Journal of Environmental Management 374 (2025) 124091

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Lost ecosystem service costs and impact fees: Modelling scenarios for oil and gas development on U.S. public land☆

Pete Morton[a,*], Joe Kerkvliet[b]

[a] Conservation Economics Institute, USA
[b] Conservation Economics Institute, USA and Oregon State University, USA

ARTICLE INFO

Keywords:
Ecosystem services
Impact fees
Oil and gas
Scenarios
U.S. Bureau of land management

ABSTRACT

The U.S. Department of Interior's Bureau of Land Management regulates oil and gas development on 23 million acres of U.S. public land. The land disturbances associated with oil and gas development result in lost ecosystem service costs (LESC). LESC vary with the restorative characteristics of the land being developed, the duration of oil and gas production, the reclamation efforts that occur during production and the restoration occurring post-production. In order to understand the range and magnitude of LESC, we developed a model to quantify cumulative LESC totals for terrestrial ecosystems for 32 scenarios on a per acre basis. Total LESC calculated with a 0% discount rate range from $26,051 to $250,709 per acre depending on the years of energy production, interim reclamation rates and final restoration rates. LESC totals are lower when quantified at discount rates of 2, 4 and 10%. Internalizing LESC compensates public landowners and creates financial incentives for oil and gas companies (OGC) to reduce the initial disturbance footprint, invest in reclamation to reduce the footprint over time and to decrease the years of energy production in order to reduce the number of years between reclamation and final restoration. Charging impact fees for LESC would generate billions of dollars in revenue.

1. Introduction

The U.S. Department of Interior's Bureau of Land Management (BLM) currently regulates oil and gas development on 33,702 oil and gas leases with 90,298 wells on U.S. public land, covering over 23 million acres, and producing 11 percent of U.S. oil and 9 percent of U.S. natural gas (U.S. Department of the Interior Bureau of Land Management, 2024a; U.S. Department of the Interior Bureau of Land Management, 2024b). In the last 20 years, the fast pace and large scale of oil and gas development (OGD) has resulted in cumulative environmental impacts including lost ecosystem service costs (LESC). LESC accumulate each year during energy production, are reduced by interim reclamation, and continue post production until a site is fully restored.

The authors have more than 20 years of experience reviewing and commenting on BLM policies and resource management plans. Historically, BLM land use planning emphasized commodity extraction and gave scant consideration to other environmental values (e.g., wildlife, recreation). The BLM now explicitly recognizes the need to consider ecosystem services in its resource management plans (National Ecosystem Services Partnership, 2014).

1.1. Purpose of paper

The purpose of our research is to develop a model for measuring the LESC resulting from the land disturbances caused by oil and gas development. Our model incorporates BLM's policy of distinguishing between interim reclamation (occurring after first well drilled through the end of production) and final restoration (occurring from the end of production until restoration of full ecosystem functions).

This paper represents a proof of concept for our model. Key variables include years of oil and gas production, rates of interim reclamation, and rates of final restoration. We choose a range of values for these variables representative of oil and gas wells on BLM-managed land. We quantify LESC for 32 scenarios to show how the various components of the model affect LESC and provide guidance on just how much LESC might be.

We confine LESC to the land-based ecosystem services that are lost or

Abbreviations: OGD, oil and gas development; OGC, oil and gas companies; LESC, lost ecosystem service costs; IRR, interim reclamation rate; FRR, final restoration rate; FLPMA, Federal Land Policy and Management Act; $, reported are U.S. dollars.

☆ This research did not receive any specific grant from funding agencies in the public, commercial, or not-for profit sectors.

* Corresponding author.
E-mail address: pete@conservationecon.org (P. Morton).

https://doi.org/10.1016/j.jenvman.2025.124091
Received 1 November 2024; Received in revised form 17 December 2024; Accepted 7 January 2025
Available online 17 January 2025
0301-4797/

degraded from land disturbance when top soil and vegetation are removed to create a level surface for a well pad for drilling oil and gas wells. For our purposes, LESC do not include methane leakage, water pollution, public health costs, noise pollution and the other non-market costs from OGD and the use of end products.

Finally, we discuss the fiscal tool of impact fees as an appropriate economic instrument for internalizing, levying, and collecting LESC. Our thesis is that charging impact fees for LESC from the land disturbance associated with OGD represents a significant source of revenue and provides oil and gas companies with financial incentives for more responsible development.

1.2. Research questions

The research questions addressed in this paper include.

Research Question 1. What is the magnitude and variability of LESC among scenarios?

Research Question 2. What incentives are created by internalizing LESC for oil and gas companies?

Research Question 3. What is a first order estimate of the total LESC revenue from charging impacts fees for the land disturbance associated with oil and gas development on U.S. public land?

Our paper begins with background information in Section 2 followed by Materials and Methods for quantifying LESC and the scenarios modelled in Section 3. Results are presented in Section 4 with discussion in Section 5 and conclusions in Section 6.

2. Background

This section provides background information on: 1) ecosystem services; 2) the distinction between BLM's reclamation and restoration policies; 3) BLM policies relevant to ecosystem services; 4) impact fees; and 5) the discount factor.

2.1. Lost ecosystem service costs (LESC)

The ecological and environmental impacts of OGD are extensive and well documented (Weller et al., 2002; Morton et al., 2004; Nallur et al., 2020; Ott et al., 2021; Hill and Ma, 2021; Bonetti et al., 2021). Land disturbance from well pad construction and associated road building removes vegetation and top soil, causes soil erosion, disrupts water flows, reduces or eliminates agricultural production and livestock and wildlife grazing, and fragments wildlife habitat. Waste water, mud, and chemicals are spilled or stored in containment ponds during drilling and production. Both can contaminate soils and groundwater if not properly remediated or removed. During the production period, well pads are occupied by pumps, generators, storage tanks, and constructed waste pits that must be removed or remediated (U.S. Government Accountability Office, 2010, 2011, 2018, 2019). Even when production ends, the effects of construction and production disturbances can persist for years and sometimes decades.

Ecosystem services are the benefits provided by nature to humans in the forms of functions and products. Although classifications are evolving (see Chen and Sloggy, 2023), typically there are four recognized types of ecosystem services: provisioning (e.g., food, wood); regulating (e.g., pollination, erosion control); cultural (e.g., bird and wildlife viewing); and supporting (e.g., soil building, nutrient recycling). Although there are many challenges, economists and other environmental scientists use a variety of methods to attach monetary values to ecosystem services and aggregate these values into useful spatial and temporal scales, such as ecotypes (e.g., wetlands, grasslands).

Several recent studies use estimated monetary values of ecosystem services to measure the impact of oil and gas development. Moran et al. (2017) report that 200,000 ha of land in the U.S. were disturbed by OGD between 2004 and 2015, at a cost of $272 million annually in lost ecosystem service costs. Depending of rates of future oil and gas production to the year 2040, the authors estimate OGD will result in lost ecosystem services values at $9.4 billion to $31.9 billion. Allred et al. (2015) measured the lost ecosystem services from removing vegetation for OGD in the Central U.S. The authors use the loss in net primary production (NPP) as their measure of lost ecosystem services. NPP measures the amount of carbon accumulated by plants as biomass. They estimate that, from 2000 to 2012, OGD reduced NPP by 4.5 billion kilograms of carbon or 10 billion kilograms of dry biomass. The NPP lost in rangelands was enough to support five million animal unit months, the forage needed to support a cow and calf for one month. With an average of $20 per AUM, this is a $100 million cost.[1] The NPP lost in croplands was the equivalent of 120.2 million bushels of wheat. At a rough average price of wheat, this is a $600 million cost.[2] The authors conclude that "The loss of NPP is likely long-lasting and potentially permanent, as recovery or reclamation of previously drilled land has not kept pace with accelerated drilling".

McClung and Moran (2018) document the ecosystem services impacts of OGD in three U.S. regions, including two that contains much federal public land (Great Plains and northern Chihuahuan desert. The authors call for "targeted studies to improve our understanding of how … development will impact these ecosystems and which strategies can mitigate the negative impacts".

Chomphosy and Varriano (2021) identify over 1.5 million acres of U.S. land disturbed by 430,000 wells, which are now abandoned. The authors use the value of ecosystem services to compare the benefits of restoring these lands with the costs of their restoration. Overall they estimate $21 billion in discounted benefits over 40 years compared to $7 billion in restoration costs. The benefit/cost ratios vary with the ecotype and the authors conclude that the value of ecosystem services approach can be used to prioritize restoration funding. Nallur et al. (2020) also use the value of ecosystem services to estimate that over 1000 abandoned wells in Arkansas can be restored with annual net benefits of over $2 million.

Jones et al. (2015) note that both OGD and renewable energy sources, such as wind, create ecological disturbances. They review the literature on the ecological and ecosystem services impacts of both energy sources and call for more research to support energy development policy. Davis et al. (2018) answer this call and use the values of ecosystem services to compare OGD to wind energy development in the Anadarko Basin of Oklahoma. They find that the two energy sources have about the same ecosystem service costs per unit of energy, although the results differ by the ecotype of the disturbed land.

Our approach for quantifying LESC is consistent with these authors but differs in that we incorporate interim reclamation and final restoration rates into our methods and results. In order to understand the range and magnitude of LESC, we quantify cumulative LESC totals for 32 oil and gas production scenarios by varying the years of energy production, interim reclamation rates and final restoration rates.

For our scenarios, we quantify per acre LESC based on the terrestrial ecosystem service monetary values reported by DeGroot et al. (2012). Adjusted for inflation (2022 dollars) this is $2801 per acre per year. Terrestrial ecosystems were chosen to provide a mid-range, relatively common ecotype for model demonstration purposes.

LESC accumulate each year until a site is fully restored. The relationship between final restoration rate (FRR) and cumulative LESC for terrestrial ecosystems is shown in Fig. 1. A 4% FRR results in LESC of $36,416 per acre. In contrast, a 2% FRR results in higher LESC of $71,431 per acre because annual LESC are reduced at a slower rate and

[1] https://www.nass.usda.gov/Charts_and_Maps/Grazing_Fees/gf_am.php.

[2] https://www.statista.com/statistics/190384/top-10-us-states-by-price-per-bushel-of-wheat/.

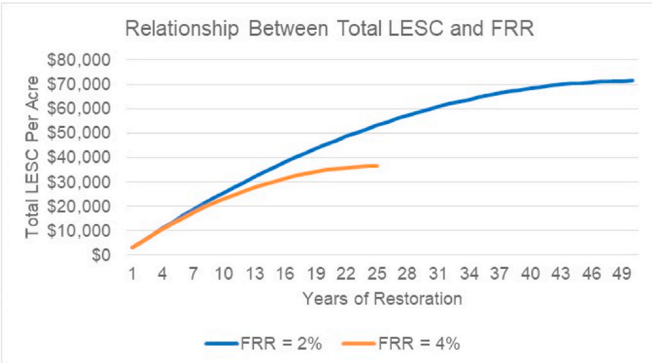

Fig. 1. Relationship between total LESC per acre and FRR for terrestrial ecosystems.

accumulate over a longer period of time.

2.2. BLM reclamation and restoration policies

BLM recognizes that OGD disturbs land, water, and other natural resources. Its policies distinguish between reclamation and restoration. BLM directs oil and gas companies (OGC) to reclaim the well-site to be on a trajectory leading eventually, but not immediately, to complete restoration. BLM's guidelines for surface reclamation of the well-site state: "*The objective of reclamation in the short term is to provide site stability and basic resource productivity. The final goal is to restore the land to its pre-disturbance level. The … [OGC] is responsible for completing the reclamation activities necessary to achieve the short-term objective and … establishing the conditions … so that no impediment exists that would prevent achieving the final goal.*" (U.S. Department of the Interior and U.S. Department of Agriculture, 2007, p. 3). Reclamation is achieved when "*a self-sustaining, vigorous, diverse, native (or otherwise approved) plant community is established …, with a density sufficient to control erosion and non-native plant invasion and to re-establish wildlife habitat or forage production*" (U.S. Department of the Interior and U.S. Department of Agriculture, 2007, p. 43).

Ecologists recognize the difference between reclamation and restoration, explaining as follows. A site is never fully restored quickly even after the reclamation work is complete. Whereas reclamation work may take several years to finish, full restoration of a site to its original condition can take several decades (Walsh and Rose, 2022). Reclamation returns a degraded site to a basic level of productivity (Bradshaw, 1987), while restoration finishes the job by actively assisting ecosystem recovery (Gann et al., 2019).

Planning for site reclamation before drilling an oil or gas well is critical to achieving successful restoration in the long run. When an OGC applies for a drilling permit, BLM requires it to submit a Surface Use Plan of Operation which includes interim and final reclamation plans. Interim reclamation occurs during production and includes activities affecting land not needed to support oil and gas production. Interim reclamation activities include noxious weed control, revegetation of road berms and other areas to within a few feet of land needed for production, water and soil erosion control, and safeguarding top soil needed for post-production reclamation (U.S. Department of the Interior and U.S. Department of Agriculture, 2007). Importantly, more interim reclamation means less time and expense required for final restoration, *ceteris paribus*. The rate of interim reclamation is somewhat at the discretion of the OGC and will determine how much restoration needs to occur post production.

Reclamation costs are covered by surety bonds posted by OGC. Effective bonding policies require bonding amounts sufficient enough to accomplish the purposes and goals of the bonding policy. In 2024, the BLM updated its oil and gas leasing policies, including bonding reform. BLM increased the single lease bond from $10,000 to $150,000, the statewide bond from $25,000 to $500,000, and eliminated nationwide bonds (U.S. Department of the Interior Bureau of Land Management, 2024c).

2.3. BLM policies and LESC

The Federal Land Policy and Management Act (FLPMA), the organic act for the BLM, requires "a standard of care that prevents unnecessary or undue degradation, avoids permanent impairment, and ensures sustained yield of natural resources" (Pleune et al., 2021).

As noted in Section 102(8) of FLPMA:

> The public lands (will) be managed in a manner that will protect the quality of scientific, scenic, historical, ecological, environmental, air and atmospheric, water resource, and archeological values; that, where appropriate, will preserve and protect certain public lands in their natural condition, that will provide food and habitat for fish and wildlife and domestic animals, and that will provide for outdoor recreation and human occupancy use.

The high standard of care established by FLPMA requires the BLM to account for environmental impacts such as LESC. FLPMA contains additional language to give consideration to the long-term needs of future generations as part of BLM's multiple use mandate (Pleune et al., 2021).

BLM is also required to modify its policies to incorporate new knowledge. When BLM policies were developed, there was little recognition of many of the ecosystem service values that might be compromised by OGD, whereas these values are now well established and widely recognized (DeGroot et al., 2012; Kerkvliet, 2012; Costanza et al., 2014; Nallur et al., 2020; Pleune et al., 2021).

In 2013, the BLM issued guidance for considering nonmarket environmental values when preparing BLM resource management plans and Environmental Impact Statements (EIS) as required by the National Environmental Protection Act (NEPA). From the document (U.S. Department of the Interior Bureau of Land Management, 2013):

> All BLM managers and staff are directed to utilize estimates of nonmarket environmental values in NEPA analysis supporting planning and other decision-making where relevant and feasible, in accordance with the attached guidance … The use of quantitative valuation methods should contribute to the analysis of one or more issues to be addressed in the environmental analysis supporting planning or other decision-making. A quantitative analysis of nonmarket values in EIS-level NEPA analyses is strongly encouraged where one or more of the criteria described in the attached guidance apply.

A review of BLM's research needs pointed to the explicit recognition of the need to consider ecosystem services (National Ecosystem Services Partnership, 2014) in its land management decisions and led BLM to conduct several pilot projects incorporating ecosystem services into its plans and projects.

Kline and Massotta (2013) discuss the evolution of U.S. public land management agencies toward management focused on ecosystem services, stating current public land planning and management can be "viewed as striving to produce a portfolio of ecosystem services that provides the greatest overall benefit to the public within a landscapes' capacity to produce services" (p. 149). The authors also discuss some of the challenges of applying the ecosystem services approach including predicting how ecosystem services will be affected by management activities.

Additional support for accounting for LESC comes from the BLMs recently finalized Conservation and Landscape Health Rule which prioritizes the health and resilience of ecosystems across public lands. The rule defines the resiliency of ecosystems as the ability to withstand disturbance. As noted in the rule:

Establishing and safeguarding resilient ecosystems has become imperative as the public lands experience adverse impacts from climate change and as the BLM works to ensure public lands and ecosystem services benefit human communities (U.S. Department of the Interior Bureau of Land Management, 2024d).

The Conservation and Landscape Health Rule features restoration as a key strategy for building and maintaining the resilience of ecosystems on public lands (U.S. Department of the Interior Bureau of Land Management, 2024d).

2.4. Impact fees

Impact fees are monetary payments assessed on property developers by local governments to internalize the external costs of residential and commercial development (Libby and Carrion, 2004; Burge and Ihlanfeldt, 2013). Impact fees have two general purposes: (1) to generate revenue to cover the proportionate costs of needed improvements arising from new development; and (2) to manage the pace of growth and the scale of development (Nicholas and Juergensmeyer, 2003; Nelson et al., 2017). Impact fee revenue has been used to fund transportation, water, sewers, parks, law enforcement, public buildings, emergency services, affordable housing, and open space.

Impact fees can also be used to reduce the legacy costs to U.S. taxpayers of reclaiming old wells on public land when bonding is inadequate (U.S. Government Accountability Office, 2008; Morton et al., 2022). In this paper we explore expanding the use of impact fees to compensate landowners for ecosystem services damaged or lost as a result of OGD on U.S. public land. Charging per acre impact fees based on LESC provides OGC with incentives for improve land stewardship.

2.5. Discount factor

Annual LESC are multiplied by the discount factor in order to obtain the present value of LESC. The discount factor is a function of the discount rate chosen and the year the LESC are incurred. The discount factor is applied to LESC from the beginning of land disturbance preproduction until final restoration is complete.

3. Materials and Methods

Our model quantifies per acre LESC as a function of the ecotype of land disturbed, the number of years of energy production, the annual rate of interim reclamation, the annual rate of final restoration post-production, and potentially the discount rate applied to ecosystem service values.

Our model has two components. The first component calculates the accumulation of LESC during production adjusted for annual interim reclamation rates and constrained by the footprint needed for active oil and gas production. The second calculates the accumulation of LESC post production adjusted by annual final restoration rates. Fig. 2 shows a flow chart for our model with inputs and processes for calculating cumulative LESC for each scenario.

Formally, the relationship for estimating cumulative LESC totals per acre during production and post production can be expressed as follows:

Total LESC Per Acre =

$$\sum_{t=1}^{YP}\left[LESC_j{*}(1-(IRR{*}t)){*}DF_{t,DR}\right]+\sum_{t=1}^{YR}\left[LESC_j{*}1-((IRR{*}YP)+(FRR{*}t))\right]$$

where:

$LESC_j$ = annual lost ecosystem service costs per acre for ecotype (j)

YP = years of energy production.

IRR = interim reclamation rate per year during production.

IRR x YP $\leq$ 50%

FRR = final restoration rate per year post production.

YR = years of restoration -number of years post production until site fully restored

$$YR=\left(\frac{1-(IRR{*}YP)}{FRR}\right)$$

$DF_{i,\ DR}$ = discount factor for year i and discount rate chosen.

DR = discount rate chosen.

(t) = years.

(j) = ecosystem type.

3.1. Lost ecosystem service costs (LESC)

Annual LESC per acre accumulate each year from the onset of well pad construction before energy production to when a site is fully restored post production. LESC are adjusted downward during production based on IRR. LESC are adjusted post production based on FRR. To

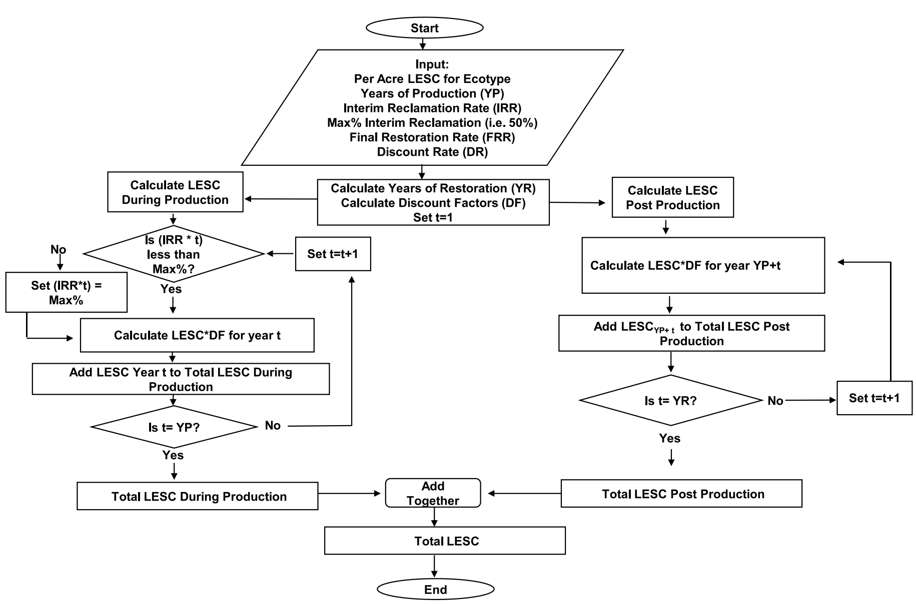

Fig. 2. Flow chart of model.

quantify and illustrate the range of LESC and sensitivity to OGD components, we model LESC with two YPs, four IRRs and four FRRs for a total of 32 scenarios with a 0% discount rate. We further examined LESC totals using 0, 2, 4 and 10% discount rates.

3.2. Years of energy production (YP)

Older conventional oil and gas wells can produce economic quantities of oil and gas for over 50 years (Stanford University, 2024). Some conventional wells produce for over 80 years (Raimi et al., 2021). Conventional oil and gas wells account for 36% and 11% of U.S. production, respectively (Stanford University, 2024).

Newer unconventional wells involving hydraulic fracturing have steeper declines in yield and are likely to produce for fewer years (Freeman, 2022). Unconventional wells in the most prolific shale plays have decline rates of more than 50% in their first year, and another 30% in their second. These high decline rates challenge the economic viability of wells that were expected to produce for 30 or more years (Jacobs, 2020). Declining rates of production combined with financial pressure to recover as much oil and gas as quickly possible will likely shorten the average life span of new wells (see Hood, 2015).

To capture this variation in our scenarios we use two years of production (YP) 10, and 40 years.

A majority of wells will produce oil and gas for 10–40 years and as such represents a reasonable range for our purposes. Since LESC is positively correlated with YP, if we had used higher years of production, total LESC would be even greater than LESC estimated with 40 years of production.

3.3. Reclamation and restoration rates

Ecological research indicates that restoration may take decades, even after reclamation. Minnick and Alward (2015) found that well pads in sagebrush shrub lands had not achieved native vegetation and soil conditions forty-seven years after well closure. Nauman et al. (2017) found that despite past reclamation efforts, half of the oil and gas well pads plugged between 1997 and 2005, had only twenty-five percent of the vegetation found on similar undrilled land.

Avirmed et al. (2015) estimated restoration of sagebrush habitat takes at least 87 years. Monroe et al. (2020) used remote sensing to predict recovery rates on 375 former oil and gas well pads. The authors predicted 60 years for cool and moist, high elevation areas to recover and over 100 years for warm and dry, low elevation areas. Monroe et al. (2022) used a dynamic reference modeling approach to assess sagebrush recovery on former oil and gas wells pads in Wyoming. The authors found recovery varied from less than 25 years to over 100 years.

To account for variation, we used a range of reclamation/restoration rates to estimate the benefits (i.e., lower LESC) from investments in reclamation/restoration. For simplicity we assumed linear rates which may not be the case. Table 1 shows the rates matched up with number of reclamation/restoration years required for a given rate. Based on the above literature, the years to reclaim and restore site represent a reasonable range for LESC modelling purposes.

Table 1
Reclamation/restoration years required for a given rate.

Reclamation/Restoration Annual Rate	Years of Reclamation/Restoration
0%	
1%	100 years
2%	50 years
4%	25 years
10%	10 years

3.4. Interim reclamation rate (IRR)

The interim reclamation rate (IRR) is the annual reclamation rate of disturbed land during production. Some aspects of interim reclamation are mandated by BLM, but others, the extent of roads, the area disturbed for drilling and material storage, and the diligence and care used in interim reclamation activities are at the discretion of the OGC. For our scenarios we model four IRR's- 0, 1, 2 and 4 percent per year. We included 0% as the low end to represent a site where no interim reclamation occurred. Reclamation is capped at 50% of an acre as we assume active producing well operations and roads require the remaining 50% of the initial footprint.

3.5. Final restoration rate (FRR)

The final restoration rate (FRR) is the annual rate at which all the ecological functions of a site are restored once production ends. For our scenarios we model four FRR's- 1, 2, 4 and 10 percent per year. We included 10% to represent an optimistic high end restoration rate. The 10% rate also provides a low-end estimate for total LESC.

3.6. Discount rate (DR)

We quantify LESC using a zero percent discount rate which is consistent with BLM's long-term perspective as well as the implicit rate of current BLM bonding policies. The U.S. Office of Management and Budget (OMB) requires discounting when completing a Regulatory Impact Analysis (RIA) for new regulations.[3] Charging impact fees for LESC would certainly be considered a new regulation requiring a RIA. U. S. Office of Management and Budget (2023a) recommends a social discount rate of 2–3% when for example, calculating the social cost of carbon. Private corporations universally use higher discount rates to make investment decisions. To illustrate the influence of higher discount rates on LESC, we completed a sensitivity analysis of three additional discount rates: 2%, 4% and 10%.

4. Results

4.1. Cumulative LESC totals

Calculating LESC for various years of production (YP), interim reclamation rates (IRR), and final rates of restoration for the disturbed land (FRR), illustrates that LESC per acre are heterogeneous. LESC from OGD vary based on: 1) choices made by OGC and BLM in planning and implementing interim reclamation rates (IRR); 2) how many years a well stays in production (YP); and 3) how quickly the disturbed land is restored (FRR).

We show total calculated LESC graphically in Fig. 3 for 10-year production scenarios and Fig. 4 for 40-year production scenarios. Both graphs illustrate how LESC decline as IRR increases and as the final restoration rate (FRR) increases. Table 2 shows LESC calculations for all 32 scenarios for production, post production and total LESC.

Fig. 3 shows the total calculated LESC for 16 scenarios with 10 years of production and various combinations of FRR and IRR. The calculated values are arranged in 4 bar chart groups of 4 bars, one for each assumed level of FRR (1%, 2%, 4%, and 10%) and within each bar chart group, the bars show the calculated LESC for four assumed levels of IRR (0%, 1%, 2%, 4%).

In Fig. 3, the calculated LESC range from $166,672 per acre (for FRR

[3] Executive Order 12,866 issued by President Clinton, requires RIA for new regulations with an estimated annual effect on the economy of more than $100 million. President Obama issued E.O. 13563 to quantify anticipated benefits and costs of proposed rulemakings as accurately as possible using the best available techniques.

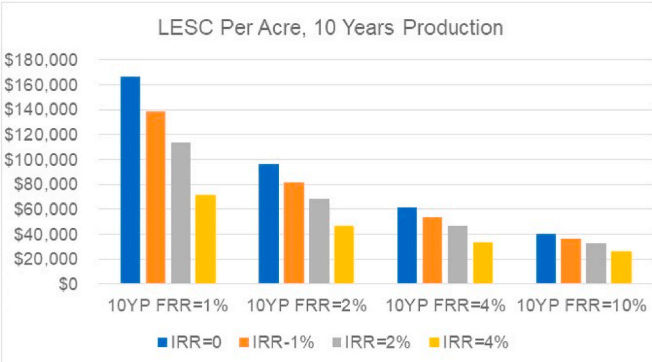

Fig. 3. Total LESC per acre, 10 Years of production for terrestrial ecosystems.

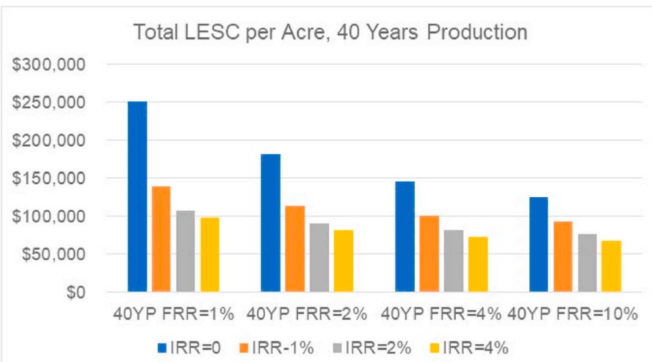

Fig. 4. Total LESC per acre, 40 Years of production for terrestrial ecosystems.

= 1% and IRR = 0%) to $26,051 (for FRR = 10 % and IRR = 4%). The average LESC are $69,668 (standard deviation = 39,445). LESC decrease 84% when moving from the scenario with the lowest FRR and IRR to the scenario with the highest rates. This illustrates how LESC vary substantially with FRR (which is likely to depend on the inherent characteristics of the land being drilled) and with the level of IRR (which is likely to be discretionary for BLM and the OGC).

To illustrate the sensitivity of LESC to variations in FRR, we calculate an average 71% decrease in LESC when moving from the lowest to the highest final restoration rate. The average percentage change in LESC moving from the lowest to the highest IRR is −47%.

Fig. 4 shows the calculated LESC for 16 scenarios with 40 years of production and various combinations of FRR and IRR. In Fig. 3, the calculated LESC range from $250,709 per acre (for FRR = 1% and IRR = 0%) to $66,893 (for FRR = 10 % and IRR = 4%). The average is $113,726 (standard deviation = 43,859). We calculate a 73% decrease in LESC when moving from the scenario with the lowest final restoration and interim reclamation rates to the scenario with the highest FRR and IRR.

We calculated the average percentage decrease in LESC of 36% when moving from the lowest to highest FRR. The average percentage change in LESC from the lowest to the highest IRR is −53%.

4.2. *Effects of discounting on LESC*

Fig. 5 shows the effects of discounting on LESC for four illustrative scenarios, two each for 10 years and 40 years of production. In increasing the discount rate from zero to 10%, calculated LESC decrease by over 80 percent for both the ten year and forty-year scenarios with low FRR (1%) and low IRR (0%) and more than 40 percent for the ten- and forty-year scenarios with high FRR (10%) and high IRR (4%).

These results imply that discounting more strongly decreases LESC for OGC's performing little interim reclamation on land that recovers more slowly. Clearly discounting lowers LESC and, if a high enough discount rate is used the calculated LESC would be effectively zero. Implicitly, in not making OGC's responsible for post-production LESC, BLM is applying a very high discount rate, much higher than that recommended by OMB.

Table 2
Summary of LESC calculations for 32 scenarios.

Scenario	LESC Production	LESC Post Production	Total LESC
10 YP IRR = 0% FRR = 1%	$28,012	$138,660	$166,672
10 YP IRR = 0% FRR = 2%	$28,012	$68,630	$96,642
10 YP IRR = 0% FRR = 4%	$28,012	$33,615	$61,627
10 YP IRR = 0% FRR = 10%	$28,012	$12,605	$40,618
10 YP IRR = 1% FRR = 1%	$26,471	$112,189	$138,660
10 YP IRR = 1% FRR = 2%	$26,471	$55,464	$81,936
10 YP IRR = 1% FRR = 4%	$26,471	$27,116	$53,587
10 YP IRR = 1% FRR = 10%	$26,471	$10,084	$36,556
10 YP IRR = 2% FRR = 1%	$24,931	$88,518	$113,449
10 YP IRR = 2% FRR = 2%	$24,931	$43,699	$68,630
10 YP IRR = 2% FRR = 4%	$24,931	$21,289	$46,220
10 YP IRR = 2% FRR = 10%	$24,931	$7843	$32,774
10 YP IRR = 4% FRR = 1%	$21,849	$49,581	$71,431
10 YP IRR = 4% FRR = 2%	$21,849	$24,371	$46,220
10 YP IRR = 4% FRR = 4%	$21,849	$11,765	$33,615
10 YP IRR = 4% FRR = 10%	$21,849	$4202	$26,051
40 YP IRR = 0% FRR = 1%	$112,049	$138,660	$250,709
40 YP IRR = 0% FRR = 2%	$112,049	$68,630	$180,678
40 YP IRR = 0% FRR = 4%	$112,049	$33,615	$145,663
40 YP IRR = 0% FRR = 10%	$112,049	$12,605	$124,654
40 YP IRR = 1% FRR = 1%	$89,079	$49,581	$138,660
40 YP IRR = 1% FRR = 2%	$89,079	$24,371	$113,449
40 YP IRR = 1% FRR = 4%	$89,079	$11,765	$100,844
40 YP IRR = 1% FRR = 10%	$89,079	$4202	$93,280
40 YP IRR = 2% FRR = 1%	$72,832	$34,315	$107,146
40 YP IRR = 2% FRR = 2%	$72,832	$16,807	$89,639
40 YP IRR = 2% FRR = 4%	$72,832	$8067	$80,899
40 YP IRR = 2% FRR = 10%	$72,832	$2801	$75,633
40 YP IRR = 4% FRR = 1%	$64,092	$34,315	$98,407
40 YP IRR = 4% FRR = 2%	$64,092	$16,807	$80,899
40 YP IRR = 4% FRR = 4%	$64,092	$8068	$72,159
40 YP IRR = 4% FRR = 10%	$64,092	$2801	$66,893

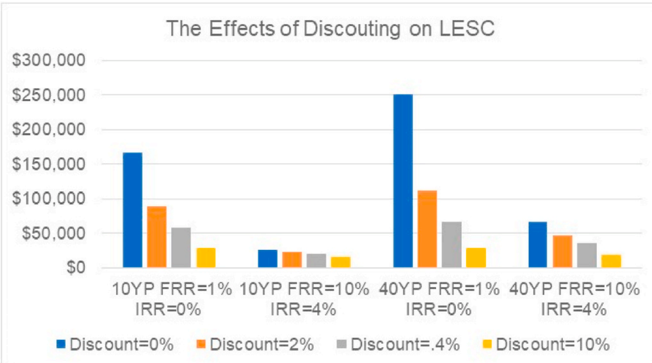

Fig. 5. The effects of discounting on LESC

4.3. Cumulative LESC totals for U.S. Public lands

In order to calculate LESC of a per well basis for the 90,298 oil and gas wells on U.S. public land we have to estimate the total land disturbed per well. The total area of disturbed land includes the acres of land required to build the well pad plus the associated access roads, infrastructure (e.g., storage tanks, injection and water wells) and oil and gas pipelines.

Well pads vary in size depending on location, topography, type and depth of well and rig size. Older vertical well pads commonly have a single well while newer horizontally drilled wells have larger well pads that co-locate multiple wells. In the Northern Great Plains of North Dakota and Montana, well pads range from 4 to 6 acres for single wells to 5–7 acres for well pads with multiple wells (Preston and Kim, 2016).

Well pads in remote areas will require more miles of roads and connecting pipelines than wells in close proximity to existing road and pipeline infrastructure. A mile of 14-foot-wide single land access road disturbs 1.7 acres of land without consideration of land disturbed from cut and fill activities. A pipeline in a 3 feet wide trench disturbs .36 acres per mile.

A proposed horizontal drilling project on BLM lands in New Mexico provides an example of total land disturbed when multiple horizontal wells are drilled from one well pad (U.S. Department of the Interior Bureau of Land Management, 2022). The 4 well pads are estimated to disturb 29.8 acres and have up to 23 wells equaling 1.3 acres per well. When the land disturbed from the .14 miles of access roads, infrastructure and pipelines are include the acres per well increases to 2.2 acres per well.

To quantify a wide range of LESC on a per well basis, we assume 2 acres and 5 acres of land disturbed for each well drilled (inclusive of roads, infrastructure and pipelines) and base our estimates on average per acre LESC for 10 and 40 years of production ($69,668 and $113,726 per acre). For a well that produces for 10 years, LESC range from $139,336 to $348,340. For a well that produces from 40 years, LESC range from $227,452 to $568,629.

As a first order estimate of the magnitude of cumulative LESC totals from OGD on public land, we assume terrestrial ecosystems represent all acres of U.S public land. To provide a wide range we utilize the low LESC total for 10 years of production ($139,336) and the high LESC total for 40 years of production ($568,629). Multiplying the low and high LESC per well calculations by 90,298 producing wells results in $13 to $51 billion in LESC from OGD on U.S. public land.

5. Discussion

In this paper we develop and apply our model by calculating LESC for 32 oil and gas development scenarios. The logic behind our model is intuitive. LESC accumulate over time. The more years LESC accumulate the greater the total. LESC can be reduced if successful reclamation occurs. LESC can be reduced faster if successful reclamation rates are higher. Higher discount rates reduce LESC.

Research Question 1. LESC magnitude and variability. Our model shows that LESC per acre of disturbed land range from $26,051 to $250,709 representing a significant source of negative externalities. LESC are heterogenous and vary depending on years of production, interim reclamation rates, and final restoration rates. LESC will also vary depending on the ecosystem impacted and if rates of reclamation and restoration are non-linear, but this is a subject for future research.

Research Question 2. Incentives created. Our results show that internalizing LESC with impact fees could compensate public landowners and create financial incentives for OGC to reduce the initial disturbance footprint over time and increase reclamation rates. OGC also have incentive to decrease the number of years of energy production in order to reduce the number of years between reclamation and final restoration.

Using impact fees to internalize LESC provides OGC with incentives to invest in IRR during production and to invest in FRR post-production leading to improved stewardship of the land disturbed. The effectiveness of the restoration incentives is reduced as discount rates are increased.

While restoration of pre-disturbance conditions is the stated goal of BLM policy, current policy focuses on reclamation (Nauman et al., 2017): Under current BLM policy, the OGC are not actually responsible for achieving full site restoration. "Instead, the operator must achieve the short-term stability, visual, hydrological, and productivity objectives of the surface management agency and take the steps necessary to ensure that long-term objectives will be reached through natural processes" (U.S. Department of the Interior and U.S. Department of Agriculture, 2007, p. 44). Charging impact fees for LESC provides financial incentives for improving the effectiveness of BLM oil and gas policies at accomplishing the stated goal.

Research Question 3. First order estimate of total LESC revenue. The magnitude of LESC revenue is large as cumulative LESC from OGD on U. S. public land are in the billions of dollars. While further research is needed for more accurate calculations of total LESC, our initial estimates suggest additional research is justified.

Research on interim reclamation rates and final restoration rates by ecotypes is needed to refine the values used in the model. There is a need to establish measurable quantitative performance standards for measuring the effectiveness of reclamation practices at restoring ecosystem function (see DiStefano, 2022). While reclamation is meant to provide conditions for successful restoration, Rottler et al. (2017) found that current reclamation practices in Wyoming may not promote recovery of plant communities similar to undisturbed control areas. Monitoring is also needed to verify IRR and FRR and to identify additional inputs that might be needed to adjust the trajectory of restoration. Monitoring costs can be covered by impact fees, rental fees or as part of bonding.

While the focus here is on OGD, developing wind, solar and geothermal energy also results in LESC. Our method for quantifying LESC is applicable for estimating impact fees for LESC associated with developing renewable energy sources (Morton and Kerkvliet, 2023).

6. Conclusion

U.S. Office of Management and Budget (2023b) guidance for regulatory impact analysis directs federal agencies to include ecosystem services in benefit-cost analysis (Tallis et al., 2024). Internalizing LESC with impact fees is consistent with laws guiding BLM policies. Under the FLPMA, the BLM's organic statute, BLM is granted broad management discretion, but within limits. These limits direct BLM to prevent unnecessary and undue land degradation, avoid permanent impairment, ensure sustained yield of natural resources, provide for multiple uses, and include multigenerational values in its decisions.

Incorporating LESC into BLM's policies has several advantages. First, it provides a unifying framework for representing myriad points of view and broad representation in natural resource policy debates. Second, interests and values represented in LESC, such as recreation, livestock grazing, the social costs of carbon, and fossil fuel provisioning services can all be represented in a consistent fashion in natural resource management plans. Third, an ecosystem services framework can reveal knowledge gaps and analytical needs for directing useful research efforts. Fourth, incorporating LESC provides important information needed to guide oil and gas development away from public lands that provide high values for non-fossil fuel provisioning ecosystem services. Fifth, LESC are amenable to the cost-benefit analyses required by the Office of Management and Budget to inform proposed regulatory changes (Nallur et al., 2020).

Internalizing LESC with impacts fees is consistent with the letter and spirit of FLPMA. Charging impact fees for LESC is consistent with recommendations to design policy incentives to drive adoption of innovation and "nature-based solutions" (Tallis et al., 2024). The BLM can however, use our model even if impact fees are not being charged. BLM planners can use our model to calculate LESC when evaluating reasonably foreseeable oil and gas development scenarios in resource management plans. Our model provides one method to calculate cumulative environmental impacts of plan alternatives as measured by LESC.

CRediT authorship contribution statement

Pete Morton: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joe Kerkvliet:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

An early version of our model was presented to members of the Navajo Nation and at an Oregon State University Applied Economics Seminar. Our paper also benefited from comments from two anonymous reviewers.

Data availability

Data will be made available on request.

References

Allred, R., et al., 2015. Ecosystem services lost to oil and gas in North America. Science 348 (6233), 401–402.
Avirmed, O. W. Lauenroth, Burke, I., Mobley, M., 2015. Sagebrush steppe recovery on 30-90-year-old abandoned oil and gas wells. Ecosphere 6, 115.
Bonetti, P., Leuz, C., Michelon, G., 2021. Large-sample evidence on the impact of unconventional oil and gas development on surface waters. Science 373, 896–902.
Bradshaw, A., 1987. The reclamation of derelict land and the ecology of ecosystems. In: Jordan, W.R., Gilpin, M.E., Aber, J.D. (Eds.), Restoration Ecology: A Synthetic Approach to Ecological Research. Cambridge University Press, Cambridge, UK, pp. 53–74.
Burge, G., Ihlanfeldt, K., 2013. Promoting sustainable land development patterns through impact Fee programs. In: Cityscape: A Journal of Policy Development and Research, 15, pp. 83–105.
Chen, H., Sloggy, M., 2023. Boundary of ecosystem services: guiding future development and application of the ecosystem services concepts. J. Environ. Manag. 344, 1–6.
Chomphosy, H., Varriano, S., 2021. Ecosystem Services Benefits from the restoration of non-producing U.S. oil and gas lands. Nat. Sustain. 4, 547–554.
Costanza, R., de Groot, R., Sutton, P., et al., 2014. Changes in the global value of ecosystem services. Global Environ. Change 26, 152–158.
Davis, K., Nguyen, M., McChung, M., Moran, M., 2018. A comparison of the impacts of wind energy and unconventional gas development on land-use and ecosystem services: an example from the Anadarko Basin: Oklahoma. Environ. Manag. 61, 796–804.
DeGroot, R. L. Brander, Vander Ploeg, S., Costanza, R., Bernard, F., Braat, Leon, Christie, M., Crossman, N., Ghermand, A., Hein, L., Hussaij, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L., Brink, P., van Beukering, P., 2012. Global estimates of the value of ecosystems and their services n monetary units. Ecosyst. Serv. 1, 50–61.
DiStefano, S., 2022. Oil and Gas Reclamation on US Public Lands: Improving the Process with Land Potential Concepts. University of Idaho. Ph.D. Dissertation.
Freeman, L., 2022. Aging US shale wells: years of remaining opportunities or growing asset retirement obligations? J. Petrol. Technol. 74, 10=15. https://jpt.spe.org/aging-us-shale-wells-years-of-remaining-opportunities-or-growing-asset-retirement-obligations.
Gann, G.D., McDonald, T., Walder, B., Aronson, J., Nelson, C.R., Jonson, J., et al., 2019. International principles and standards for the practice of ecological restoration. In: Restoration Ecology, second ed., vol. 27, pp. S1–S46.
Hill, H., Ma, L., 2021. The fracking concern with water quality. Science 373, 853–854.
Hood, G., 2015. In: Colorado, What's the Lifespan of an Oil and Gas Well? Colorado Public Radio. https://www.cpr.org/2015/07/14/in-colorado-whats-the-lifespan-of-an-oil-and-gas-well/.
Jacobs, T., 2020. Life after 5: how tight-oil wells grow old. J. Petrol. Technol. https://jpt.spe.org/life-after-5-how-tight-oil-wells-grow-old. (Accessed 21 January 2020).
Jones, N., Pejchar, L., Kiesecker, J., 2015. The energy footprint: how oil, natural gas, and wind energy affect land for biodiversity and the flow of ecosystem services. Bioscience 65, 290–301.
Kerkvliet, J., 2012. Making estimates of ecosystem services useful. Int. J. Wilder. 18, 4–7.
Kline, J., Massotta, M., 2013. Applying the ecosystem services concept to public land management. Agric. Resour. Econ. Rev. 42, 139–158.
Libby, L., Carrion, C., 2004. Development Impact Fees. Ohio State University Community Development Extension Fact Sheet. CDFS-1558-04.
McClung, M., Moran, M., 2018. Understanding and mitigating impacts of unconventional oil and gas development on land-use and ecosystem services in the U.S. Curr. Opin. Environ. Sci. Health 3, 19–26.
Minnick, T., Alward, R., 2015. Plant-soil feedbacks and the partial recovery of soil spatial patterns on abandoned well pads in a sagebrush shrubland. Ecol. Appl. 25, 3–10.
Monroe, A., Aldridge, C., O'Donnell, M., Manier, D., Homer, C., Anderson, P., 2020. Using remote sensing products to predict recovery of vegetation across space and time following energy development. Ecol. Indicat. 110, 05872.
Monroe, Nauman, A.T., Aldridge, C., O'Donnell, M., et al., 2022. Assessing vegetation recovery from energy development using a dynamic reference approach. Ecol. Evol. 12, e8508. https://doi.org/10.1002/ece3.8508.
Moran, M., Taylor, N., Mullins, T., Sardar, S., McClung, M., 2017. Land-use and ecosystem services costs of unconventional US oil and gas development. Front. Ecol. Environ, 15, 237–242.
Morton, P., Weller, C., Thomson, J., Haefele, M., Culver, N., 2004. Drilling in the rockies: how much and what cost? Special Energy Session of the 69th North American Wildlife and Natural Resources Conference. Spokane, WA. Wildlife Management Institute, Washington, DC, p. 33.
Morton, P., Kerkvliet, J., Hjerpe, E., 2022. Impact fees, bonding reform, and oil and gas development. Colorado Environ. Law J. 33, 103–149.
Morton, P., Kerkvliet, J., 2023. The land and water conservation fund at 60: revenue options for the next 60 years. Conserv. Econ. Inst.
Nallur, V., McClung, M., Moran, M., 2020. Potential for reclamation of abandoned gas wells to restore ecosystem services in Fayetteville shale of Arkansas. Environ. Manag. 66, 81–90.
National Ecosystem Services Partnership, 2014. Federal resource management and ecosystem services guidebook. National Ecosystem Services Partnership. Duke University, Durham. https://nespguidebook.com/ecosystem-services-and-federal-agencies/bureau-of-land-management/. (Accessed 1 December 2024).
Nauman, T., et al., 2017. Disturbance automated reference toolset (DART): assessing patterns in ecological recovery from energy development on the Colorado Plateau. Sci. Total Environ. 584–585, 476–488. https://doi.org/10.1016/j.scitotenv.2017.01.034.
Nelson, A., Nicholas, J., Juergensmeyer, J., 2017. Impact Fees: Principles and Practice of Proportionate-Share Development Fees. Taylor and Francis Publishing.
Nicholas, J., Juergensmeyer, J., 2003. Market based approaches to environmental preservation: to environmental mitigation fees and beyond. Nat. Resour. J. 43, 837–863.
Ott, J., Hanberry, B., Khalil, M., Paschke, M., Post, M., van der Burg, M., Prenni, A., 2021. Energy development and production in the Great Plains: implications and mitigation opportunities. Rangel. Ecol. Manag. 78, 257–272.
Pleune, J., Ruple, J., Culver, N., 2021. The BLM's duty to incorporate climate science into permitting practices and a proposal for implementing a net-zero requirement into oil and gas permitting. Colorado Nat. Resour. Energy Environ. Law Rev. 32, 253–340.
Preston, T., Kim, K., 2016. Land cover changes associated with recent energy development in the Williston Basin; Northern Great Plains, USA. Sci. Total Environ. 566–567, 1511–1518. https://doi.org/10.1016/j.scitotenv.2016.06.038.
Raimi, Krupnick, J.A., Shah, J., Thompson, A., 2021. Decommissioning orphaned and abandoned oil and gas wells: new estimates and cost drivers. Environ. Sci. Technol. 55, 10224–10230, 2021.
Rottler, C., Burke, I., Palmquist, K., Bradford, J., Lauenroth, W., 2017. Current reclamation practices after oil and gas development do not speed up succession or plant community recovery in big sagebrush ecosystems in Wyoming. Restor. Ecol. 26, 114–123.

Stanford University, 2024. Drilling, completing, and producing from oil and natural gas wells. https://understand-energy.stanford.edu/energy-resources/fossil-fuel-energy/drilling-completing-and-producing-oil-and-natural-gas-wells.

Tallis, et al., 2024. Mainstreaming nature in US federal policy. Science 385 (6708). (Accessed 2 August 2024).

U.S. Department of the Interior and U.S. Department of Agriculture (USDOI and USFS), 2007. Surface Operating Standards and Guidelines for Oil and Gas Exploration and Development. BLM/WO/ST-06/021+3071/REV 07. Bureau of Land Management, Denver, Colorado, p. 84.

U.S. Department of the Interior Bureau of Land Management, 2013. Guidance on estimating nonmarket environmental values. In: Instruction Memorandum 2013-131 Ch.1. Washington D.C. https://www.blm.gov/policy/im-2013-131-ch1.

U.S. Department of the Interior Bureau of Land Management, 2022. DJR crow canyon unit I19, P19, C20, E20, crow canyon WSW/CLF well pads. In: Access Roads, Wells, and Pipelines Environmental Assessment. https://eplanning.blm.gov/eplanning-ui/project/2003311/510.

U.S. Department of the Interior, Bureau of Land Management, 2024a. Oil and Gas Statistics FY2023 (Table 1,2 and 9). Washington, D.C. https://www.blm.gov/programs-energy-and-minerals-oil-and-gas-oil-and-gas-statistics.

U.S. Department of the Interior, Bureau of Land Management, 2024b. About Oil and Gas. Washington, D.C. https://www.blm.gov/programs/energy-and-minerals/oil-and-gas/about.

U.S. Department of the Interior, Bureau of Land Management, 2024c. Onshore Oil and Gas Leasing Rule Fact Sheet – Bonding Updates. Washington, D.C. https://www.blm.gov/sites/default/files/docs/2024-04/BLM-Final-Onshore-Oil-and-Gas-Leasing-Rule-Bonding-Fact-sheet.pdf.

U.S. Department of the Interior, Bureau of Land Management, 2024d. Conservation and Landscape Health Final Rule. Washington, D.C.

U.S. Government Accountability Office, 2008. Federal User Fees: A Design Guide. GAO-08-386SP. Washington, D.C.

U.S. Government Accountability Office, 2010. Oil and Gas Bonds: Bonding Requirements and BLM Expenditures to Reclaim Orphaned Wells. GAO-10-245. Washington, DC.

U.S. Government Accountability Office, 2011. Oil and gas bonds: BLM needs a comprehensive strategy to better manage potential oil and gas well liability. GAO-11-292.

U.S Government Accountability Office, 2018. Oil and gas wells: Bureau of land management needs to improve its Data and oversight of its potential liabilities. GAO-18-250.

U.S. Government Accountability Office, 2019. Oil and Gas: Bureau of Land Management Should Address Risks from Insufficient Bonds to Reclaim Wells. GAO-19-615. Washington, DC.

U.S. Office of Management and Budget, 2023a. Guidelines and discount rates for benefit-cost analysis of federal programs. Circular NO. A-94. Revised, Nov. 9, 2023.

U.S. Office of Management and Budget, 2023b. Guidance for Assessing Changes in Environmental and Ecosystem Services in Benefit-Cost Analysis.

Walsh, K., Rose, J., 2022. A review of restoration techniques and outcomes for rangelands affected by oil and gas production in North America. Ecol. Restor. 40, 259–269.

Weller, C., Thomson, J., Morton, P., Aplet, G., 2002. Fragmenting our lands: the ecological footprint from oil and gas development. A Spatial Analysis of a Wyoming Gas Field. The Wilderness Society, Washington, DC, p. 24.