished org. matter or C/N ratio [04] Area with significant change in bare ground [05] Area with accelerated soil erosion [12] Spatial extent of vegetation communities [20] Population and geographic range of rangeland dependent-species
7	Public/private investment and capacity building	[32] Return on investment in livestock, wildlife, water, biofuel, etc. [33] Area of rangelands under conservation ownership [56] Extent to which government agencies and NGOs affect conservation/management of rangelands [57] Extent to which economic policies support conservation/management of rangelands [59] Professional education/technical assistance support [60] Conservation/rangeland management support [63] Resources for monitoring rangeland condition [64] Conservation/management research/development support
8, 9, 10, 11, 12	Soil condition Water quality Biodiversity	[01] Soil area with significantly diminished org. matter or C/N ratio [04] Area with significant change in bare ground [05] Area with accelerated soil erosion [06] Percent water bodies with significant changes biotic composition [07] Percent surface water with significant deterioration of chemical, physical, and biological properties from acceptable levels [12] Spatial extent of vegetation communities [14] Fragmentation of rangeland plant communities [20] Population and range of rangeland dependent species

[a] Numbers in the first column indicate the corresponding link in Fig. 2.
[b] Indicators for monitoring sustainability of rangeland ecosystems identified by SRR with (number in brackets represent the SRR indicator number) (Source: Maczko and Hidinger, 2008).

knowledge gaps relate to linkages [A2], [B] and [E] in socio-economic subsystems and feedback effects on delivery of ecosystem goods and services and biophysical processes, which are represented by linkages [7] through [12].

Using the ISEEC framework to specify linkages within rangeland socio-ecological systems that may be affected by alterative energy development enables us to identify areas where integrated research could be conducted to simultaneously fill several knowledge gaps about energy development effects. Conducting this research will require a suite of indicators to measure conditions before, during, and after energy development (see Maczko and Hidinger, 2008; Fox et al., 2009). Such indicators range from area of soils with significantly diminished organic matter and/or carbon/nitrogen ratios (SRR indicator 1) to level of support for conservation management research and development (SRR indicator 64). Table 1 provides a list of indicators specifically related to the knowledge gaps and linkages identified above.

7. Conclusion

While substantial knowledge exists about alternative energy production and effects of their development on rangelands, there are still numerous knowledge gaps that must be filled to obtain a comprehensive understanding of these energy exploitation impacts. These knowledge gaps include a lack of understanding about factors that drive human perceptions regarding alternative energy development; a lack of knowledge of the effects of hydraulic fracturing to access oil and gas from shale plays on surface vegetation, wildlife and water resources; the comparative efficacy of alternative land reclamation methods; and the effects of changes in legislation to facilitate alternative energy development on local communities and land use rights.

The Integrated Social, Economic and Ecological Conceptual (ISEEC) framework, developed by the Sustainable Rangeland Roundtable (SRR) in the USA, provides a useful tool for developing an integrated approach for filling such knowledge gaps. It does this by facilitating systematic identification of linkages within rangeland social-ecological systems that affect the delivery and use of ecosystem goods and services, and feedback effects of such usage on the biophysical processes that produce these goods and services. These linkages can then be used to identify standardized indicators, such as those developed by the SRR, to obtain data to fill these knowledge gaps.

Using these indicators, the next step is to develop a multi-disciplinary research team and to source research funding to fill the knowledge gaps using indicators such as the ones identified here to obtain data before, during and after development of these energy sources. This will enable development of policies and regulations that help minimize and mitigate these impacts on rangeland ecosystems and the critically important goods and services they deliver.

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