RESEARCH ARTICLE

A Review of Restoration Techniques and Outcomes for Rangelands Affected by Oil and Gas Production in North America

Kathryn Bills Walsh and Jackson Rose

ABSTRACT

Rangelands of the American West host over 600,000 oil and gas production sites. Domestic oil and gas extraction expanded during the last two decades, creating restoration needs. This review article synthesizes the growing body of literature on restoring arid and semi-arid rangelands of the U.S. and Canada following oil and gas production, including restoring soils, re-establishing vegetation, and preventing or mitigating any surface or water contamination. Existing studies reveal that even soils on treated sites are permanently changed by oil and gas production. However, certain in situ treatment techniques result in less bare ground and increased site revegetation on contaminated sites. Various reseeding techniques are effective, and research results promote the use of diverse, native, locally adapted seed, including plant species known to be better suited to specific post-production conditions. Research suggests that less grazing at restoration sites might generate better restoration outcomes than prolonged moderate or heavy grazing during the full season. Open questions remain regarding: 1) techniques for successfully remediating soil after oil and brine spills; 2) the use of cover crops to accelerate recovery of a perennial plant community suitable to the site; and 3) the effects of cattle grazing on restoration outcomes. Resources needed to complete restoration on an extensive scale are also discussed, including economic and labor requirements, as well as potential ecosystem service benefits.

Keywords: ecological restoration, oil and gas, rangelands, revegetation, review

Restoration Recap

- Rangelands of the American West host over 600,000 oil and gas production sites.
- This review article synthesizes the growing body of literature on restoring arid and semi-arid rangelands of the U.S. and Canada following oil and gas production.
- Soils on treated sites are permanently changed by oil and gas production but certain in situ treatment techniques (chemical amendments) result in less bare ground and increased site revegetation on contaminated sites.
- Prioritize diverse, native, locally adapted seed, including plant species known to be better suited to specific post-production conditions.
- Less grazing at restoration sites might generate better restoration outcomes than prolonged moderate or heavy grazing.

The increase in domestic oil and gas production during the last two decades has propelled the United States (U.S.) to the top of world production rankings, while also increasing the number of sites needing restoration after production ends in a variety of ecological contexts. Active production sites require restoration when production ends, as do the inventory of oil and gas wells that are currently abandoned, unplugged, or orphaned. Unplugged refers to wells that have not been properly sealed, are subject to deterioration, and therefore pose a greater risk of leaks and spills. Orphaned status refers to idle wells in which the operator is out of business, unknown, or has gone bankrupt. More broadly, abandoned status refers to any wells that have ceased to produce and are no longer actively managed, regardless of whether the operator is still in business or not.

Color version of this article is available through online subscription at: http://er.uwpress.org

doi:10.3368/er.40.4.259
Ecological Restoration Vol. 40, No. 4, 2022
ISSN 1522-4740 E-ISSN 1543-4079

The U.S. Environmental Protection Agency (U.S. EPA 2018) estimated that only one-third of abandoned wells have been plugged, leaving an inventory of as many as 2.3 to 3 million unplugged abandoned wells, inclusive of unplugged orphaned wells. This wide range in EPA's estimates is largely the result of limited data and records on the location and status of older wells drilled prior to the 1950s, although it is not atypical for oil and gas wells to be abandoned or orphaned today. As of 2018, there were at least 56,600 unplugged orphaned oil and gas wells documented across the U.S., and perhaps as many as 700,000 when including undocumented unplugged orphaned wells (Raimi et al. 2020) that have not undergone restoration. Together with an estimated 969,140 producing oil and gas wells in the U.S. (U.S. Energy Information Administration 2020), 600,000 in rangeland systems, the number of oil and gas wells and associated acreage potentially in need of restoration is extensive.

In the absence of restoration, wells can pose risks to groundwater quality and are a source of fugitive methane emissions (Townsend-Small et al. 2016). Additionally, surface disturbance contributes to habitat loss, the occurrence and spread of invasive species (Allred et al. 2015, Gaskin et al. 2021), and reduced ecosystem services (Moran et al. 2017). Both restoration and reclamation activities are undertaken after production ceases, and in some cases beforehand while the well is still producing. According to the Society for Ecological Restoration (SER), restoration is, "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (Gann et al. 2019, S7) while reclamation practices return the degraded landscape to some productive capacity with improved ecosystem functionality (Bradshaw 1987).

While research among the petroleum engineering community presents different technologies that are successful for well plugging (Achang et al. 2020, Akbari and Taghavi 2021), there has yet to be a comprehensive review of the scientific research on site restoration after oil and gas development, particularly in rangeland ecosystems. Many oil and gas production areas in the Great Plains and American West occur on rangelands, which support livestock production and provide critical habitat and ecosystem services (Moran et al. 2017, Brown and MacLeod 2018, Smith et al. 2020a) (Figure 1). Rangelands are defined as, "Land on which the indigenous vegetation (climax or natural potential) is predominantly grasses, grass-like plants, forbs, or shrubs and is managed as a natural ecosystem. If plants are introduced, they are managed similarly. Rangeland includes natural grasslands, savannas, shrublands, many deserts, tundras, alpine communities, marshes and meadows" (Society of Range Management 1998).

Generally, rangelands are relatively difficult to restore because of ecological constraints related to soil type, low precipitation, and erosion by wind and water (Norton and Strom 2013) which make unassisted ecosystem recovery,

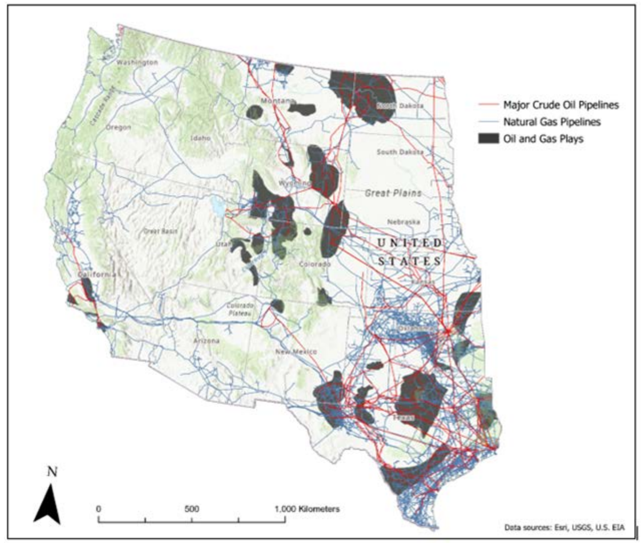

Figure 1. ***Oil and gas production footprint in the Western United States.*** **Many oil and gas plays, as well as pipeline infrastructure, overlay rangeland ecosystems.** *(Map author: Jackson Rose)*

or passive restoration, unlikely. The legacies of oil and gas production in U.S. rangelands include orphaned and abandoned wells along with the surface disturbances associated with a network of remaining infrastructure, such as access roads, power lines, pipelines, and compressor stations (Allred et al. 2015, Wolaver et al. 2018). Trainor et al. (2016) identify 'energy sprawl', or the land area required for energy resource production, as the most significant driver of land-use change in the U.S. between 2012 and 2040. The authors found that, by the year 2040, the landscape impacts of oil and gas production, or the total land area required for production including the direct footprint and spacing requirements, will affect at least 589,882 km^2 in the U.S., which is an area greater than the state of California.

In the U.S., there is no overarching federal legislation regulating restoration and reclamation activities for oil and gas production sites (Zirogiannis et al. 2016). Instead, states are responsible for governing how wells, well pads, and other oil and gas infrastructure are restored after production ends. Legislative variability from state-to-state produces different restoration outcomes across geographies. Restoration is regulated differently in Canada and certain criteria must be met to obtain a reclamation certification and liability release. Criteria are based on legislative requirements which do not necessarily include all recommendations from the latest scientific research. This paper includes results of research studying restoration techniques in Canadian rangelands to summarize the available science in the broader North American context.

The Infrastructure Investments and Jobs Act, signed by President Biden in November 2021, assigns $4.7 billion to orphaned well site plugging, remediation, and restoration. Funds will support federal and state programs to (§ 40601):

1) identify, inventory, and prioritize orphaned wells for plugging and remediation; 2) plug, remediate, and reclaim orphaned wells; 3) measure emissions from orphaned wells and instances of groundwater or surface water contamination by orphaned wells; 4) remediate soil and restore native species habitat; 5) decommission or remove associated pipelines, facilities, and infrastructure; 6) identify and address any disproportionate burden of adverse health or environmental effects of orphaned wells on communities of color, low-income communities, and Tribal and indigenous communities; 7) support the administrative costs of program development and implementation.

Here, we present an overview of the known environmental effects of oil and gas production, followed by a review of the existing research on restoring rangelands affected by oil and gas development. The review is organized around restoration techniques for eliminating contamination, restoring soil health, reseeding and revegetation, and understanding cattle grazing impacts on restoration efforts. The discussion section examines economic and environmental benefits along with the financial costs of undertaking restoration. Lastly, our conclusions suggest possible directions for future research on rangeland restoration.

Environmental Effects of Oil and Gas Production

A growing body of research has focused on assessing the environmental effects of oil and gas production (Jacquet 2014, Lave and Lutz 2014, Cooper et al. 2016). Even though many energy resource plays have yet to reach the end-of-life phase, some studies have exclusively focused on the legacies of oil and gas production (Davies et al. 2014, Allred et al. 2015, Kang et al. 2016). These related bodies of literature discuss the risk of fugitive methane emissions (Howarth 2014), the scale and severity of surface disturbance (Baynard et al. 2017, Pierre et al. 2020), soil health and revegetation (Arnold 2009, Varona-Torres et al. 2017), surface and groundwater contamination (Fontenot et al. 2013, Hildenbrand et al. 2015), habitat loss (Bernath-Plaisted and Koper 2016), and reclamation of abandoned wells and infrastructure (Ho et al. 2018, Nallur et al. 2020).

Ott et al. (2021) summarize research on the environmental impacts of energy production (both renewable and fossil fuels) on Great Plains grasslands. They determine that the primary ecological impacts of oil and gas production on grasslands are fragmentation and habitat loss, soil disturbance, loss of vegetation, and air, water, and terrestrial contamination. Importantly, the authors provide explicit recommendations for how environmental impacts can be mitigated throughout the energy planning and production phases, including techniques to restore vegetation. Our paper expands the work of Ott et al. (2021) by focusing on the final phase of energy development: reclamation and restoration. We focus, more specifically, on post-production rangeland restoration including remediating contamination, restoring soil health, reseeding and revegetation, and livestock grazing. We review recent publications and introduce economic analysis of post-production costs and labor inputs.

Environmental Effects of Rangeland Restoration

Rangelands cover about 30% of the area within the U.S. and host over 600,000 oil and gas wells (U.S. Energy Information Administration 2020). At least half of all U.S. shale energy resources occur on rangelands (Holechek and Sawalhah 2014). Chomphosy et al. (2021) found that U.S. grasslands/pasture contain at least 183,887 restoration-eligible wells covering a land area of 360,642 hectares. Restoration may occur on any or all components of an energy production site, including wells, well pads, and rights-of-way for access roads, powerlines, and pipelines (Figure 2).

Several studies show that active restoration of rangeland ecosystems after oil and gas production is important because passive restoration is unlikely to occur. Nasen et al. (2011) studied grasslands in southwestern Saskatchewan to determine the rate of recovery for thirty-one sites impacted by petroleum or natural gas development. No mitigation or reclamation work was undertaken at these sites post-production. The authors found that impacts persisted for at least fifty years after abandonment, including low range-health scores and high diversity and species richness of undesirable species on lease sites compared to reference sites. In sagebrush steppe ecosystems of southern Wyoming, Avirmed et al. (2015) found that, without any restoration, sagebrush took at least eighty-seven years to recover naturally, and forbs showed no signs of recovery over the same time period. Forbs are herbaceous flowering plants that are critical to species richness. Similarly, study sites in southwestern Wyoming showed a lack of forb re-establishment (Rottler et al. 2017). Additional studies have revealed that colonization of native plant communities into areas previously disturbed by oil and gas activity is limited (Simmers and Galatowitsch 2010, Viall et al. 2011). In other words, it is highly unlikely that adjacent native rangelands will successfully colonize a disturbed site, even decades later.

Even with restoration, ecosystem recovery is not guaranteed (Rottler et al. 2017). Sylvain et al. (2019) examined oil and gas production sites in western North Dakota that had been reclaimed between two and thirty-three years ago. Exact reclamation methods were unknown due to inadequate records, but it is likely that various reclamation practices were employed across sites. The authors found that, even three decades after reclamation, soils and plant communities on reclaimed land did not match those on undisturbed rangeland. Specifically, soil salinity was higher and reclaimed areas had less plant cover overall, more exotic plant cover, and less species richness among native plant species compared to undisturbed

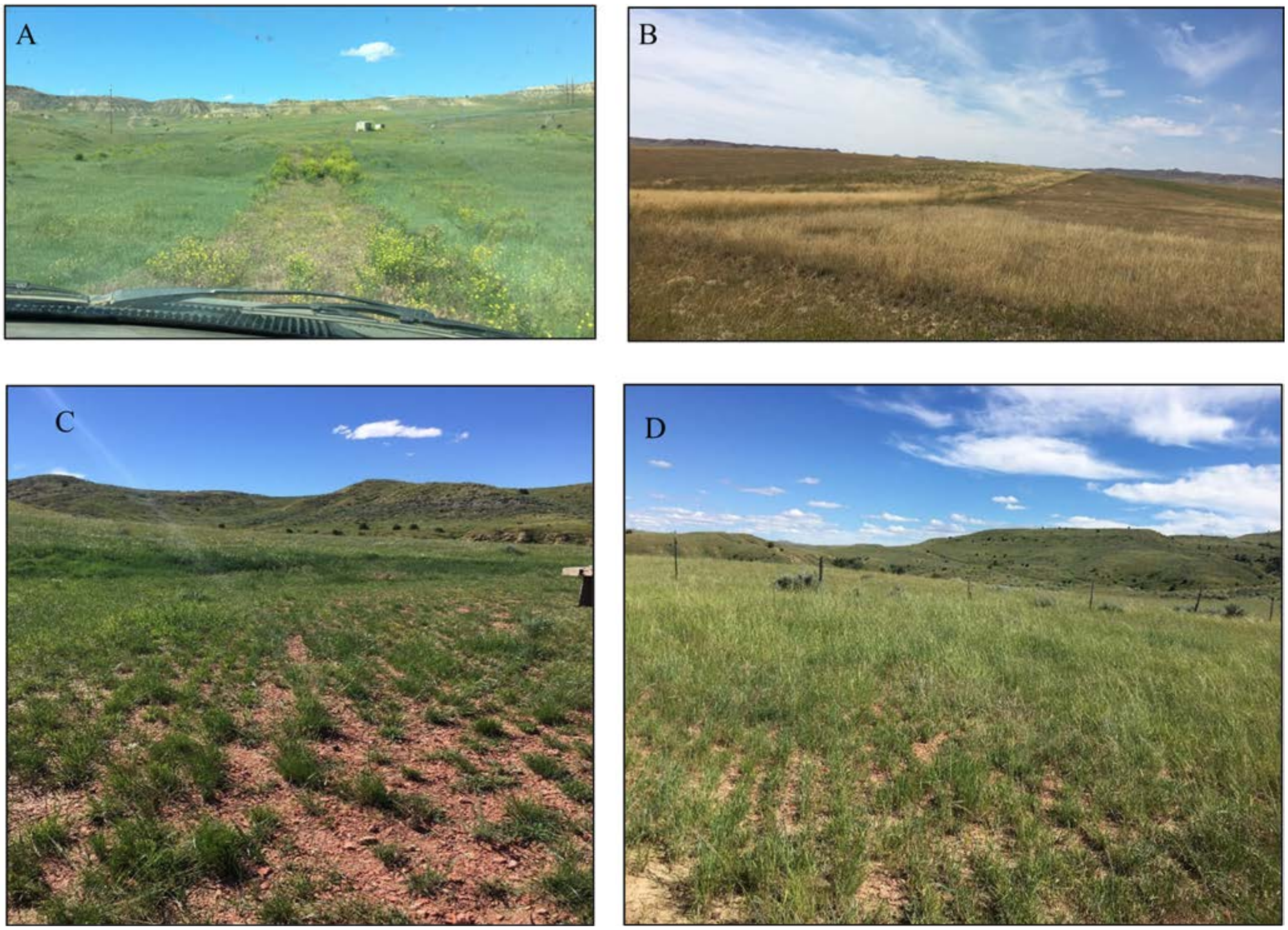

Figure 2. A) An un-restored coalbed methane access road in northeastern Wyoming rangelands. B) Revegetation of a natural gas pipeline infrastructure site in northeastern Wyoming rangelands. C) A restored and revegetated coalbed methane well site in northeastern Wyoming rangelands. D) A restored and revegetated coalbed methane well site in northeastern Wyoming rangelands. *(Photo credit: Authors)*

prairie (Sylvain et al. 2019). However, nematode communities did fully recover on reclaimed sites. Insights from Sylvain et al. (2019) and other rangeland reclamation studies that we review can help improve rangeland restoration of oil and gas production sites by identifying techniques that have been scientifically tested and shown to have some promise.

Literature Search for This Review

We used a systematic search method to gather literature that reports on restoration techniques for rangelands affected by oil and gas production. We queried key academic databases, including Academic Search Complete, ProQuest Central, and Science Direct, using several keywords (i.e., rangelands, grasslands, restoration, oil, gas, energy, reclamation) to identify relevant literature. Criteria for inclusion were studies: 1) conducted in rangelands in the U.S or Canada; 2) examining surface restoration after oil and gas production; 3) published in a peer-reviewed academic journals; and 4) producing original research results (e.g., not review articles or perspectives pieces). To further ensure a thorough search, article reference lists were used as another tool to locate appropriate scholarship for review. Our searches recovered 137 research articles that potentially fit the scope of this paper. Upon review, articles that did not fit our criteria because they were related to mining, social science, spatial science, data science, and non-oil and gas disturbance were excluded. In total, findings from nineteen discrete research articles published between 2004–2020 are described in this paper.

Rangeland Restoration after Oil and Gas Development

From Saskatchewan, Canada, to Texas, U.S., studies of post-production rangeland restoration span vast geographies and diverse landscapes. Across North American rangelands there is significant variability in soils, precipitation, plant species, and elevation, which influence the success of restoration efforts. Rangeland vegetation types within the western U.S. alone include shortgrass, mixed-grass, and tallgrass prairies, desert grasslands and shrublands, and sagebrush steppe. As described in much of the research included in this review, restoration techniques tailored to local conditions typically produce more desirable outcomes (Falk et al. 2017, Wester et al. 2019).

Reducing Contamination and Restoring Soil Health

The first strategy to reduce environmental hazard after oil and gas production is to properly plug the well. Unplugged or improperly plugged wells can cause ecological damage, for example, as a source of fugitive emissions, or by contaminating nearby surface and groundwater (Mitchell and Casman 2011). Despite extensive research on well integrity (Davies et al. 2014, Kiran et al. 2017, Al Ramadan et al. 2019), spills are a common source of site contamination, which can result from improperly plugged wells and trigger a need for remediation.

Although significant research has been conducted to better understand spill remediation in water bodies (Nordvik et al. 1996) as well as tropical rain forests (Odokuma and Dickson 2003) and wetlands (DeLaune and Wright 2011, Sam and Zabbey 2018), fewer studies have examined techniques to restore rangelands after oil or brine spills (Meehan et al. 2017). Brine is byproduct water that often contains high soluble salts and a wide array of other constituents. Oil and brine spills range in volume and extent, though they generally impair soils and inhibit vegetation growth (Dornbusch et al. 2020).

Dornbusch et al. (2020) examined the efficacy of in situ and ex situ brine spill soil remediation techniques in North Dakota's portion of the Bakken formation. The authors compared conditions on paired undisturbed reference sites to conditions on ten sites where remediation was conducted by applying chemical amendments (in situ) and eleven sites where remediation was done by excavating topsoil (ex situ). After remediation, they found evidence of brine contamination at all soil depths tested at both in situ and ex situ treatment sites. However, plots remediated with chemical amendments (i.e., in situ remediation) had just 15% more bare ground than reference sites, whereas sites that featured topsoil excavation (ex situ remediation) had 55% more bare ground than the reference sites. Dornbusch et al. (2020) concluded that in situ strategies create less surface disturbance, increase revegetation, and require less management than ex situ techniques. Klaustermeier et al. (2017) found that the use of crystallization inhibitors helped to remediate brine contaminated soils in North Dakota, especially if applied soon after spill occurrence. Crystallization inhibitors limit the amount of salt migration at the spill site and promote soil conservation since this method does not require excavation. Avirmed et al.'s (2014) Wyoming study suggests that the practice of removing and stockpiling soils increases the loss of soil organic matter.

Other in situ techniques have been used to remediate oil spills, namely in situ burning (Walton and Jason 1998), although the bulk of research is focused on marine and shoreline applications. Anthony and Wang (2006) tested the feasibility of remediating oil-contaminated gravel by incineration. Results indicated that after incineration in a fluidized bed combustor, gravels were effectively decontaminated. However, this study did not test remediation of oil-contaminated soils, only gravel, and this technique is only feasible at small scales due to cost and the harm to microbial constituents in the soil. Additional research is needed to further examine in situ burning methods for remediating soils polluted by oil or brine spills, and whether altering soils by incineration improves quality enough to outweigh the degradation that results from burning.

Croat et al. (2020) studied the effects of crude oil soil remediation on wheat and field pea crop production in North Dakota's portion of the Bakken formation. Although this study concerns crop production, findings are relevant to rangelands because they speak to the efficacy of different soil remediation techniques in a region with similar ecological characteristics. The authors investigated the growth of both crops in soils remediated using two different strategies: 1) topsoil excavation and refilling with thermal-desorption treated soil (soil heated at low temperature), stockpiled soil, and/or noncontaminated soil; and 2) a modified landfarming technique. According to the U.S. Environmental Protection Agency, landfarming is "a remediation technology for soil that reduces concentrations of petroleum constituents through biodegradation" (U.S. EPA 1994, V-1). After three growing seasons, the authors found that "crop production was 61 ± 20% lower in modified land-farm soils and 52 ± 25% lower in thermal desorption treated soils" (Croat et al. 2020, 130) in comparison to native topsoil. Lower levels of soil organic carbon in the treated soils contributed to reduced yields. The authors indicate that soil mixing techniques, where remediated soil is mixed with native undisturbed soil, are helpful for cropland soil restoration because the resulting soil organic carbon levels and protein content more closely match that of native soils.

Remediating soil contamination is the first step in restoring soil health within rangelands impacted by oil and gas production. Even without spills, the construction and productions phases of energy development involve removing, compacting, or otherwise degrading topsoil. Wester et al. (2019) studied soil restoration in semi-arid grasslands of south Texas after pipeline development. They studied 126 plots, each treated with a different combination of physical (erosion control blanket), chemical (humic substance), and biological (native seed mix vs. native + cover crop seed mix) amendments. Compared to adjacent undisturbed soil, the authors found that all soil properties were changed by pipeline construction and that the application of chemical (humic) substances made no significant difference. Use of an erosion control blanket, however, was associated with higher soil water content and cooler soil temperatures, as well as the emergence of 3–8 more seedlings/0.09 m^2 (or 3–8 more seedlings per square foot). As for seed mix, the authors found that, "seeded plots had more native grass biomass than non-seeded plots" (Wester et al. 2019, 28) but native species biomass did not differ on the plots seeded only with native species versus those seeded with native species plus the cover crops.

Reseeding and Revegetation

Strategies for reseeding and revegetation in rangeland restoration have long-term implications for the landscape (Espeland 2014). In a study of fifty-eight restored oil access roads in western North Dakota grasslands, Simmers and Galatowitsch (2010) compared the extant vegetation at sites restored between three and twenty-two years prior to original seeding records. Findings revealed a higher percent cover of seeded species than non-seeded species on roadbeds, suggesting that seed mixes do in fact have direct and lasting influence on restoration outcomes.

Falk et al. (2017) studied the restoration of four oil and gas well sites in south Texas using diverse, native, locally adapted seed sources—or ecotypic seeds. They evaluated vegetative reestablishment and found that, seven months after seeding, species were restored at a density of ≥ 0.9 seeded plants/m^2, with eight different native species present on average. They concluded that an optimal seed mix includes diverse native grasses, legumes, shrubs, and forbs specifically suited to the local geography, soil conditions, and climate. Another study found, for pipeline restoration in south Texas, that "locally-adapted native seeds are preferable" (Wester et al. 2019, 33). That said, an emerging body of research suggests that plant traits vary more widely within the same species than previously thought, even at the same location (Havrilla et al. 2021). More specifically, individual plants can dynamically change which traits they express at different growth stages depending on environmental conditions. This emerging insight may have important implications for ecological restoration.

For sites with contaminated soils, Robson et al. (2004) identified hydrocarbon-tolerant plant species that might be desirable for restoration. Their study examined vegetation and soils on 14 hydrocarbon contaminated sites compared to uncontaminated plots in mixed grasslands of southern Saskatchewan. The authors found that certain plant species and functional groups can persist in contaminated soil conditions, including *Hordeum jubatum* (foxtail barley), *Distichlis spicata* (desert saltgrass), *Pascopyrum smithii* (western wheatgrass), *Elymus trachycaulus* (slender wheatgrass), and *Poa canbyi* (canby bluegrass). However, uncontaminated plots (i.e., those with less hydrocarbon concentration in the soil) had more vegetation and litter cover.

In addition to strategic plant selection for reseeding, research has also shown that various reseeding techniques can be used to promote more successful revegetation. Pawelek et al. (2015) found that broadcast seeding, no-till drill seeding, and hydroseeding of ecotypic native seed mixes were all successful at restoring pipeline rights-of-way in south Texas. By analyzing fifteen different combinations of restoration techniques on five natural gas well pads in western Colorado, Eldridge et al. (2012) found that traditional broadcasting (scattering seed to blanket a relatively large area) was preferable to the island broadcasting method (creating separate vegetative islands of shrubs and forbs using different seed mixes broadcast in separate areas) in reducing presence and cover of noxious species. Results from a study in south Texas recommends that, "seeds should be broadcast seeded onto a clean seedbed and rolled or culti-packed to improve seed-soil contact" (Wester et al. 2019, 33).

Mulch can also promote seedling reestablishment on restoration sites, especially where temperature and rainfall conditions are less favorable (Wester et al. 2019). In the northern mixed-grass prairie of southern Alberta, Canada, Mollard et al. (2016) found that amending seedbeds with mulch (wheat straw and rangeland hay) facilitated early revegetation by conserving soil water. Similarly, Desserud and Hugenholtz (2017) found that oil and gas well sites in the mixed-grass prairie of Alberta, Canada, showed very good recovery seven years after being reseeded with native hay as vegetative cover was consistent with adjacent undisturbed grassland and many mixed-grass species were present.

A few studies have examined the influence of cover crops on restoration success. In a south Texas study, researchers found that inclusion of a warm season cover crop on restoration sites was beneficial when suited to local conditions (Wester et al. 2019). However, Espeland et al. (2017) determined that applying cover crop and grass-mix treatments did not significantly contribute to the establishment of perennial grass in their study of oilfield restoration in northwestern North Dakota. To assess whether cover crops accelerate site recovery, the authors compared a perennial grass mix in the absence of cover crops to that same grass mix with two different cover crop treatments: one with an oat cover crop, and another with a "cover crop cocktail". Rangeland health was only slightly greater on sites where a cover crop was planted, with reestablishment driven primarily by soil nutrients that were not necessarily linked to cover crop treatments.

Cattle Grazing Effects on Restoration Outcomes

Oil and gas development on rangelands often occurs on lands used for grazing. However, a limited number of studies examine cattle grazing effects on restoration outcomes, with varied results. In a study of revegetation of oil pads in south Texas using locally adapted plant species, cattle grazing had very minor impact on the plant community and had no effect on species richness (Falk et al. 2017). On the other hand, Koper et al. (2014) studied the effects of livestock grazing on vegetation surrounding shallow natural gas wells in the mixed-grass prairies of southern Alberta, Canada, and found that grazing did contribute to shorter, sparser vegetation near wells.

Desserud and Naeth (2014) analyzed how temperate grassland plant communities changed after oil and gas activities and grazing in central Alberta, Canada, over an eleven-year period. The authors compared no, low, moderate, and heavy grazing on oil and gas production sites that ranged from being minimally disturbed (i.e., small well sites) to majorly disturbed (i.e., topsoil stripping). Results indicated that heavy grazing (maximum AUM level during full growing season) caused a complete change in the state of plant communities; specifically, it increased bare ground and presence of unwanted species like *Bromus inermis* (smooth brome). Light or no grazing did not result in these effects, whereas moderate grazing (60% of maximum AUM) had the potential to alter the state of plant communities into a different stable state or to mimic undisturbed conditions.

Economics of Restoration

The almost one million wells producing oil and gas in the U.S. today (U.S. Energy Information Administration 2020) raises questions about future resource needs to implement effective restoration at an extensive scale. For example, studies recommend application of native seeds for optimal restoration outcomes in rangeland systems (Falk et al. 2017, Wester et al. 2019). Considering the level of oil and gas activity occurring in the Permian Basin of west Texas, Smith et al. (2020b) examined the native seed supply that would be required to restore all production sites in the region. They estimate that 247,000–1,330,000 pounds (112,000–603,00 kilograms) of pure live seed of native grasses would be required to restore land altered by oil and gas through the year 2050 at a cost of $10–57 million USD. The broad ranges they report account for low, medium, and high oil and gas production projections through 2050.

In an analysis of 19,500 orphaned wells, the median cost of orphaned well plugging and surface restoration was about $76,000 per well (Raimi et al. 2021a) with deeper and older wells being more expensive to restore. It would therefore cost an estimated $4.9 billion to plug and restore the surface of all (approximately 56,000) U.S. orphaned well sites, an estimate closely aligned with by $4.7 billion allocated by the 2021 Infrastructure Investment and Jobs Act. Doing so would also reduce methane emissions by 7,400 metric tons per year (Raimi et al. 2021b). Chomphosy et al. (2021) identified 430,000 restorable wells across the U.S. and found that the potential value of ecosystem service benefits that could be derived from restoring these sites is $21 billion. Although the study did not consider rangelands specifically, restoring wells in grassland ecosystems was deemed to have one of the highest returns on investment in terms of environmental and other economic benefits.

An expanded workforce would be needed to conduct restoration work at a national scale on lands impacted by oil and gas development. Although restoration costs are high, job growth in this sector also generates economic benefits for workers and their local communities. Pollin and Chakraborty (2020) estimate that, for every $1 million invested in plugging and restoring orphaned oil and gas wells, 7.1 direct jobs are created. Using this estimate, Raimi et al. (2021b) surmise that at least 28,400 direct jobs could be created over five years in this specific sector.

Discussion

Restoration science can help inform future financial and human capital investments in the restoration of rangelands affected by oil and gas production by identifying tested techniques that are most likely to produce desired outcomes. Research on soil remediation has revealed that treated sites are even permanently changed by oil and gas production, but that chemical remediation (in situ) techniques for brine-contaminated soils result in less bare ground and increased site revegetation (Dornbusch et al. 2020). To restore soil contaminated with oil, Croat et al. (2020) demonstrate the effectiveness of soil mixing techniques at mitigating reduced crop yields on contaminated sites. The limited research on in situ burning to decontaminate polluted soils suggests that incineration techniques might effectively remediate soil (Anthony and Wang 2006), but additional research is needed to study the effects of incineration on soils exposed to different types and levels of pollutants and to expand and improve techniques for remediating soils polluted by oil or brine spills. For example, research about bioremediation, or using microbes or plants to uptake toxins, in the context of rangelands is one area for potential research. Following decontamination of soils, or for soils that have been disturbed but not contaminated (e.g., pipeline construction sites), other soil restoration research has revealed that the application of an erosion control blanket increases soil water content, reduces soil temperature, and facilitates site revegetation (Wester et al. 2019).

For the reseeding phase of restoration, the literature strongly suggests the use of diverse, native, locally adapted seed (Falk et al. 2017, Wester et al. 2019), including plant species known to be better suited to specific post-production conditions (Robson et al. 2004). Future studies should still consider whether the added cost and effort of acquiring locally adapted seeds is reflected in better restoration outcomes. A recent study considering restoration of the Great Basin, U.S. suggests that an evolutionary perspective to restoration ecology is needed, specifically, "Adjusting seed-selection priorities to account for the existence of locally adapted, intraspecific variation" to support resilient plant communities (Baughman et al. 2019, 6272). Moreover, local conditions are shifting due to climate change with some researchers emphasizing the importance of climate-appropriate restoration using seed species suited for changing conditions (McKone and Hernández 2021). Hardegree et al. (2018) describe a weather-centric approach to revegetation where reseeding is timed for greatest potential success of seedling reestablishment using projections based on site-specific historical weather observations and climate data along with associated ecological site conditions.

Various reseeding techniques are effective, such as broadcast seeding, no-till drill seeding, and hydroseeding, especially when applied to a clean seedbed with measures taken to improve seed-soil contact (Eldridge et al. 2012, Pawelek et al. 2015, Wester et al. 2019). Subsequent mulching of seedbeds also enhances site recovery (Mollard et al. 2016, Desserud and Hugenholtz 2017, Wester et al. 2019). Additional research is needed, however, to more comprehensively test and determine whether cover crops influence rangeland restoration outcomes after oil and gas production. In this context, cover crop research should both consider potential ecological benefits as well as the time and expense of implementation.

Similarly, future studies should research the effects of livestock grazing on rangeland restoration outcomes to analyze different grazing intensities across a wider array of rangeland geographies. Nonetheless, a few practical tips have emerged from the limited amount of existing research, such as installing 'rubbing posts' and other cattle attractants (e.g., food, water, minerals) away from restoration sites within a grazing allotment or pasture to reduce undesired grazing impacts (Koper et al. 2014). Targeted livestock grazing, using fencing, herding, or supplement placement, can be used to alter the distribution of livestock away from restoration efforts (Bailey et al. 2019). Although a clear consensus has not yet emerged, initial research suggests that light or no grazing at restoration sites might generate better restoration outcomes than moderate or heavy grazing (Desserud and Naeth 2014).

Conclusion

Restoring rangelands affected by oil and gas production is challenging but necessary for eliminating contamination, mitigating surface disturbance, and enhancing ecosystem services. Increased attention to the scale and resources needed to execute extensive restoration across rangelands speaks to the need for synthetic reviews of the scientific literature to inform restoration project planning by identifying the most thoroughly tested and effective techniques.

Existing studies have revealed practical insights that can help guide current and ongoing restoration efforts; however, additional research to investigate restoration techniques in different rangelands systems could further enhance the quality and reduce the cost of restoration activities. Future research should consider expanding on existing studies of: 1) techniques for remediating soil after oil and brine spills; 2) the effects of cover crops on site recovery; and 3) the influence of different cattle grazing practices on restoration outcomes.

Acknowledgments

We would like to thank Julia Haggerty, Justin Derner, Dannele Peck, Lauren Porensky, and David Hoover for providing input on earlier drafts of this manuscript. Comments from the editor and two anonymous reviewers provided insightful feedback on earlier versions of this article.

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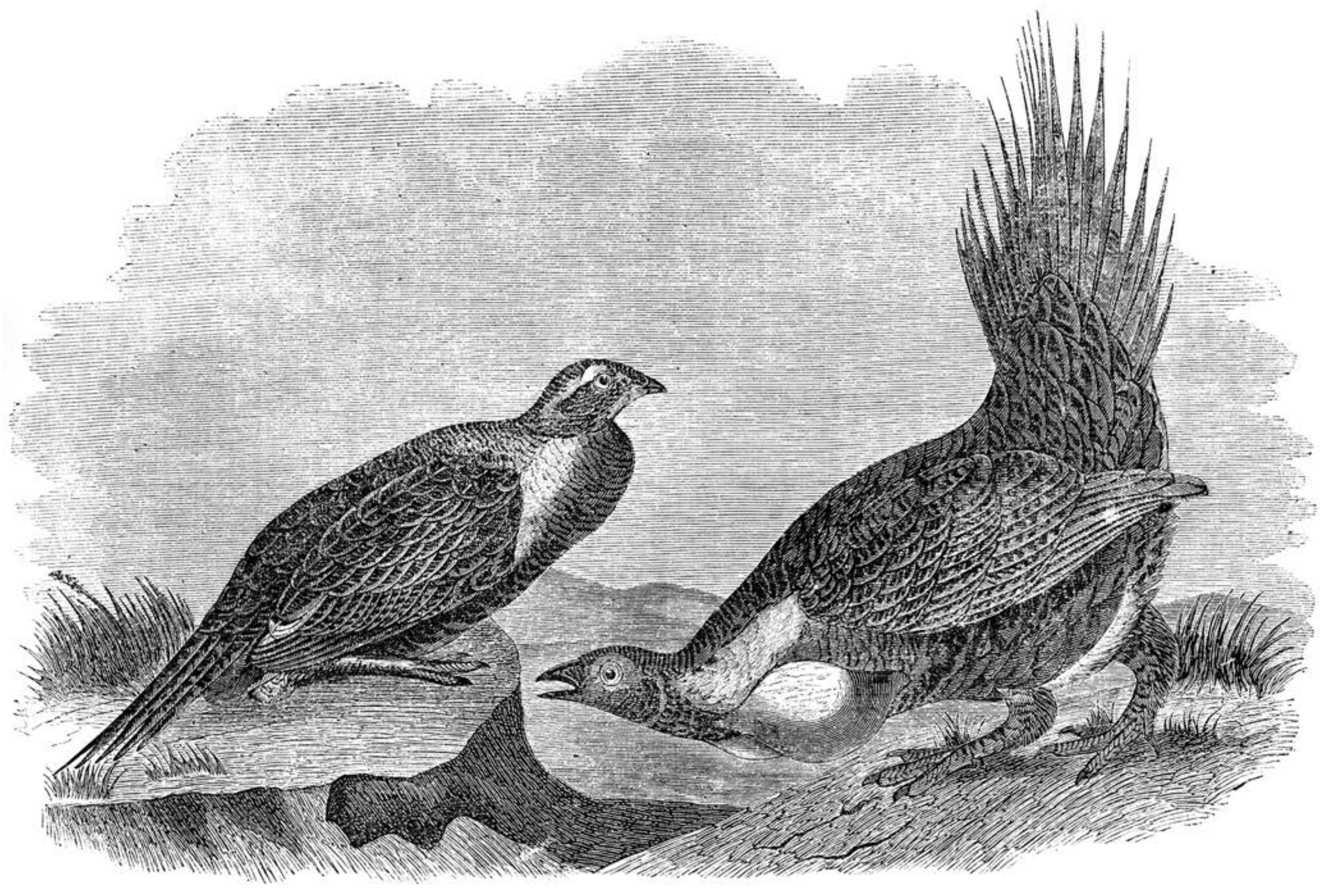
Kathryn Bills Walsh (corresponding author), Department of Natural Resources and the Environment, G20 Fernow Hall, Cornell University, Ithaca, NY 14853, kbw45@cornell.edu; (formerly U.S. Department of Agriculture–Agricultural Research Service, USDA Northern Plains Climate Hub).

Jackson Rose, Department of Earth Sciences, Montana State University, Bozeman, MT.



Greater sage grouse. *Centrocercus urophasianus.* Source: Commissioner of Agriculture Report for the year 1864 (Washington D.C.: Government printing office, 1865) 360, The Florida Center for Instructional Technology, College of Education, University of South Florida, fcit.usf.edu.