Oil and gas reclamation on US public lands: improving the process with land potential concepts

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Abstract

There is an increasing concern in the US for the current and long-term environmental impacts of oil and gas development such as severe habitat fragmentation, disruption of plant-water relationships, increased soil toxicity, and altered hydrology of landscapes. One of the primary areas of concern has been on public lands where the government is under a multiple use mandate to manage for all the ecosystem services a site has to offer. There is also a need to conduct monitoring on public lands affected by oil and gas development to quantify the impact of disturbance and ensure that management goals are being met (Derner et al., 2022; Jones et al., 2020). There are no standardized quantitative benchmarks or monitoring methods though for measuring long-term oil and gas reclamation effectiveness on public lands in the U.S. The methods and standards that do exist vary widely by location, are usually qualitative, and are often subjective to an individual reclamation manager’s opinion. This situation makes it difficult for the private industry to meet reclamation goals over large landscapes and across multiple regulatory entities.

In this dissertation, I evaluated the utility of using land potential in reclamation evaluations by 1) reviewing the current status of oil and gas reclamation on US public land, 2) defining land potential in the context of oil and gas reclamation, 3) conducting a time series analysis of reclaimed well pads before and after development, and 4) analyzing field data for reclaimed well pads of different times since reclamation completion (i.e., reclamation age), based on plant and soil traits found to be sensitive to oil and gas development. In the time series analysis, differences in reclamation management had a high impact on reclamation outcomes making it difficult to discern typical plant community structural changes at different reclamation ages. On the ground, I found that differences between reclamation ages was greatest between 5 years and 15 years, with 15 years appearing to experience the full effects of reclamation such as having a higher amount of native perennial grasses and decreased soil electrical conductivity. Additionally, I was able to evaluate for altered land potential based on a group of indicators and not by any individual indicator. Overall, I recommend that a group of indicators should be evaluated as a whole, preferably with data collected more than once before the final reclamation evaluation, and that a standardized set of methods should be used to improve the consistency and transparency of reclamation evaluation on US public land. By doing so, communication and collaboration between the federal government and private industry may improve to help alleviate the widespread loss of ecosystem services to oil and gas development on US public lands.

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Dedication

Thank you to my parents, Robert and Irene Perry, for instilling a love of the pursuit of knowledge into me at a young age and for supporting me financially, emotionally, and spiritually throughout my time in college. Thank you to my husband Ezequiel for being my rock and constant support. I could not have done this without your encouragement, patience, and love. Thank you to my sons, Miguel and Simon, for your love, kindness, and patience with your mom during the stressful times. You both are the light of my life and bring so much laughter and joy to me and your dad. Lastly, thank you to my great-grandmother Elma for fighting for your right to an education and starting a family tradition of women pursuing graduate degrees. I'm proud to carry on your legacy.

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Ch 1: Introduction

Oil and gas Reclamation on US Public Land

Approximately 3 million ha of land was approved for oil and gas development (roads, pads, pipelines) between 2000 and 2012 in an area spanning the central US through central provinces of Canada (Allred et al., 2015). On US public land, oil and gas development is primarily administered by the Bureau of Land Management (BLM) which oversees about 99 million surface ha (245 million acres) of public land and 283 million subsurface ha (700 million acres) with ~5 million subsurface ha (12.8 million acres) producing oil and gas in profitable quantities (Allred et al., 2015; Bureau of Land Management, 2021; Di Stéfano et al., 2021). As of 2022, drilling on public land has become an increasingly fraught process because of the moratorium on leasing for new wells starting in January 2021 which was later reversed in April 2022 in response to a global shift in sourcing for oil and natural gas resources (Davenport, 2022; U.S. Department of the Interior, 2021). Additionally, the presidential administration in 2022 committed $33 million to reclaim the more than 130,000 orphaned wells (i.e., abandoned wells lacking a legal owner) on public land which have caused "pollution, water contamination, and safety hazards" for many communities across the western US (Bureau of Land Management, 2022; DeFazio et al., 2021; U.S. Department of the Interior, 2022).

In some large landscapes, oil and gas development has created a vast network of discrete disturbances from well pads, pipelines, and connecting access roads. Examples of the direct and indirect effects of oil and gas development are habitat degradation, increased susceptibility to invasive plant species, and altered landscape hydrology, impacts which often impair or inhibit other important ecosystem values and permitted uses such as livestock grazing, wildlife habitat, and recreation.(Allred et al., 2015; Walker et al., 2007; Waller et al., 2018; Yu et al., 2015)

In the US there is no national standard for reclamation from oil and gas development, like there is for mining (Udall, 1977). On US public land there is patchwork of localized (e.g., States and BLM field office) reclamation requirements which makes it difficult to evaluate reclamation effectiveness on larger landscape scales (e.g., BLM district, state, region) (Di Stéfano et al., 2021). Additionally, reclamation actions are not well documented in publicly available records, preventing the sharing of information about the efficacy of various management actions across regulatory boundaries. The vastness of the impact of oil and gas development combined with the lack of reclamation information and regulation creates a seemingly impossible framework for land managers to move towards ecosystem recovery post-reclamation.

Objectives

The overarching goal for my dissertation was to define land potential relative to the unique soil and vegetative circumstances on reclaimed well pads and to develop a set of consistent land potential indicators that signaled long-term plant community recovery on reclaimed well pads. Specific objectives were:

1. Review the status of reclamation monitoring and practices within the BLM to understand how reclamation is currently managed and explore opportunities to improve BLM’s surface management following oil and gas development (Ch. 2).
2. Develop a functional definition of land potential with respect to reclaimed well pads and identify land-potential-based monitoring indicators for reclamation sites (Ch. 2).
3. Identify and evaluate the influence of management actions on reclamation outcomes using remotely sensed vegetation indices and time series analyses (Ch. 3).
4. Identify plant community trends and indicators of reclamation success at different times since reclamation completion (i.e., a chronosequence) (Ch. 4).
5. Develop a proposed, consistent monitoring and assessment framework of soil and vegetation indicators to determine the trajectory of a site’s plant community relative to its potential (Ch. 5).

Land Potential

Land potential concepts are used by the BLM and other resource managers in planning and decision processes and are generally not used used in oil and gas management.(Bestelmeyer et al., 2015) Land potential refers to the types and amounts of vegetation that can occur at a site given the circumstances and available resources (e.g., soil nutrients, climate conditions) and is slow-moving in time (i.e., does not change drastically year-to-year).(Duniway et al., 2010). Land potential not only determines a site's plant community potential but also possible ecosystem services and human uses (e.g., wildlife habitat, livestock grazing, water filtration).(Brown and Havstad, 2016) By using the principles of land potential for guiding reclamation planning and assessing reclamation outcomes, requirements, and expectations could better reflect the soil and vegetative possibilities post-reclamation.

Predicting land potential after reclamation requires a basic understanding of the ecological processes that determine plant community structure.(Lupardus et al., 2020) As part of this, I must account for reclaimed soils being physically and biologically different than the surrounding area, because of the topsoil be scraped during pad establishment and being re-spread at the time of reclamation. Because of the mixing of soil coupled with low unpredictable precipitation, we cannot assume that complete plant recovery will have occurred at the time of a reclamation evaluation which typically occurs 3-5 years after reclamation completion (Bestelmeyer et al., 2015; Munson and Lauenroth, 2012).

Remote Sensing – Management Effects on Reclamation

The majority of oil or gas well pads on public land in the US lack information on pre-disturbance vegetation and soil conditions.(Di Stéfano et al., 2021) The lack of a baseline for comparison makes it difficult to interpret and manage for post-reclamation vegetation trends, allowing for a subjective array of evaluations on reclamation outcomes.(Di Stéfano et al., 2021) Remote sensing has been commonly used to monitor landscape change over time and specific vegetative indices have been used to characterize plant community cover (e.g., Waller et al., 2018). Application of remote sensing and time series analysis has been limited though for oil and gas development, but these technique have been found to be appropriate baselines for pre-disturbance conditions on pads when reference information is not available or there’s insufficient field data. (Di Stéfano et al., 2020; Nauman et al., 2017; Waller et al., 2018)

To look at plant community change over time since reclamation, I conducted a series of time series analyses methods (TSS-RESTREND) that identified significant deviations or breaks in the relationship between precipitation and vegetation response (Burrell et al., 2017). Burrell et al., 2017 found that these breaks can signal changes within a plant community’s structure. When breaks were found, I consulted the reclaimed well pad’s documentation and Google Earth imagery to identify possible causes such as well pad establishment or reseeding during reclamation. The overall goal was to identify what plant community changes occurred after reclamation, if management actions influenced reclamation outcomes and evaluate the utility of TSS-RESTREND for detecting plant community change post-reclamation.

Altered Land Potential Post-Reclamation

Plant community change after oil and gas reclamation is not well understood and has not been well studied, making it difficult to measure, assess, and manage reclamation outcomes. Additionally, Rottler et al., 2019 and Rottler et al., 2018 found that reclamation has not been a primary determinant in soil or vegetation outcomes and may occasionally cause more harm than good. Because reclamation is an expensive and lengthy process, it is important to determine consistent indicators of soil and vegetative outcomes post-reclamation to help prevent reclamation failure.

To look at specific soil and vegetative indicators of a reclaimed well pad’s altered land potential, I collected field data at 36 reclaimed well pads that were reclaimed at different points in time, over a 20-year time span. I then calculated the relative influence of soil and vegetation indicators on overall plant community structure at different stages since reclamation completion (i.e., 5, 10, 15, 20 years) using multivariate statistical analyses such as community-weighted means and principal components analysis. I also compared plant community diversity and types of plant canopy cover between different reclamation ages. Overall, my goal was to detect soil and vegetative characteristics at different points in reclamation age and evaluate if there was a group of indicators that had a sizeable influence on differences between reclamation ages. Once the group was identified, I could then determine how the indicators could be used to improve and standardize reclamation evaluations.

Reclamation Evaluations for Land Potential

I found based on current literature and analysis of my data that the most influential indicators on the altered land potential of reclaimed well pads are soil electrical conductivity (EC), soil bulk density (BD), native perennial canopy cover and diversity, presence of late successional species, dominant plant drought tolerance (e.g., xeric vs. mesic), introduced annual canopy cover, and proximity to other active well pads. Even though reclamation evaluations happen long before full plant community recovery, indicators of land potential can help determine if a site is on a desirable successional trajectory. This suite of indicators helps to characterize the key ecological processes of soil water retention and nutrient cycling that I found based on current literature to be crucial to long-term reclamation outcomes.

The indicators and their ranges that I state in later chapters should be viewed as a guide and not an absolute standard. Expert opinion and judgement will always be needed and regional adjustments for local environmental conditions may be appropriate with strong scientific justification. The goal of my recommendations is to improve consistency and transparency in the reclamation evaluation process so that reclamation expectations can be more clearly communicated to operators and that by having standardized data, reclamation knowledge may be more easily passed on to future generations of management. By managing for the suite of recommended indicators and expected ranges, land managers could increase the likelihood of a establishing a stable native plant community, prevent noxious weed dispersal, and prevent a reclaimed well pad from persisting on a permanent alternative trajectory to the surrounding area.

It is difficult to determine and manage for the altered land potential of a reclaimed well pad. By adjusting concepts and indicators of land potential for the unique circumstances created by oil and gas development, land managers may more easily put reclaimed well pads on pathway to recovery. Additionally, monitoring for land potential can help re-focus reclamation goals from unattainable pre-disturbance conditions, that are no longer possible because of climate change and highly altered soils, to more closely matching the successional trajectory of the surrounding area (i.e., what the site would look like without disturbance).

Chapter 2: Oil and gas reclamation on US public lands: how it works and improving the process with land potential concepts

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Introduction

On US public land, oil and gas development is primarily administered by the Bureau of Land Management (BLM) where the agency oversees about 99 million surface ha (245 million acres) of public land and 283 million subsurface ha (700 million acres) with ~5 million subsurface ha (12.8 million acres) producing oil and gas in profitable quantities (Fig. 2.1)(BLM, 2021; DOI, 2017). US federal land management agencies, like the BLM, are required to manage for multiple natural resource uses without permanent impairment of the productivity of the land and the quality of the environment, commonly referred to as the multiple-use mandate (Haskell, 1976). Within the past decade the boom in extraction of crude oil and natural gas on US public lands has challenged the multiple-use mandate because of the unique nature of oil and gas development. In some large landscapes, oil and gas development has created a vast network of discrete disturbances from well pads, pipelines, and connecting access roads. Examples of the direct and indirect effects of the development are habitat degradation, increased susceptibility to invasive plant species, and altered landscape hydrology, impacts which often impair or inhibit other important ecosystem values and permitted uses such as livestock grazing, wildlife habitat, and recreation (Allred et al., 2015; Walker et al., 2007; Waller et al., 2018; Yu et al., 2015). Reclamation is the process by which lands damaged by oil and gas development are repaired (Table 2.1). US federal land management agencies lack a common environmental and legal framework that clearly communicates to private drilling companies the expected outcome of reclamation activities of lands damaged during development. This has put US federal land management agencies in a contentious, and often litigious, environment with private drilling companies to manage oil and gas development.

To help provide clarity in expectations and lessen some of the contention surrounding reclamation management, the concept of land potential could act as a guiding principle for reclamation requirements and expectations to better address the unique impacts to plants, soils, and wildlife caused by oil and gas development. Land potential concepts are often used by the BLM and other resource managers in planning and decision processes, and are occasionally used in oil and gas management, but not consistently or universally (Bestelmeyer et al., 2015). Land potential refers to the types and amounts of vegetation that can occur at a site given the circumstances and available resources (e.g., soil nutrients, climate conditions) and is slow-moving in time (i.e., does not change drastically year-to-year)(Duniway et al., 2010). Land potential not only determines a site's plant community potential but also possible ecosystem services and human uses (e.g., wildlife habitat, livestock grazing, water filtration) (Brown and Havstad, 2016). By using the principles of land potential for guiding reclamation planning and assessing reclamation outcomes, requirements and expectations could better reflect the soil and vegetative possibilities post-reclamation (Fig. 2.2).

I review the current process and explore the diversity of requirements for oil and gas reclamation as administered by the BLM. I propose applying land potential concepts, modified to address the unique nature of highly disturbed lands resulting from oil and gas development, to guide principles for reclamation, to increase clarity of expectations, and to lessen some of the contention surrounding reclamation management.

Overview of Reclamation on US public land

There are three general stages of oil and gas development on US public land: 1) the permitting process to drill, 2) drilling and active extraction of fossil fuel resources, and 3) plugging and abandonment of the well (Table 2.1)(USDI BLM and USDA FS, 2007). Interim reclamation and final reclamation are conducted at the second and third stages of the well's life, respectively.

Interim reclamation and final reclamation are first outlined in the Surface Use Plan of Operations (SUPO) in an Application for Permit to Drill (APD) submitted by a company to a federal land-management agency (e.g., BLM, US Department of

Agriculture Forest Service [USDA FS], Bureau of Indian Affairs [BIA]) to obtain a lease for extracting fossil fuel resources(USDI BLM and USDA FS, 2007). Whatever is outlined in this plan becomes legally binding once the APD is approved, an environmental bond is paid, and the site is drilled. The Final Abandonment Notice (FAN) is submitted by the operator once the well has been plugged, all equipment removed, and final reclamation has been completed. Once received, the federal agency inspects the well location for compliance with the reclamation plan agreed upon in the APD and considers releasing the bond back to the company (i.e., FAN approval). If the FAN is denied, the company may reattempt reclamation or refuse to carry out further reclamation and forfeit their bond, if applicable.

There are two types of reclamation: interim (while well is active) and final (well is no longer active; Table 2.1). Interim reclamation is executed when initial drilling has been completed and production has commenced (USDI BLM and USDA FS, 2007). The goal of interim reclamation is to minimize the footprint of the well pad by reclaiming the immediately surrounding area that is no longer needed for production activities (USDI BLM and USDA FS, 2007). Previously removed and stored topsoil is re-spread and revegetation is attempted (e.g., drill seeded). Final reclamation begins once the well is plugged and all other production activities are discontinued (Table 2.1) (USDI BLM and USDA FS, 2007). Notably, this initial step of plugging the well is the most expensive in reclamation and the most crucial because it prevents pollution of surrounding ground water and soil (Andersen and Coupal, 2009). Subsequent steps for reclamation completion are: 1) removal of all equipment, 2) site preparation (e.g., recontouring of landscape), 3) revegetation, and 4) submission of the FAN (USDI BLM and USDA FS, 2007). Final reclamation normally takes 3-5 years, sometimes longer, because vegetation needs sufficient time to establish and monitoring data are usually needed to determine if a site is on a trajectory towards meeting reclamation success criteria, as agreed upon in the APD (Waller et al., 2018).

Regulation of Oil & Gas Reclamation

In the US, there is no national standard for reclamation of oil and gas development nor how reclamation outcomes are assessed, and as such, reclamation requirements are at the discretion of regional offices of the federal government (primarily BLM and USDA FS). This has created inconsistent, vague, and/or conflicting regulations that may contribute to poor reclamation outcomes or operators not completing required reclamation activities (Igarashi et al., 2014). In addition, current federal regional (e.g. BLM State Offices) and local (e.g. BLM Field Office) standards for monitoring and evaluating oil and gas reclamation outcomes are often inadequate for determining plant community trajectories, hampering regulations that account for the long-term environmental efficacy of reclamation practices (Curran et al., 2014; Janz et al., 2019). The lack of a national, outcomes-based monitoring and assessment reclamation framework leaves federal land agencies open to litigation from private companies, because they disagree on when a private company is no longer financially responsible for the environmental impacts of their development. A better understanding of what is possible post-reclamation (i.e., post reclamation land potential) and what reclamation practices operators can apply to achieve that potential, are required to fill a critical knowledge gap, put reclaimed well pads on a path to recovery, and reduce conflict among stakeholders and agencies.

Existing Guidelines for Oil and Gas Reclamation

The only national guidelines for oil and gas reclamation in the US can be found in the BLM’s Surface Operating Standards and Guidelines for Oil and Gas Exploration and Development (i.e., the Gold Book), but these guidelines are not legally binding (USDI BLM and USDA FS, 2007). The Gold Book guidelines were first published in the 1980’s and were last revised in 2007. The last chapter of the Gold Book covers reclamation and abandonment, focusing on general procedural steps for reclaiming areas disturbed by wells, pipelines, and roads.

The Gold Book stipulates the operator will not be released from financial liability of the environmental impacts of its wells until the local field office determines the operator has fulfilled the obligations agreed upon in the SUPO of the APD (Fig. 2.3). Throughout the reclamation process, the Gold Book states the operator is “responsible for monitoring reclamation progress and taking the necessary actions to ensure success,” but there is no guidance on the meaning of reclamation success (p.49) (USDI BLM and

USDA FS, 2007). The lack of guidance or understanding of reclamation success and the environmental factors affecting reclamation outcomes has put FAN decisions at the discretion of individual offices or federal employees, causing a wide range of interpretations of reclamation success.

Summary of State Reclamation Guidelines

In 2019, the top ten energy producing states included Wyoming, Colorado, and New Mexico which were also the top three states for number of active wells on public land (U.S. EIA, 2018; USDI BLM, 2019). I focus on these three western states because oil and gas revenues are a driving state and local economies, and most of the drilling occurs on BLM land (USDI BLM, 2019). Below I summarize each states' guidelines (as described in state directives and resource management plans [RMPs]) for reclamation practices and the metrics and data used to assess reclamation outcomes. These guidelines range from vague directives such as returning "vigorous ground cover on these areas to its original condition or better" (p. A3-1)(BLM, 2006), to designating specific seed mixes to be used in reclamation.

Wyoming — Wyoming has a statewide BLM reclamation policy (BLM, 2012), which is uncommon within the BLM. Like the Gold Book, the BLM reclamation policy has general directives for reclamation practices with an emphasis on establishing a "self-perpetuating native plant community" (p. 3)(BLM, 2012), soil stabilization, and establishing a native plant community resistant to noxious weed invasion (e.g., cheatgrass [*Bromus tectorum* L.]). The policy includes instructions for the BLM to 1) develop and implement a reclamation monitoring strategy, and 2) use monitoring to inform decisions on the compliance and effectiveness of a company's reclamation. The policy stresses the importance of documenting and reporting monitoring data, especially if the data were used to revise reclamation strategies. The documented plant and soil inventories assist the BLM Field Office in understanding factors involved in the observed reclamation outcomes at the time of the FAN inspection. Local reclamation requirements that are in additional to the state-wide provisions can be found in the RMPs which are administered by individual BLM Field Offices.

To assess reclamation outcomes in Wyoming RMPs, 75-80% similarity to a reference plant community is a frequently used quantitative metric (BLM, 2015, 2008, 2006). However, the RMPs differ in what constitutes a reference plant community, with some RMPs using pre-disturbance cover and others using a corresponding ecological site's reference plant community. This is an example of varying expectations on reclamation outcomes within a state. Notably, oil and gas reclamation goals and success criteria in Wyoming include physical, biological, and chemical factors in their reclamation evaluation, which helps account for the unique environmental characteristics affecting reclamation outcomes. Thus, in Wyoming reclamation plans capture the principles of land potential but also likely could benefit from greater understanding on how post-reclamation land potential varies across the state and thereby allow for more standardization in reclamation outcomes.

Colorado — Despite lacking statewide reclamation guidelines, Colorado BLM has one of the most developed regulatory frameworks in the US for oil and gas reclamation on public lands (BLM, 2020). This framework contains a level of detail for reclamation plans that exist in the BLM's RMPs across the state, particularly on the western slope of Colorado. These detailed reclamation plans attempt to consider all possible environmental circumstances for oil and gas reclamation and to capture a site's post-reclamation land potential.

Colorado's reclamation goals are similar to Wyoming's because they focus on soil stabilization and establishing desirable plant communities. However, there is an added stipulation of establishing and maintaining healthy, biologically active topsoil post-reclamation (BLM, 2015b, 2015c, 2015d, 2011). Additionally, all RMPs acknowledge the outsized influence of cheatgrass on soil and plant community viability throughout Colorado. To address the complexity and difficulty of eliminating cheatgrass, most RMPs allow for a low level of cheatgrass to be present on a site if the surrounding area had a noticeable presence of cheatgrass (see Table 2.2 for an example of cheatgrass parameters from one Colorado RMP).

Like Wyoming, Colorado's western slope RMPs include the directive to monitor the progress of reclamation and emphasizes the need for quantitative data to reliably measure reclamation success, but there is no guidance on data or resources to be used for setting a reference against which to compare reclamation data (e.g., pre-disturbance, off site transects, or Ecological Site Description [ESD] reference community). Each BLM Field Office differs in their approach to reclamation monitoring. One BLM Field Office required "vegetation transect analysis" (i.e., quantitative, not ocular estimates) only when a reclamation site was consistently failing land health standards (p.32) (BLM, 2015b). While, another required the collection of BLM Assessment, Inventory, and Monitoring (AIM) type data at each reclamation site at the time of FAN approval (Bureau of Land Management, 2015b, 2015d; Herrick et al., 2017; Mackinnon et al., 2011).

In summary, while Colorado had some of the most detailed oil and gas reclamation plans on BLM lands, they were inconsistent among BLM Field Offices. This is challenging for operators, who work across field offices (as well as states) to have a clear understanding of expectations for reclamation success (Hale, 2019). Additionally, the variation in reclamation criteria among offices likely reflects divergent staff opinions on the soil and vegetative characteristics most pertinent to reclamation outcomes and for determining a site's land potential post-reclamation.

New Mexico — Of all the states where oil and gas development occurs on public land, New Mexico had the highest number of active leases in the US as of 2019 (USDI BLM, 2019). Most of this development is in southeastern New Mexico, commonly referred to as the Permian Basin, which is administered by the BLM Carlsbad Field Office. Northwestern New Mexico also has a significant portion of this development overseen by the BLM Farmington Field Office. Therefore, I focused on the reclamation guidelines of these two Field Offices which are also the most detailed in the state.

Reclamation guidelines in the RMPs of the Carlsbad and Farmington BLM Field Offices deferred to the Gold Book without much additional instruction. As opposed to the RMPs of Wyoming and Colorado which focused on restoring pre-disturbance vegetation conditions, the reclamation focus in New Mexico BLM's RMPs was restoring site condition to support other land uses and permitted activities (e.g., livestock grazing). For example, the Carlsbad BLM Field Office defines reclamation as "returning the land to a condition approximate or equal to that which existed prior to disturbance, or to a stable and productive condition compatible with the land use plan" (p. 23)(BLM, 2018). In addition, the RMPs state that reclamation regulations must be "justifiable and reasonable" which does not mean the land should be better than before the oil and gas development (p. 75)(BLM, 2018). Similar to other states, there is the goal of soil and plant community stabilization (i.e., minimal erosion and invasive species), and stabilization should result in "reducing or eliminating impacts [of development] over time" (p. 110) (BLM, 2018). Apart from restoring site condition to support other land uses and site stabilization, few guidelines or goals are outlined by field offices in New Mexico. Unlike Wyoming and Colorado, there are no quantitative measures for reclamation success, which leaves the interpretation of success to each reclamation manager.

The reclamation goals for New Mexico's BLM Field Office are pragmatic but lack specific guidance on reclamation practices and clear expectations of reclamation outcomes, both which likely hamper reclamation success. Additionally, the reclamation plans focus on restoring sites to support forage for domestic livestock, which demonstrates a lack of understanding in the alteration of soil-vegetation relationships caused by oil and gas development that limits or severely alters future potential land uses (i.e., not considering site land potential following oil and gas reclamation).

Long-Term Effectiveness of Oil and Gas Reclamation in the US

In the long-term, current reclamation practices and standards fail to achieve long-term effectiveness across the western US. The most common reasons for these poor outcomes include: reclamation plans do not match the complexity of the project; oil and gas development acts as a catalyst for further spread of invasive species (e.g., cheatgrass); oil and gas development occurs in areas with low reclamation potential; and deterioration of soil structure and function (Barlow et al., 2017; Janz et al., 2019; Lupardus et al., 2020, 2019; Rottler et al., 2019, 2018). Additionally, focusing on immediate site stabilization where managers are trying to rapidly grow grasses and forbs, can push sites to novel soil types and plant communities (i.e., modified land potential) that do not recover their pre-disturbance ecosystem services.(Lupardus et al., 2020) Furthermore, there is a lack of consistently applied monitoring methods, which hinders evaluations of reclamation effectiveness across regions and time periods (Curran et al., 2014). In summary, inconsistent guidance on reclamation practices and wide variation on expectations of reclamation outcomes introduces uncertainty and complexity for operators who work across government entities (i.e., state and local), and likely impedes post-reclamation recovery of plant communities.

Despite these challenges, reclamation plans established throughout the western US share a goal of reestablishing a self-perpetuating plant community consisting of native plants, resistant to invasion, and prevents further soil erosion. This goal is rooted in the idea of moving a site towards a condition or state that provides necessary ecosystem functions (e.g., forage for wildlife and livestock, biodiversity, water filtration, i.e., a site’s land potential). Reclamation plans in Wyoming, Colorado, and New Mexico have failed to establish frameworks that: 1) account for the unique environmental circumstances created by oil and gas development, 2) consider the long timeframe required to achieve the highest site potential (i.e., meets or exceeds the desired attributes) given its modified land potential, and 3) impede further degradation of land potential from erosion or noxious weed invasion.

High disturbance land use, such as oil and gas development, permanently alters a site’s soil and vegetative potential, but managers need to restore a site’s ecosystem services to meet their multiple-use mandate. To determine reclamation effectiveness and provide a guide for operators and managers to follow, it is vital to measure and predict a site’s post-development (i.e., modified) land potential to determine if a site is on a desirable reclamation trajectory to restore ecosystem services. This determination can be achieved through regular quantitative monitoring and assessment of site characteristics indicative of plant community recovery to a desired successional pathway.

Building Blocks of Post-Reclamation Land Potential

Soil and vegetation properties (both static and dynamic) and processes are the building blocks for post-reclamation land potential (Fig. 2.2).

Static Properties

The most predominant properties that can affect reclamation outcomes are a site's topography and climate (Nauman et al., 2017). Static properties form the foundation of a site's land potential and reclamation managers must work within their constraints. These static properties operate over long enough time spans to be considered stationary within the time frame of management actions and are not usually changed by management actions. Unlike traditional understanding and uses of the concept of land potential (e.g. Ecological Sites), many traditionally static properties are managed and manipulated for reclamation (e.g. soil depth, topography) while others are inherited from the site setting (e.g., aspect, climate).(Bestelmeyer et al., 2015)

Western US rangelands are characterized by heterogeneity in climate, precipitation and water availability, which are the main limitations for vegetation establishment and in which there is variability in recovery rates after reclamation (Villarreal et al., 2019; Waller et al., 2018). For example, well pads abandoned during multi-year droughts have decreased plant community recovery and may require re-seeding, while well pads reclaimed during wet periods experience more paid recovery (Waller et al., 2018). Additionally, changes in timing of precipitation affects the composition of plant communities. For example, higher than average winter precipitation followed by multiple dry years increases the risk of exotic species invasion at reclaimed well pads (Villarreal et al., 2019). Overall, managers can only mitigate for the effects of climate rather than manage climate itself.

Topography affects water availability and sediment movement. It is one of the most common considerations for reclamation in BLM RMPs. Topography (e.g., slope, slope shape and aspect) can affect reclamation outcomes because it influences soil erosion and is a main determinant for the spatial distribution of soil water (Gómez-Plaza et al., 2001; McBroom et al., 2012). Unlike climate and broader topography, local topography (e.g., a site's slope) is directly influenced by development and reclamation because well pads are typically established as flat surfaces, regardless of the surrounding landscape (e.g., well pad cut into the side of a mountain). When local topography is not accounted for at a reclamation site (e.g., abandoned well pad is not recontoured to match surrounding area), the flow of water and sediment is permanently altered, which decreases the likelihood the site will follow a desirable plant community trajectory as determined by its new modified land potential (i.e., cannot restore ecosystem services).(Sinha et al., 2017)

Dynamic Properties

Dynamic soil and vegetation properties have a role in setting post-reclamation land potential by influencing soil processes (Fig. 2). These dynamic properties are important to consider in reclamation practices because they are easily and directly affected by management.

Soil Properties —Apart from immediate soil stabilization (i.e., reduce soil erosion), most reclamation requirements in the US focus on vegetative outcomes of reclamation practices, and not on creating soils to foster desirable conditions to restore ecosystem services. Recent research has shown that many years after oil and gas development reclaimed sites maintain soil legacy effects, such as higher bulk density, lower organic matter content, and changes in soil texture (Janz et al., 2019; Lupardus et al., 2020, 2019). These results are expected because topsoil is removed, and soil horizons are mixed during the establishment of well pads which permanently alters movement and retention of water and nutrients in soils. In these circumstances, soil surface properties (i.e., within the first 11.8 inches [30 cm] of the soil profile) are modified, including bulk density, texture, organic matter, electrical conductivity, and pH, which alters the water availability and nutrient cycling at the site. Thereby affecting the establishment and persistence of plant communities on a site. Soil texture influences water infiltration and holding capacity, resulting sometimes catastrophic increases in runoff and erosion (Barlow et al., 2017; Meiers et al., 2011; Zeleke and Si, 2005). The unique nature of reclaimed soils created by development and reclamation practices permanently alters a site's land potential, and makes it unlikely to reach pre-disturbance conditions.

Salvaging topsoil during development as well as storing, and respreading topsoil during reclamation has become common practice in oil and gas development that has improved vegetative outcomes (Zvomuya et al., 2007). However, salvaged topsoil often sits for years to decades, loses organic matter over time (depending on surface cover), and increasingly becomes biologically inactive compared to the surrounding soil (Rottler et al., 2019; Zvomuya et al., 2007). When the salvaged is topsoil is respread during reclamation, it differs physically and biologically from its pre-disturbance condition. Therefore, reclamation outcomes need to be evaluated relative to these altered soil conditions, and soil properties should be considered in reclamation requirements and expectations.

Vegetation — As the most visible and easily measured outcomes of reclamation, vegetation cover and composition, as well as functional and trait-based characteristics of vegetation (e.g., mesic vs. xeric vegetation), are the most common indicators for evaluating reclamation success (Lupardus et al., 2020). However, it is critical to assess these vegetative outcomes with respect to altered land potential following site and soil reclamation.

To prevent the establishment of invasive plant species, many reclamation projects seed with bridge or early pioneer plant species (Jacobs et al., 2011; Rottler et al., 2018). Common species include antelope bitterbrush [*Purshia tridentata* (Pursh) DC], blue grama [*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths], and the non-native crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.]. Seeding with these plant species stabilizes soil and provides cover to facilitate the transition to late-successional species such as sagebrush (*Artemisia* L.)(i.e., acting as nurse plants) (Jacobs et al., 2011; Rottler et al., 2018). Using ruderal plant species for immediate site stabilization may impede establishment of shrubs or other late-successional plants that were dominant pre-disturbance and potentially causing reclaimed sites to have vegetation not observed in undisturbed or less-disturbed settings (Lupardus et al., 2020; Rottler et al., 2019, 2018). Many seed mixes used in reclamation are likely altering land potential by limiting recovery of desired ecosystem services.

The modified land potential of reclamation sites could be the result of seeded species having different plant community traits (e.g., mesic vs. arid) than the surrounding native vegetation, which suggests the need for focusing on plant functional traits in reclamation, and not solely on community composition (Lupardus et al., 2020). The plant community trajectory after restoration is determined by sequential changes in functional groups in response to abiotic and biotic factors such as available water and wildlife use (Helsen et al., 2013). During this time, overall plant diversity and ground cover can be consistent while the functional group composition changes (i.e., overall plant traits remain the same but plant species vary)(Helsen et al., 2013). The goal of reclamation should be to establish a plant community trajectory that progresses towards the plant functional groups and associated ecosystem services (e.g., soil stabilization, habitat, etc.) observed in the surrounding area which can take decades. Because land potential at reclaimed sites is often altered, it may not be reasonable, or even desirable, to expect reclaimed sites to have similar plant species composition compared to a reference site or the surrounding area at the time of bond release.

Soil Processes

In contrast to oil and gas reclamation which has largely focused on revegetation outcomes, mining reclamation research focuses on soil functional processes that determine land potential (Feng et al., 2019). Soil nutrient cycling, and water retention are not well understood but in oil and gas reclamation many of the concepts applied in mining reclamation are applicable to oil and gas reclamation because both involve establishing vegetation and functioning soils in disturbed lands (Feng et al., 2019; Zvomuya et al., 2007).

Nutrient cycling — Arid and semiarid soil are characterized by low soil organic matter, which is further exacerbated by oil and gas development (Ingram et al., 2005; Rottler et al., 2019). Drilling and establishing well pads involves removal of the soil surface (usually A+B horizons) which is respread during reclamation. This soil-handling process breaks down soil aggregates (i.e., structure) which accelerates the decomposition of organic matter and loss of nutrients previously contained in soil aggregates (e.g., soil carbon, nitrogen, and phosphorus) (Ingram et al., 2005; Rottler et al., 2019). In addition, reclaimed soils typically have a higher pH and salt concentration compared to reference conditions (Sylvain et al., 2019). The restoration of soil organic matter (SOM) and other nutrients is crucial to long-term reclamation success because they are the building blocks of the soil nutrient pool. Soil nutrient cycling determines water holding capacity, soil structure, and nutrient absorption, which influences the "establishment and maintenance of a permanent and stable plant community" that creates a desirable land potential leading to restoration of ecosystem services. (p. 2)(Ingram et al., 2005)

Water retention — Oil and gas development and reclamation change the physical structure and biological function of soil, often decreasing water filtration and increasing erosion which affects the establishment and persistence of plant communities. Soil hydraulic conductivity (K_s), which describes how water flows through soil pores, is affected by changes in soil structure and is a predictor of reclamation success (Huang et al., 2015; Shukla, 2014). As such, K_s is an indicator of water retention on a site and determines a site's land potential post-reclamation.

The homogenization of reclaimed soils causes the pore geometry (i.e., configuration of open spaces) to be consistent throughout the soil (Meiers et al., 2011). This leads to reclaimed soils having a different K_s than the surrounding undisturbed soil that underwent natural pedogenesis (i.e., horizonation). Thus, reclaimed soil interacts differently with water than undisturbed soils. For example, the loss of more coarse textured soils from topsoil removal leads to reduced infiltration when replaced by finer textures - by a factor of 10 or more (Herrick et al., 2010). Mining reclamation research has found that K_s increases with time since reclamation due to soil development processes (e.g., freeze-thaw cycle) and is also affected by soil surface treatments (e.g., mulch vs. surfactant) (Huang et al., 2015; Meiers et al., 2011). Increases in K_s often correspond with increases in root development, indicating greater water availability to plants over time (Huang et al., 2015; Meiers et al., 2011). For these reasons, it is recommended that K_s and properties related to it (e.g., bulk density) be monitored to evaluate long-term reclamation success (Huang et al., 2015).

Time: the Last Consideration

It is important to consider time since reclamation because it affects how I evaluate reclamation outcomes and land potential and plant community establishment is manifested over time. A common assumption is that, if done properly, reclamation puts a site on a path to the reference or expected plant community and positive effects should be seen over time. Recent research findings dispute the time over which desirable outcomes can be expected. The BLM evaluates reclamation outcomes 3-5 years after completion, but significant plant community changes post-reclamation typically cannot be observed until at least 10-20 years after completion (Di Stéfano et al., 2020; Lupardus et al., 2020; Rottler et al., 2018). Additionally, complete plant community recovery and/or establishment of late-successional species (e.g., sagebrush) has been observed 50-100 years after well pad abandonment, if at all (Rottler et al., 2019, 2018). How and within what time period can BLM or any regulatory agency fairly decide a company's responsibility for the environmental outcomes of their reclamation.

Meaningful ecological recovery within 3-5 years post reclamation is problematic given that oil and gas development involves the complete removal of soil layers, which were created over thousands of years, and plant communities, which were formed over decades. Accordingly, reclamation outcomes cannot be measured under the same assumptions or using the same vegetation indicators as other restoration projects, which may show meaningful ecological recovery within 5-10 years. In other words, the unique soil and vegetative circumstances post-reclamation means that reclamation requirements and expectations cannot be solely based on pre-disturbance land potential (i.e., the Ecological Site Descriptions and associated state-and-transition models for the site pre-development). New land potential concepts are needed for these highly modified soil systems (Bestelmeyer et al., 2015).

Time since reclamation is a consideration when developing practical expectations for reclamation outcomes, but not a sufficient benchmark for predicting reclamation success. Overall, the timeframe for monitoring and making decisions to release a company from environmental liability should be based on indicators of restoration of ecosystem services, rather than restoration of pre-disturbance conditions. The expectations of restored ecosystem services should be based on (or tempered by) reasonable expectations of what is possible post-reclamation, using the concepts of modified land potential. This approach would lead to appropriate and realistic benchmarks for reclamation outcomes.

Management Implications of Using Post-Reclamation Land Potential

Instituting land potential concepts that account for shifting land potential following highly disturbing land use, into reclamation plans and activities could enable BLM and other federal land agencies to outline oil and gas reclamation requirements and expectations consistently and clearly. Additionally, using post-reclamation land potential to frame reclamation requirements and monitoring will improve the clarity and repeatability of how compliance with reclamation requirements is determined at the time of the FAN. Monitoring based on new or altered land potential could increase the capacity of private industry to practice adaptive management, which allows for detection of and response to desirable or undesirable changes in dynamic properties using the long-term soil and vegetative possibilities for the site. In contrast, interpretation of reclamation monitoring data without considering the new land potential may lead to sites with undesirable trajectories because reclamation requirements are inappropriate or unattainable for the soil and vegetative properties that define the modified land potential (Miller et al., 2011).

Implementing the land potential concepts, I outlined could improve understanding of variable site properties affecting reclamation outcomes, increase the likelihood of FAN approval, and move reclamation sites towards long-term recovery of ecosystem services. Despite the difficulty of managing oil and gas reclamation in the arid and dynamic systems of the western US, land potential concepts provide a framework for what to expect, and reclamation plans can be adjusted accordingly. Specifically, research is needed on the potential of different soil and climate contexts post-reclamation, which can inform and update local to regional reclamation plans with these new post-reclamation land potential concepts.

Some BLM field offices using quantitative monitoring and assessment have begun to implement land potential concepts in oil and gas reclamation (BLM, 2015d). Monitoring, and assessment informed by land potential concepts has given managers a broader view of natural landscape dynamics while setting practical and ecologically sound reclamation goals. Putting these methods and concepts into wider practice will require writing them into policy, particularly within the legally bound APD and SUPO. Otherwise, reclamation across the western US will continue to be piecemeal and unlikely to address the ecosystem services lost to oil and gas development.

Tables

Table 2.1: List of terms and acronyms used by the Bureau of Land Management (BLM) and other federal land agencies in the paperwork and legal process of managing and practicing oil and gas development on US public land.

Stage	Terms	Definition
General	Operator	• A private entity (individual or company) that has a lease to drill for oil or natural gas on public land.
Permitting	APD (Application for Permit to Drill)	• Initial and legally binding agreement between the BLM and operator that specifies the well's plan of operations. • Must be approved before any drilling operations are initiated.
	SUPO (Surface Use Plan of Operations)	• Section of the APD that specifies the nature and extent of the well's disturbance to the aboveground surface. • Includes the requirements for the rehabilitation of plants and soils post-establishment of the well and post-production.
	Sundry Notice	• Required paperwork submitted to the BLM if any change is made to the well, outside of what was previously agreed to.
	NOI (Notice of Intent)	• Type of Sundry Notice • Specifies drilling or new activity to be carried out at well.
Active Well	SR (Subsequent Report)	• Type of Sundry Notice • Specifies what work on well was completed that was previously agreed upon.
	Interim Reclamation	• Rehabilitation of plants and soils on surface area that is no longer necessary for well operations. • Minimizes the footprint of disturbance immediately after well establishment.
	P + A (Plugging and Abandonment)	• Closing a well permanently. • Well hole is filled with a substance that prevents leakages to surrounding area. • All well equipment is removed.
	Final Reclamation	• Salvaged topsoil is respread to match the original slope and aspect of the site. • Re-seeding of site with approved BLM seed mix.
Abandonment	FAN (Final Abandonment Notice)	• Required paperwork submitted to the BLM after the plugging and rehabilitation of the well. • Well pad's aboveground surface area has met the rehabilitation requirements outlined in the SUPO and is ready for inspection by the BLM.

Table 2.2: Acceptable cheatgrass (*Bromus tectorum* L.) cover for reclamation sites at time of final abandonment notice (FAN) approval based on undisturbed conditions found in surrounding area. These parameters come from the resource management plan (RMP) of the Bureau of Land Management's (BLM) White River field office in Meeker, CO (BLM, 2015d).

Surrounding area	Reclamation Site
<25% cover	≤5% cover
25-50% cover	≤10% cover
>50% cover	Natural Resource Specialist and Operator come to an agreement on an acceptable percentage

Figures

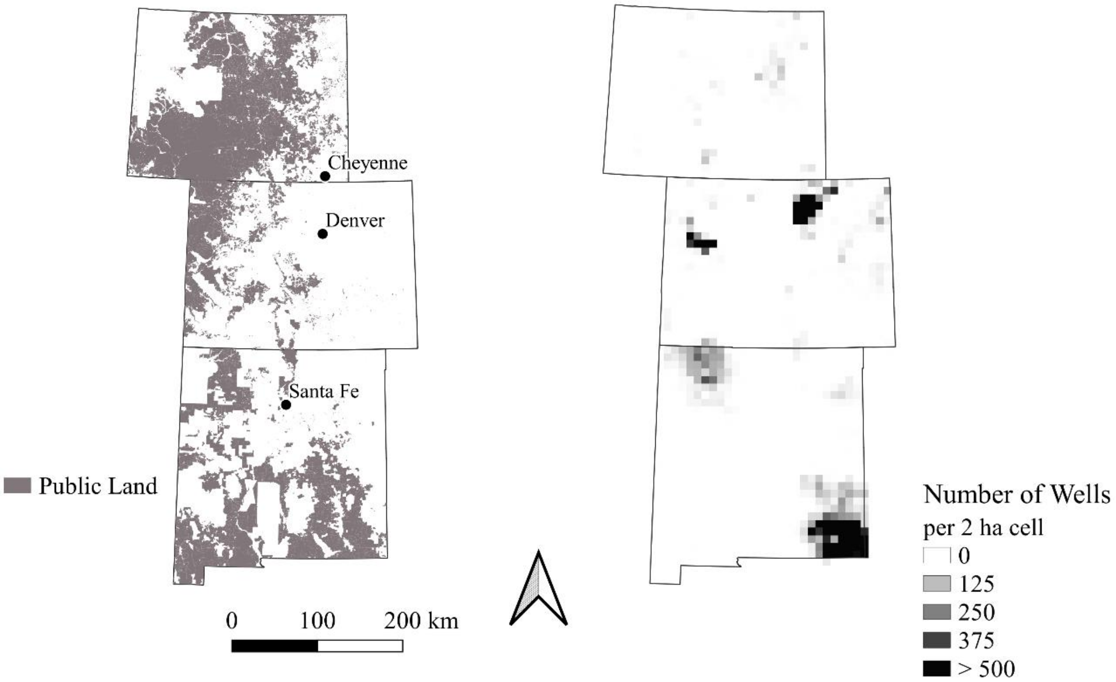

Figure 2.1: Location of federally administered land and number of active wells within 2 ha (as of 2020) in Wyoming, Utah, Colorado, and New Mexico (Eisinger, 2017; Livengood, 2020; Staley, 2020; Toner et al., 2020). Well types included oil, natural gas, and water injection (method for petroleum resource extraction).

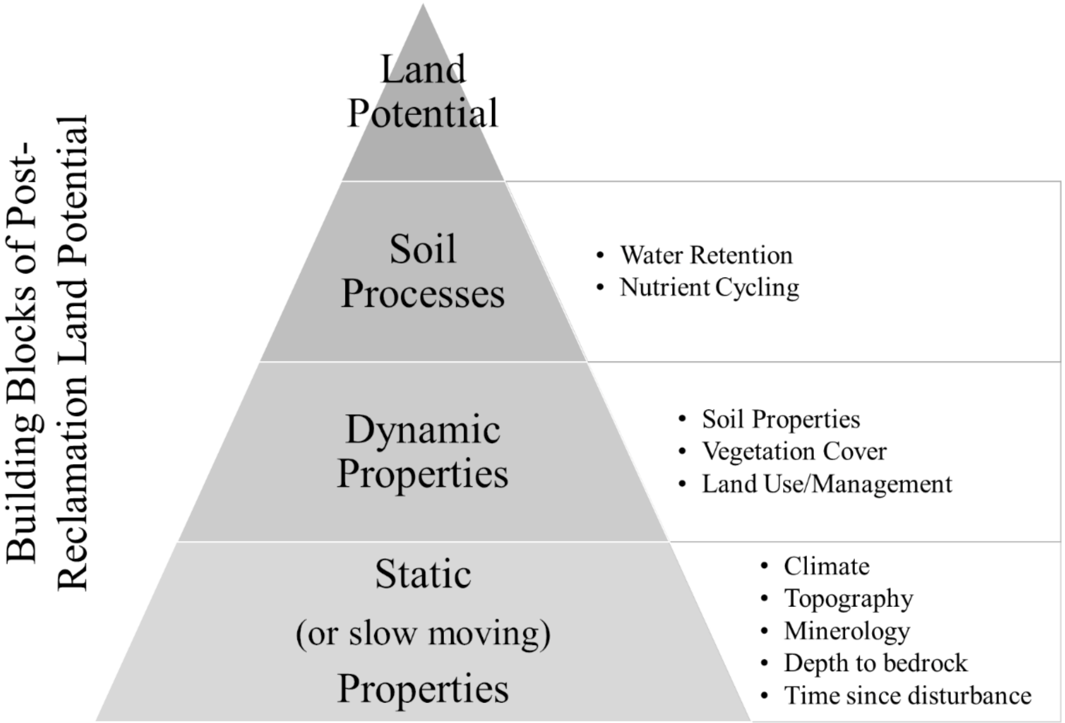

Figure 2.2: The properties that build on each other and ultimately determine a site's post-reclamation land potential. Land potential in this context is defined as the types and amounts of vegetation occurring at a site after reclamation is complete, given the site setting and the reclamation practices applied.

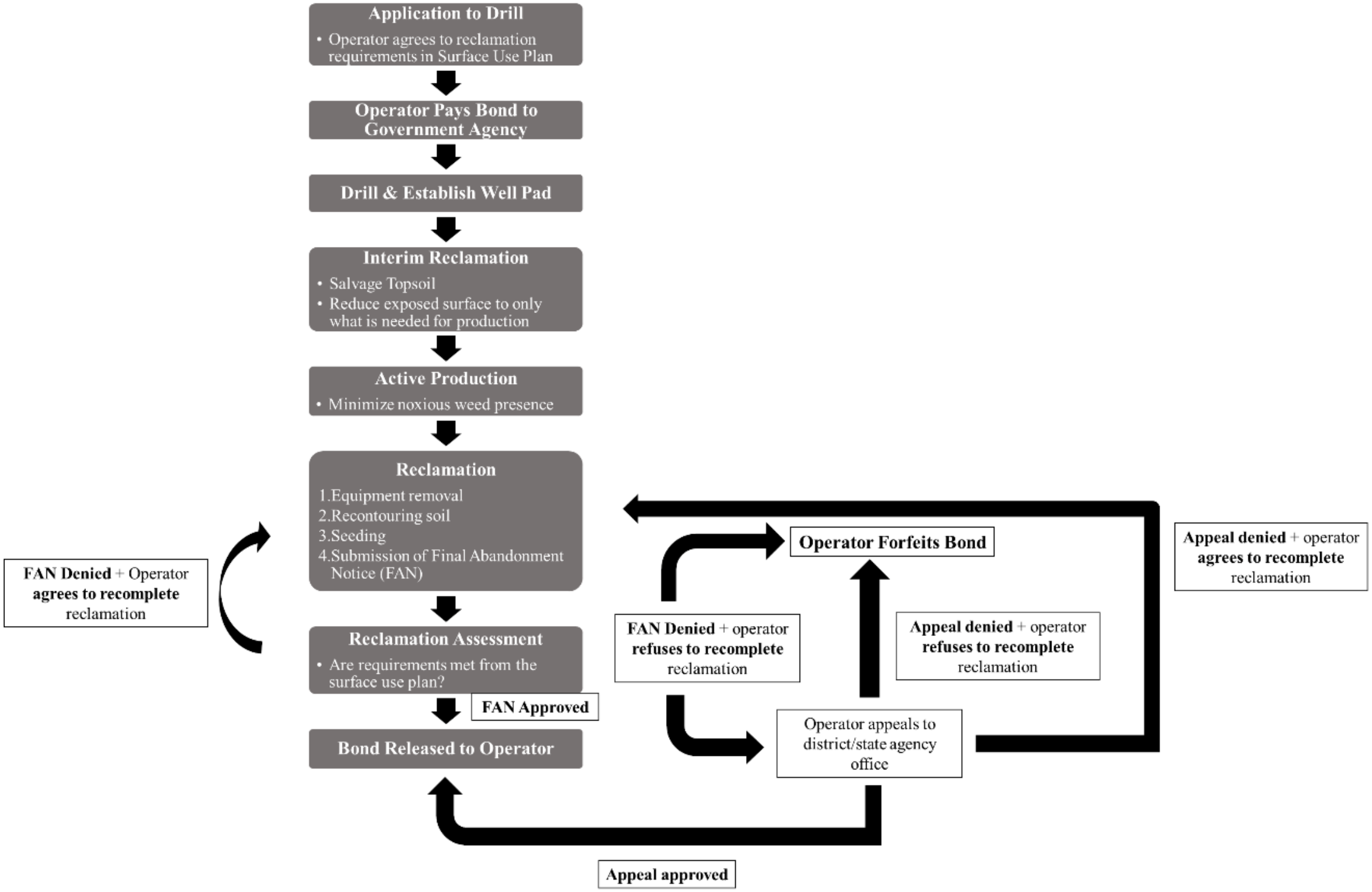

Figure 2.3: Outline of the process to oil and gas drilling and reclamation on US public land. FAN: Final Abandonment Notice.

Chapter 3: Using the TSS-RESTREND Methodology to Diagnose Post-Reclamation Vegetation Trends on the Western Slope of Colorado

Introduction

Public Land Management of oil and gas Development

On US public land, oil and gas development is primarily administered by the Bureau of Land Management (BLM) where the agency oversees about 99 million surface ha (245 million acres) of public land and 283 million subsurface ha (700 million acres) with ~5 million subsurface ha (12.8 million acres) producing oil and gas in profitable quantities (Fig. 3.1).(Allred et al., 2015; Bureau of Land Management, 2021; Di Stéfano et al., 2021) US federal land management agencies, like the BLM, are required to manage for multiple natural resource uses without permanent impairment of the productivity of the land and the quality of the environment, commonly referred to as the multiple-use mandate.(Haskell, 1976) Within the past decade the boom in extraction of crude oil and natural gas on US public lands has challenged the multiple-use mandate because of the unique nature of oil and gas development. In some large landscapes, oil and gas development has created a vast network of discrete disturbances from well pads, pipelines, and connecting access roads. Examples of the direct and indirect effects of the development are habitat degradation, increased susceptibility to invasive plant species, and altered landscape hydrology, impacts which often impair or inhibit other important ecosystem values and permitted uses such as livestock grazing, wildlife habitat, and recreation. (Allred et al., 2015; Walker et al., 2007; Waller et al., 2018; Yu et al., 2015)

Reclamation is the process to repair highly damaged landscapes, such as what is caused by oil and gas development (Di Stéfano et al., 2021). Reclamation objectives are normally guided by policy and/or reference conditions (Di Stéfano et al., 2021). For the reference condition to be appropriate and attainable for reclamation, it must be framed within the correct ecological context and based on the most relevant information available (Kirkman et al., 2013; Nauman and Duniway, 2016). The correct ecological context helps land managers understand the potential of disturbed land post-reclamation and develop metrics for when disturbed lands can be considered reclaimed (Di Stéfano et al., 2020). Ecological context for assessing reclamation success generally includes similarity to a reference or pre-disturbance condition for physical characteristics, soil dynamics, ecosystem services, vegetation dynamics, and predicted responses to management activities (Twidwell et al., 2013). Pre-disturbance conditions provide a comparison based on ecological context that is similar to a reclamation area in most aspects except for the disturbance activity, so that the relative condition and theoretical potential of the reclamation site can be determined (Di Stéfano et al., 2020; Jackson and Prince, 2016).

The majority of oil or gas pads on public land in the US lack information on vegetation and soil conditions before the pad was established (i.e., pre-disturbance condition) (Di Stéfano et al., 2021). The lack of reference conditions makes it difficult to interpret and manage for post-reclamation vegetation trends, allowing for a wide and subjective array of evaluations on reclamation outcomes (Di Stéfano et al., 2021). Additionally, the conflicting evaluations and inconsistent interpretations can create an antagonistic environment for land managers and the private drilling industry (i.e., operators) to coordinate on reclamation management (Di Stéfano et al., 2020).

Time Series Analysis of Highly Disturbed Landscapes

Remote sensing has been used to monitor landscape change over time and specific vegetative indices have been used to characterize plant community cover. For example, the Soil Adjusted Total Vegetation Index (SATVI, Eq. 1) has been found to be an appropriate index for much of the western US because it accounts for the brightness of the soils in arid regions, allowing for more accurate detection of vegetation trends in sparsely vegetated areas (Marsett et al., 2006; Waller et al., 2018). To further evaluate changes in land cover, time series analysis methods such as Breaks for Additive Season and Trend (BFAST), have been employed to detect abrupt changes in cover for various time periods (Waller et al., 2018). Other time series analysis methods, such as residual trend analysis (RESTREND), have been used to detect an overall upward or downward (i.e., degradation) trend in vegetative cover (Higginbottom and Symeonakis, 2014).

Application of remote sensing and time series analysis has been limited though for oil and gas development but they have been found to be an appropriate baseline for pre-disturbance conditions on pads when reference information is not available (Di Stéfano et al., 2020; Nauman et al., 2017; Waller et al., 2018). For example, Waller et al. (2018) used BFAST modeling to “[identify] when vegetation was cleared from the site and the magnitudes and rates of vegetation change after abandonment”. Where these time series analyses have fallen short though is that the indices used (e.g., SATVI) focus on total vegetative productivity, making it difficult to detect structural changes in a plant community. This is particularly of concern for well pads where invasive weeds are a persistent post-reclamation issue and may inflate estimates of vegetative productivity (Nauman et al., 2017). In addition, BFAST has been found to be overly sensitive to climactic events (e.g., drought), making it difficult to determine vegetation responses specific to management actions (Burrell et al., 2017).

The greenness-to-cover index (GCI) has been used to detect recovery on arid lands after complete removal of vegetative cover (e.g., fire) and is calculated as the normalized difference between NDVI and Total Vegetation Fractional Cover (TVFC, Eq. 2)(Villarreal et al., 2016). Villarreal et al. (2016) found that GCI trends could be used to detect plant community changes beyond total vegetative cover that indicated whether a site was dominated by native perennial plants, annual grasses, or bare ground.

RESTREND is a time series analysis method for detecting arid land degradation, where vegetation dynamics due to climactic factors are separated from those caused by management actions (Evans and Geerken, 2004). RESTREND is limited though by its need for a strong linear relationship between vegetation indices and climate (Burrell et al., 2017; Evans and Geerken, 2004). Most arid lands, particularly those affected by oil and gas development, exhibit strong non-linear dynamics in vegetation with time (Smith et al., 2019; Waller et al., 2018). To address the limitation, Time Series Segmented Residual Trends (TSS-RESTREND) was developed by Burrell et al. (2017) for detecting and diagnosing land cover change in landscapes with unstable vegetation-precipitation relationships and was found to be particularly useful in severely degraded areas that might be missed using traditional remote sensing analysis of vegetation (e.g., BFAST, RESTREND). More specifically, TSS-RESTREND combines BFAST and RESTREND to evaluate land cover change in unstable landscapes.

The first step in TSS-RESTREND is to calculate the overall relationship between a vegetation index and local precipitation data (i.e., vegetation-precipitation relationship, or VPR) through ordinary least squares (OLS) regression. The resulting residuals (VPR residuals) from the relationship are then assumed to be the vegetation trend outside of climactic annual fluctuations or events (e.g., drought) and thus due to management actions or disturbances. The VPR residuals are then evaluated for breaks over a specified time period through BFAST modeling. The breaks in the VPR residuals are assumed to be abrupt changes in land cover and less likely to be caused by climatic events, but because BFAST has been found to be sensitive to climatic changes, the identified breaks from the time series modeling are further evaluated for significance (p value < 0.05) by the Chow test (Chow 1960).

The Chow test has not been commonly used in remote sensing but is used in economics to identify structural instability in a series based on potential breakpoints (Chow, 1960). The test assumes that if a potential breakpoint is significant (p-value < 0.05), as determined by the Chow test, a structural change in the time series has been detected such as a native perennial plant community being replaced by invasive annual plants (Burrell et al., 2017). In the TSS-RESTREND methodology, the Chow test is only applied to the most significant breakpoint, as determined by BFAST, because it was found that applying the Chow test to multiple BFAST breakpoints increased the number of false positives (Type I errors) and did not correspond to significant structural change in the plant community (Burrell et al., 2017).

Objectives

The general objective of this paper was to determine if plant community change after reclamation could be detected and evaluated using remote sensing. More specific objectives were 1) assessing if time since reclamation was related to trends in the VPR, 2) determining if breaks or trends in VPR could be related to management changes visible in aerial imagery or noted in records, and 3) evaluating the utility of using TSS-RESTREND for assessing reclamation outcomes.

I accomplished these objectives by applying the TSS-RESTREND time series methodology with the GCI vegetation index to detect structural plant community changes post-reclamation for a set of reclaimed oil and gas wells in northwestern Colorado, USA. I then determined possible effects from different types of reclamation management by finding connections between remotely sensed vegetation patterns and management actions documented in each well pad's management records. By finding and evaluating these connections, we can better understand how management actions may be promoting or hindering recovery.

Study Area

I conducted this study within the western portions of the BLM's White River and Little Snake Field Offices in northwestern Colorado, USA (40.3°N 108.3°W). This portion of the field offices covers approximately 2 million ha with 385,000 ha having an active or pending BLM oil or gas lease (Fig. 3.1, BLM Colorado State Office, 2021). Mean annual precipitation at Dinosaur, CO (central location in study area) between 1981 and 2010 was 289 mm with a mean annual snowfall of 889 mm (U.S. Climate Data, 1981). Approximately 90% of the study area is public land that is predominantly managed by the BLM and the other 10% is privately owned.

I chose to conduct this study where big sagebrush (*Artemisia tridentata* Nutt.) was the dominant vegetation to reduce environmental variability and because big sagebrush land cover is a management concern for the sensitive habitat needs of the greater sage-grouse (*Centrocercus urophasianus*). The Southwest Regional Gap Analysis Project (SWReGAP) land cover class for 38 of the sampled well pads was Inter-Mountain Basins Big Sagebrush Shrubland and for the remaining two sampled well pads was Inter-Mountain Basins Montane Sagebrush [*Artemisia tridentata* Nutt. ssp. *vaseyana* (Rydb.) Beetle] Steppe (Lowry et al., 2005). Both land cover classes were characterized by perennial herbaceous cover such as Indian ricegrass [*Achnatherum hymenoides* (Roem. & Schult.) Barkworth], bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Á. Löve], and Sandberg bluegrass [*Poa secunda* J. Presl](Lowry et al., 2005). The principal parent material for the study area is residuum and/or colluvium weathered from shale or sandstone (Soil Survey Staff, 2021). The most prevalent use of the study area is energy extraction because the region is an important source of oil shale deposits of which the BLM issues and manages permits for their extraction (Taylor, 1987). Management of these permits includes reviewing drilling applications, monitoring compliance with extraction regulations, and evaluating the success of well pad reclamation.

Methods

Pad Sampling

To detect changes in plant community over time and differences in reclamation management, I used a stratified random sample to select 40 out of the total 979 reclaimed pads in the BLM Northwest District Office of Colorado. All 40 pads had big sagebrush as the dominant vegetation, were classified into three different aridity classes (Table 3.1), and then binned within four different times since reclamation (i.e., five, ten, fifteen, and twenty years; reclamation age). Of the total 979 reclaimed pads, 46.4% had big sagebrush SWReGAP cover classes. Aridity index value of all sagebrush dominated pads were acquired from the Global Aridity Index (Trabucco and Zomer, 2019) and were classified into groups using three quantiles, as identified by the *summary* function in the *base* package in R version 4.0.2 (R Core Team, 2021). Aridity values of less than 1,777 were classified as dry, values between 1,777 and 2,248 were semi-dry, and values greater than 2,248 were wet (Table 3.1).

Spatial Datasets

To implement the TSS-RESTREND methodology on our 40 selected pads, two spatial datasets were used: 1) a greenness-to-cover (GCI) index derived from Landsat 5 and 7 imagery during the growing season (March-September) using Google Earth Engine (GEE, Gorelick et al., 2017), and 2) daily precipitation values acquired from the GridMET dataset (Abatzoglou, 2013). Both datasets were obtained for the growing seasons of each year from 1984-2020 and used in their native resolution (Landsat imagery at 30 m; GridMET at 4 km). Spatial data were projected to Universal Transverse Mercator zone 13 North (UTM 13N).

TSS-RESTREND Methodology

I first calculated the GCI ~ precipitation relationship of the entire time series (i.e., VPR) for each well pad using OLS regression with GCI as the dependent variable and time as the independent variable (Fig 3.2). The time series consisted of the growing season of each year (March-October) for the years of 1984-2020. The VPR time series of each year's growing season was then merged into an individual time series spanning the entirety of 1984-2020. The residuals of the resulting VPR time series are then assumed to be the vegetation response separate from weather events and climate, making it easier to detect vegetation response specific to management actions.

I then applied BFAST to the residuals of the GCI ~ precipitation relationship to identify a list of potentially meaningful breakpoints (Fig. 3.2). If BFAST detected breakpoints, I applied the Chow test to the most significant breakpoint of the time series using the *CHOW* function in the TSS-RESTREND package in R version 4.0.2 (Burrell, 2020) If no significant breakpoints were detected by BFAST or if a BFAST breakpoint was not significant based on the CHOW test, I performed a single RESTREND for the entire time series of the well pad's VPR residuals. When the Chow test found a breakpoint significant, I then recalculated the VPR before and after the breakpoint. Each segment of the resulting VPR residuals were then analyzed using RESTREND (i.e., segmented RESTREND). This extra step of calculating the segmented VPR and RESTREND is necessary because the Chow test has identified that there is a structural break in the relationship between vegetation and precipitation trends, requiring two new VPR relationships be calculated within the time series (Burrell et al., 2017).All methods were applied using the TSS-RESTREND package in R version 4.0.2 (Burrell, 2020).

Google Earth Imagery and COGCC files

I then compared the results from the TSS-RESTREND methodology with imagery available in Google Earth (GE) up to July 2016 (Google Earth, 2016), and well pad documents stored and maintained for the public by the Colorado Oil and Gas Conservation Commission (COGCC) ((Colorado Department of Natural Resources, 2021). Specifically, I compared break points and trends identified by TSS-RESTREND with dates of well pad abandonment, dates of vegetation reseeding, documented disputes between operators and BLM, appearance of equipment on-site beyond the reported abandonment date, and other reported management actions. I then grouped the well pads into six categories based on the relationship between TSS-RESTREND results and GE imagery/COGCC documents: 1) high surrounding disturbance, 2) well pad not developed, 3) inaccurate abandonment date, 4) reclamation failure, 5) reclamation re-disturbed vegetation, and 6) successful reclamation

Results

Change in VPR Based on Location and Time

I did not observe any apparent trend in VPR residuals based on location (Fig. 3.1) but I did observe changes based on reclamation age (i.e., time since reclamation was completed) (Fig. 3.3). There was an initial decrease in the vegetation response to precipitation from year 5 to year 10 where vegetation response to precipitation became minimal (change in residuals = 0) to negative (change in residuals < 0). This was followed by an increase in the residuals from year 10 to year 15 that was sustained into year 20.

Change in VPR Based on Management Actions

Of the 40 well pads, I found only five pad's time series that qualified for segmented RESTREND analysis (i.e., most significant BFAST breakpoint was categorized by the Chow test as a significant structural break). Additionally, these 5 well pads had high variability in their VPR residuals relative to each other (Fig. 3.4). In the GE imagery, I observed that all 5 well pads occurred in area of high surrounding disturbance, meaning there were multiple other well pads and access roads within 30 m or less of the well pad surveyed (Fig. 3.5).

For the other 35 well pads, none of the breaks identified by BFAST resulted in significant structural breaks in the plant community, as defined by the Chow test. However, trends in their VPR residuals could often be categorized by events observed in GE imagery or recorded in COGCC paperwork.

I found that well pads with minimal change in VPR residuals (~0) and having few BFAST breaks (≤ 1), were either not fully developed (i.e., plant community not removed) or full reclamation was not performed (i.e., well pad is primarily bare ground) (n=7, Figs 3.4, 3.6). For example, Figure 3.5 shows two GE images taken approximately 2 and 4 years after the pad's abandonment date. In the earlier image, seeding rows appear to have been established. But by the second image, these rows no longer appear, and the well pad is predominantly bare ground. In addition, equipment is still on the south part of the well pad after the reported abandonment date.

For 4 other well pads, I detected high variability of change in VPR residuals, and the pads had multiple BFAST breaks (≥2) corresponding with dates of interim reclamation and final reclamation observed in GE imagery but not always recorded in COGCC paperwork (Table 3.2, Fig. 3.7). For example, I detected from the GE imagery that vegetation established after interim reclamation and then removed during final reclamation resulted in a wide range of mean changes in VPR residuals, where some well pads showed an overall positive trend and others negative (i.e., inconsistent vegetation response to precipitation) (Fig. 3.4, 3.7). In figure 3.7c, the GE image shows interim or final reclamation was performed before the reported abandonment date. A break was later detected by BFAST at the time of reported abandonment. The second GE image (Fig 3.7d, taken 7 years later), showed signs of a newer disturbance including seeding rows and a new road (i.e., change made to well pad structure later followed by final reclamation).

The two situations resulting in consistently positive trends in VPR residuals (> 0) (i.e., vegetation has increased response to precipitation through time) were where: 1) an inaccurate abandonment date was recorded in the COGCC database (n=2), and 2) final reclamation was performed and vegetation appeared to be re-established (n=7) (Figs. 3.8-3.9). For those well pads with inaccurate abandonment dates, the correct date was identified by BFAST, and evidence observed in GE imagery corresponded with the BFAST breaks (Fig. 3.8). For example, in figure 3.8c the first GE image was taken approximately four years after the reported abandonment date of the well pad, but equipment could still be seen on the well pad. The second GE image (Fig. 3.8d) though corresponds with a break identified by BFAST where equipment was removed, seeding rows were visible, and a new plant community appeared to be establishing. In instances of final reclamation being performed, BFAST breaks corresponded with well pad establishment and abandonment, and the natural plant community appeared to be re-established and blend with the surrounding area in the GE imagery (Fig. 3.9). In figure 3.8, the well pad's reported establishment and abandonment dates closely aligned with the BFAST breaks. I also found that GE images for the well pad showed signs of pad establishment (i.e., area cleared) and abandonment (i.e., plant community blending with surrounding area) near the same reported dates of establishment and abandonment.

Discussion

TSS-RESTREND

The TSS-RESTREND methodology was initially sensitive to changes in the vegetation-precipitation relationship such as when potential breaks identified by BFAST corresponded with well pad establishment and abandonment dates. However, these breaks were most often not classified as significant structural breaks by the Chow test unless there was a high amount of surrounding disturbance not directly associated with the individual well pad. In this case, the Chow test may be too conservative because it creates too great of a statistical hurdle for designating a significant structural break, where segmented RESTREND analysis would be performed. Segmented RESTREND though is considered more appropriate in areas experiencing a high-level of degradation such as what occurs on well pads (Burrell et al., 2017; Waller et al., 2018). Additionally, RESTREND results for the remaining pads had weak or no relationship between time and VPR residuals (Fig. 3.6-3.8) confirming that this type of linear analysis is often not appropriate in areas with low unpredictable rainfall, limited soil nutrients, and frequent changes in vegetation cover such as what occurs on disturbed arid landscapes (Jiang et al., 2017; Lawley et al., 2013; Liu et al., 2019).

The large footprint of oil and gas development on US public land aligns with the original creation of the TSS-RESTREND methodology where Burrell et al., (2017) evaluated land cover change for the entire Australian continent. In my application of the methodology, I evaluated trends on individual pads and then aggregated by reclamation age and GE type which limited my ability to assess change in land cover due to oil and gas development at a landscape scale. Aggregating by reclamation age and GE type though did reveal that at site scale, management actions are affecting reclamation outcomes. Further studies are needed to determine if differences in reclamation outcomes based on management are sustained at a landscape scale such as by comparing impacts between low and high use areas of oil and gas development.

An additional difference in my application of TSS-RESTREND is that I used Landsat imagery at a spatial resolution of 30 m instead of the Advanced Very-High-Resolution Radiometer (AVHRR) sensors used by Burrell et al., (2017) at a spatial resolution of 1.1 km. The longer retrospective view of Landsat allowed us to evaluate pre-development trends on the well pads, all of which were developed pre-2000. Landsat has imagery back to 1984, while other sensors commonly used for land change monitoring either have courser spatial resolutions (e.g., AVHRR) or do not start to provide imagery until the late 1990’s or early 2000’s (e.g., RapidEye, PlanetScope). With the longer temporal resolution and a finer spatial resolution, Landsat can detect subtle environmental changes over time and provide a base line for evaluating reclamation outcomes which may be missed in newer satellites (Maynard et al., 2016). Newer satellites with finer spatial resolution and more frequent imagery, could serve as an important tool for land managers to evaluate the progress of reclamation effects over time when field monitoring data is not available (Maynard et al., 2016). Similarly, unmanned aerial imagery with analysis could serve as a supplement at the time of a reclamation evaluation because it provides a quantitative and objective measure of well pad conditions, but it doesn’t replace the wealth of information provided by the longer retrospective view of older satellite sensors.

One issue I had with using Landsat for assessing land cover change is that the typical size of my pads was $30m^2$ which exactly matches the 30 m pixel size of Landsat imagery. The moderate spatial resolution of Landsat coupled with the discrete nature of a pad’s footprint may have prevented me from capturing the finer vegetative characteristics typical of early successional plant communities. Without the finer vegetation characteristics, it was difficult to detect structural changes in a post-reclamation plant community (Di Stéfano et al., 2020).

Post-Reclamation Plant Community Outcomes

I observed a possible transition from early to late successional plant species on reclaimed pads based on changes observed in the VPR residuals over time. There was an initial decrease in the residuals at 10 years which was immediately followed by an increase that was sustained at 20 years. This change suggests that earlier successional plant species may be fading out by 10 years and are being replaced by later successional species (Fig. 3.3). There is concern though that as time passes the later successional species may experience long-term establishment issues meaning that the positive trend in residuals would not be sustained beyond 20 years. For example, big sagebrush establishment may be prevented by the persistent soil compaction that exists underneath the re-spread topsoil, causing insufficient rooting depth, and is a result of well pad use during active extraction (Lupardus et al., 2020; Rottler et al., 2019). Overall, reclamation may result in the re-establishment of desirable plant species but in the long-term there may be permanently altered plant community trajectories that do not match the surrounding area. These altered plant community trajectories happen because their salvaged topsoil is physically and biologically different than the surrounding soil that underwent natural pedogenesis over thousands of years (Di Stéfano et al., 2021).

Additionally, I observed in the GE imagery multiple re-disturbances not recorded in the paperwork available in the COGCC database. Sometimes these re-disturbances appeared to be the performance of interim reclamation where the well pad footprint was reduced from what was needed to establish the pad to the footprint needed for active extraction (e.g., 60x60m to 30x30m). In these types of re-disturbances, interim reclamation appeared to establish an intermediary plant community that provided site stabilization which was then completely removed at the time of final reclamation. Rottler et al, (2019) described this interim process as re-disturbing the topsoil for an additional time, for a total of 3 instances of topsoil disturbances: well pad establishment, interim reclamation, and final reclamation. The additional topsoil disturbance during interim reclamation causes further loss of soil organic matter which may impair the ability of final reclamation to support soil recovery and plant community stabilization (Costantini et al., 2016).

Reclamation Documentation and Communication

Another possible explanation for the lack of plant community change is that post-reclamation human activities prevented long term desirable outcomes. For example, management often appeared to me as inconsistent because Sundry notices and other official correspondence did not match the reported final abandonment dates. There is a significant number of records that exist solely as physical paper files stored within the BLM field offices, but I did not have access to them at the time of this paper. The lack of public access to well pad records makes it difficult for reclamation managers working across and within multiple administrative boundaries to share and pass down the successes and failures in reclamation. I have had communication from the BLM White River FO that there is an ongoing effort to digitize all well pad records but the process to do so is long and expensive. In summary, the current absence of a digital format for all well pad records creates a communicative barrier that may be preventing progress for desirable outcomes in the practice and understanding of oil and gas reclamation. Additionally, the incongruence in reclamation standards and lack of communication between agencies creates a seemingly impossible situation for federal, state, and private land managers to achieve harmonious and successful oil and gas reclamation across landscapes. Reaching plant community recovery on well pads is particularly onerous for federal land managers who are under a multiple use mandate where they manage a myriad of other land uses alongside reclamation (Di Stéfano et al., 2021).

For operators, recovery of the disturbed surface is a secondary consideration in reclamation because the bulk of reclamation cost goes toward plugging the well to prevent seepage and pollution of underground soil and water (Di Stéfano et al., 2021). This lack of focus on plant community recovery is further confirmed by the detailed information available on the COGCC database about the geology and engineering aspects of drilling and abandonment, but with little information on the surface biological impacts and their reclamation practices. In addition, Sundry notices over the life of the well and post-reclamation do not cover reclamation progress which limits the ability of land managers to pass down reclamation knowledge to future generations and requires more reliance on individual experience.

Conclusions and Recommendations

I found TSS-RESTREND to be useful for detecting high-levels of degradation over time at the scale of a singular well pad which was usually 30m^2. Identified breaks and segmented VPR trends were also helpful in parsing out which management actions resulted in specific vegetation responses. Overall, the multiple steps of the methodology were effective for describing the level of degradation before and after pad establishment and reclamation.

TSS-RESTREND could detect plant community changes that occurred, but I did not observe long-term plant community establishment or succession because it appeared to be halted by management practices identified in documentation. The lack of plant community recovery leaces the BLM vulnerable to litigation with operators, other agencies, and the public. I recommend that a set protocol be created for documenting reclamation that would include reclamation practices, plant community progress before the final inspection, and the conditions of approval used for releasing operators from environmental liability. Currently, too much of reclamation knowledge is stored on an individual and/or field office level making it difficult to manage reclamation on the landscape scale where oil and gas development occurs. Having a standardized and greater amount of documentation will allow for knowledge and expertise to be passed on to future reclamation managers. In conclusion, TSS-RESTREND was a useful diagnostic tool for me to detect reclamation management actions and begin to understand outcomes.

Equations

Equation 1: Description of the calculation for the Soil Adjusted Total Vegetation Index (SATVI) (Marsett et al., 2006). Where ρ=reflectance, SWIR1=Landsat Band 5 (1550–1750 nm), SWIR2=Landsat Band 7 (2080–2350 nm), Red=Landsat Band 3 (630–690 nm), and L is a soil-brightness correction factor (ranging from dark or no soil, 0, to 1, bright or high levels of soil). I used a soil brightness factor of 0.5.

$$SATVI = \frac{\rho\mathrm{SWIR1} - \rho\mathrm{Red}}{\rho\mathrm{SWIR1} + \rho\mathrm{Red} + \mathrm{L}} * (1 + L) - \frac{\rho\mathrm{SWIR2}}{2}$$

Equation 2: Description of the calculation of Total Fractional Cover (TVFC). TVFC is derived from Soil Adjusted Total Vegetation Index (SATVI) values).

$$TVFC = \frac{SATVI - SATVImin}{SATVImax - SATVImin} * 100$$

Tables

Table 3.1: Number of sampled well pads in each sampling strata, for a total of 40 well pads. Aridity classes are as follow: dry (aridity value < 1,777), semi-dry (1,777 < aridity value < 2,248), and wet (aridity value > 2,248) (Trabucco and Zomer, 2019)).

Time since Reclamation	Aridity class	Count
5	Dry	1
	Semi-dry	2
	Wet	0
10	Dry	3
	Semi-dry	6
	Wet	5
15	Dry	3
	Semi-dry	6
	Wet	4
20	Dry	4
	Semi-dry	5
	Wet	1

Table 3.2: Frequency table of reclaimed well pads that occurred in each group identified from TSS-RESTREND results and Google Earth imagery (n=40). Groups indicate how management affected reclamation outcomes observed in time series analysis. The first group describes where the TSS-RESTREND methodology found no significant breaks in the residuals of the vegetation~precipitation relationship, as identified by Breaks for Additive Season and Trend (BFAST).

Category	Count
No BFAST breaks	15
High surrounding disturbance	5
Not developed	2
Abandonment date inaccurate	2
Reclamation failure	5
Reclamation re-disturbed	4
Reclamation successful	7

Figures

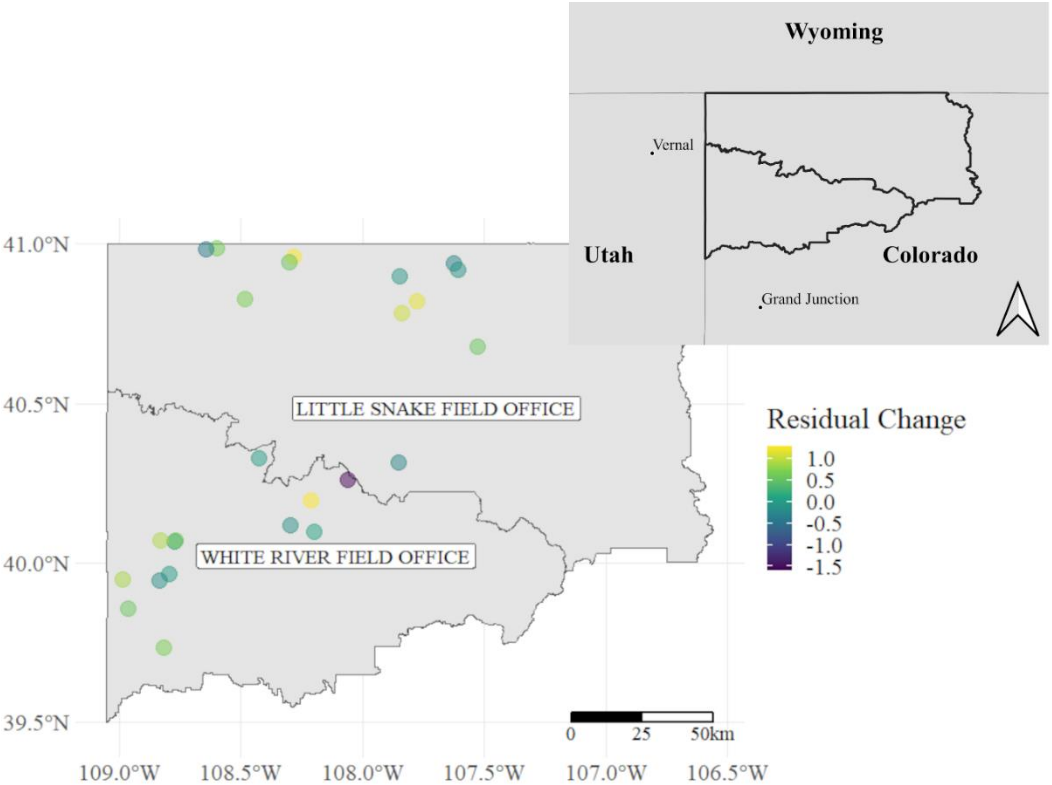

Figure 3.1: Location of all well pads surveyed in the Little Snake and White River Field Offices of the Bureau of Land Management (BLM) in Northwestern Colorado. Color indicates overall change in residuals for each pad’s vegetation-precipitation relationship (VPR).

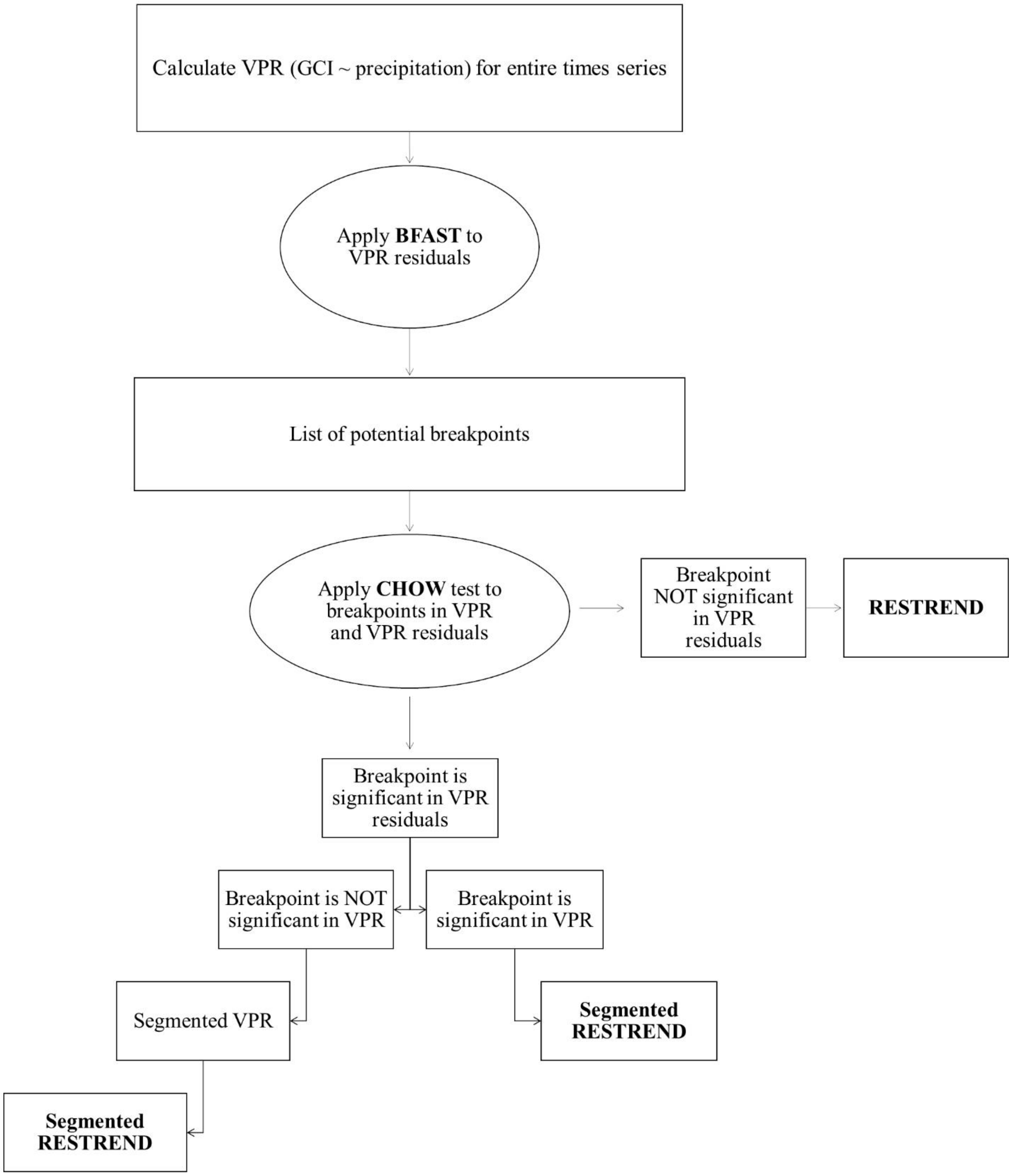

Figure 3.2: Outline of the TSS-RESTREND methodology first described by Burrell et al., 2017.

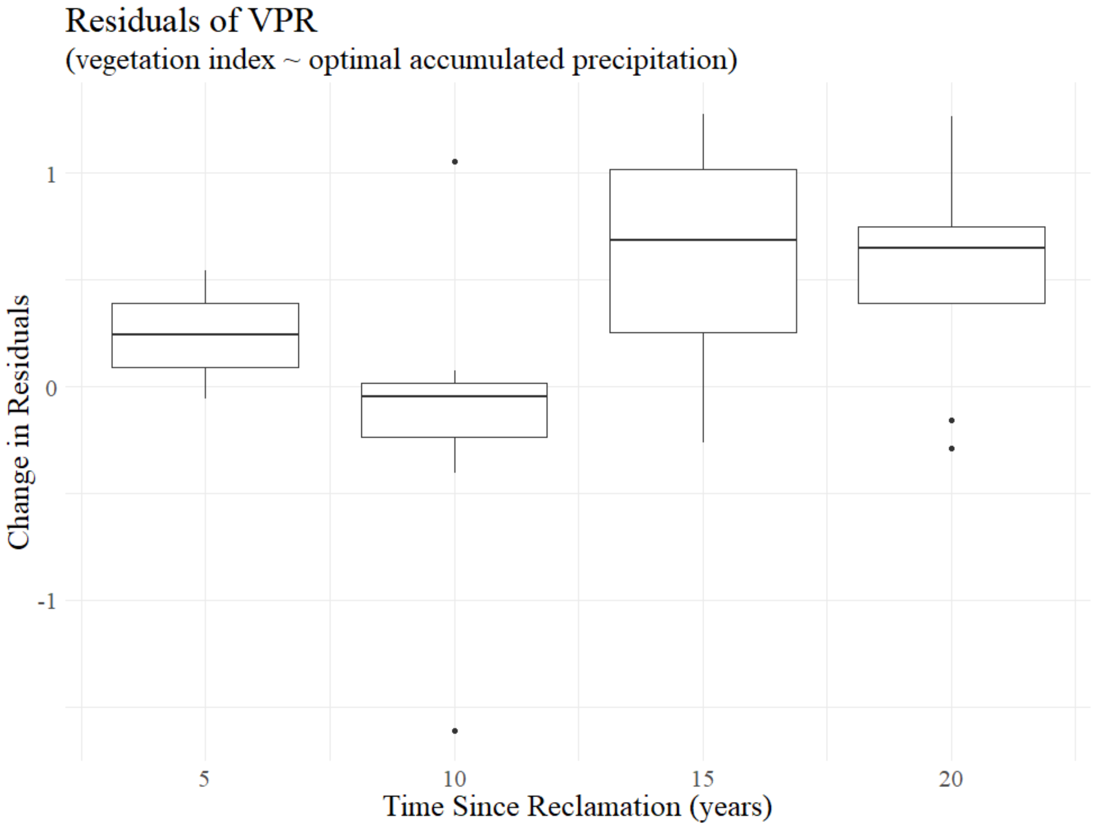

Figure 3.3: Box plots of the mean change in residuals of the vegetation-precipitation relationship (VPR) for well pads based on time since reclamation was completed. The categories are as follows: 5 years (2015-2019, n=3), 10 years (2010-2014, n=14), 15 years (2005-2009, n=13), and 20 years (2000-2004, n=10).

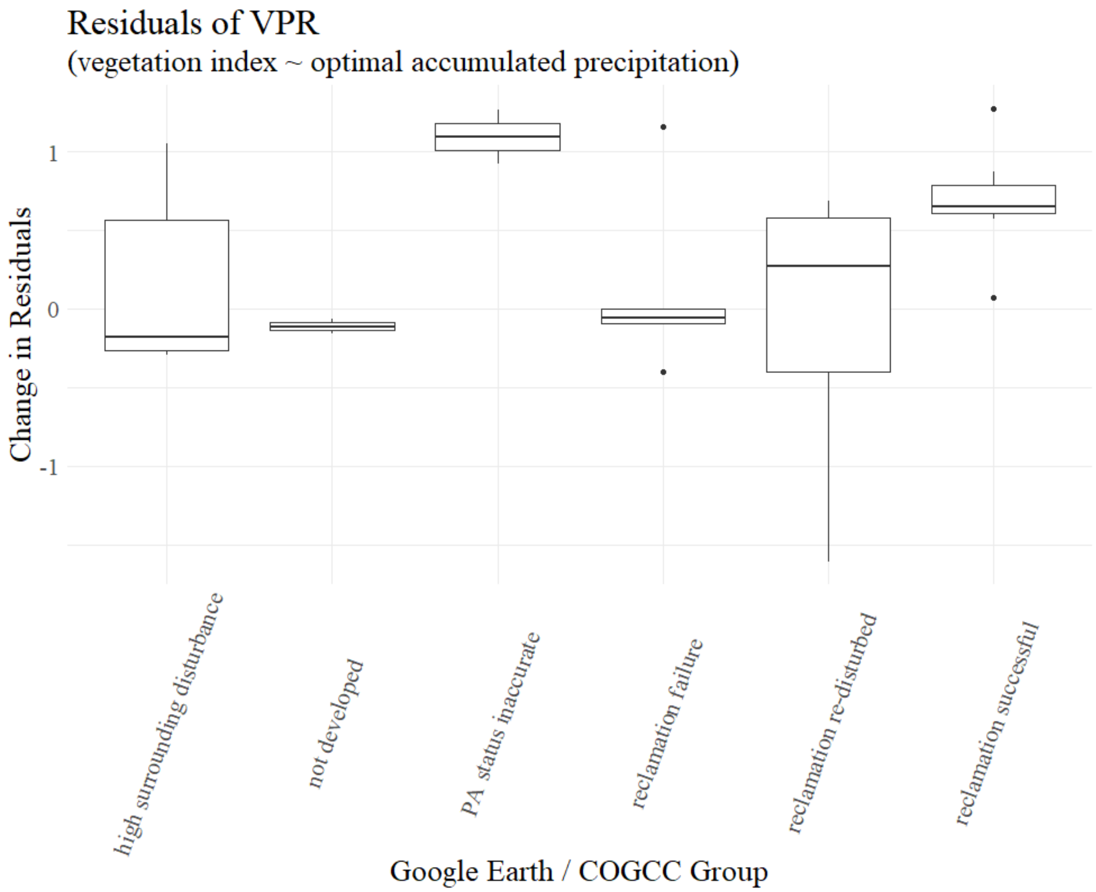

Figure 3.4: Box plots of the mean change in residuals for the vegetation-precipitation relationship (VPR) for well pads based on categories defined by interpretation of Google Earth imagery and paperwork filed with the Colorado Oil and Gas Conservation Commission (COGCC).

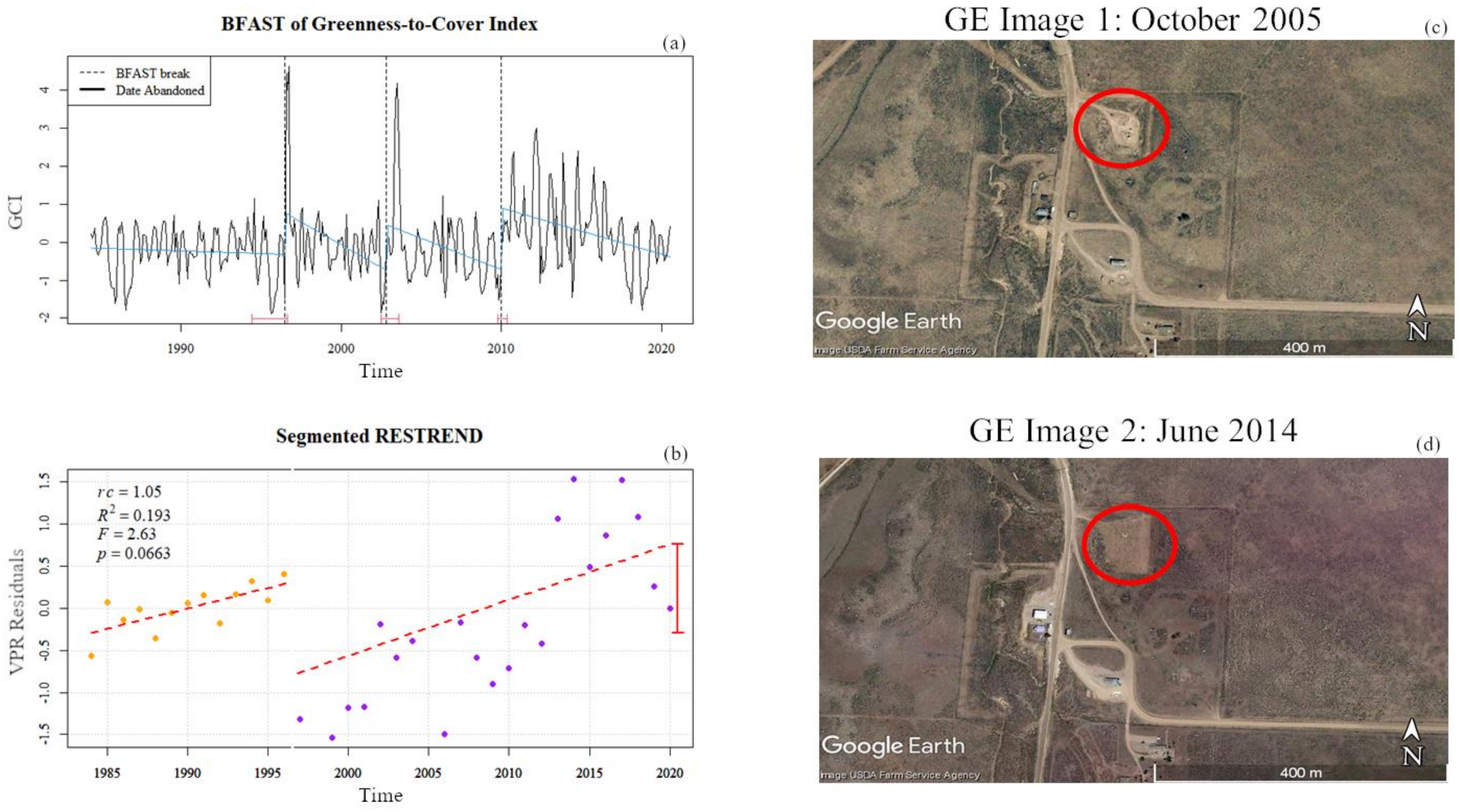

Figure 3.5: Example of well pad with high surrounding disturbance. Results for well pad 05-081-06441 (identifier for Colorado Oil and Gas Conservation Commission) for each step of the TSS-RESTREND methodology and Google Earth (GE) images that correspond with breaks in the well pad's GCI time series, as identified by BFAST. Red circle indicates location of well pad in the GE image. P-value is for the most significant break in the residuals of the vegetation – precipitation (VPR) relationship, as determined by the Chow test.

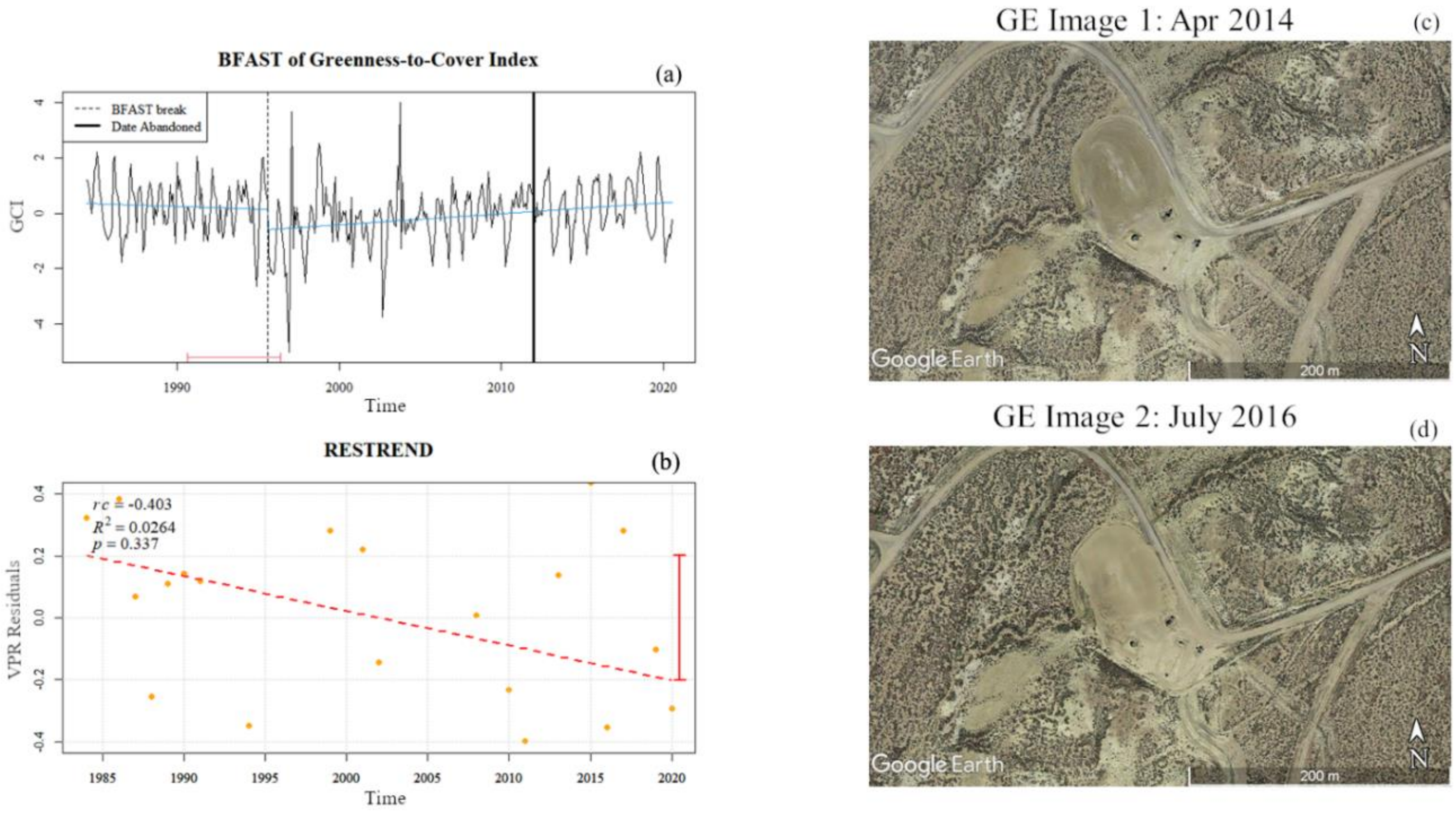

Figure 3.6: Example of well pad where final reclamation was not completed or was not successful. Results for well pad 05-081-06865 (identifier for Colorado Oil and Gas Conservation Commission) for each step of the TSS-RESTREND methodology. P-value is for the most significant break in the residuals of the vegetation – precipitation (VPR) relationship, as determined by the Chow test. Google Earth (GE) images are taken two and four years after the reported abandonment date.

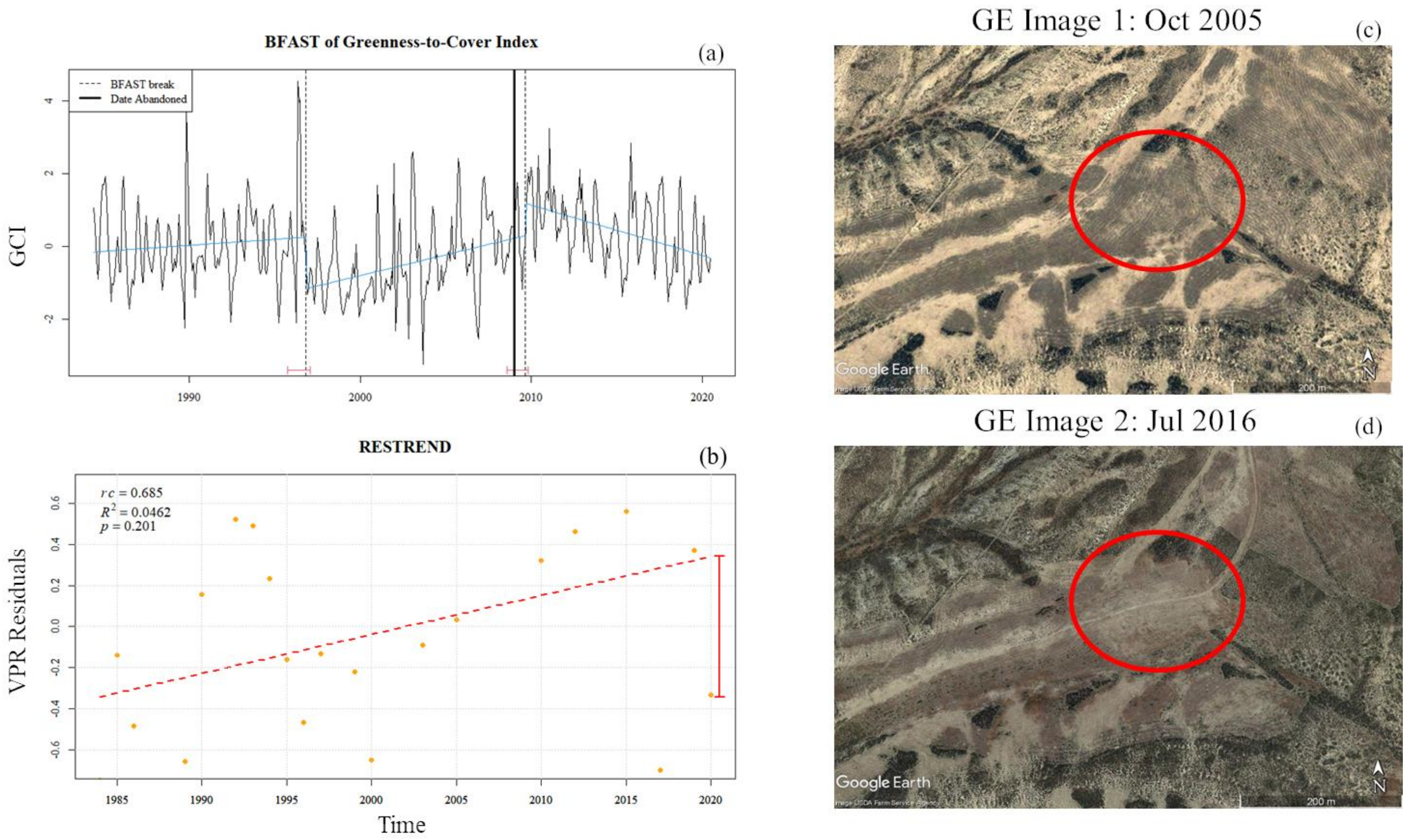

Figure 3.7: Example of well pad where reclamation disturbed a previously re-established plant community (i.e., previous interim or final reclamation). Results for well pad 05-081-07428 (identifier for Colorado Oil and Gas Conservation Commission) for each step of the TSS-RESTREND methodology and Google Earth (GE) images that are before and after the reported abandonment date. Red circle indicates location of well pad in the GE image. P-value is for the most significant break in the residuals of the vegetation – precipitation (VPR) relationship, as determined by the Chow test.

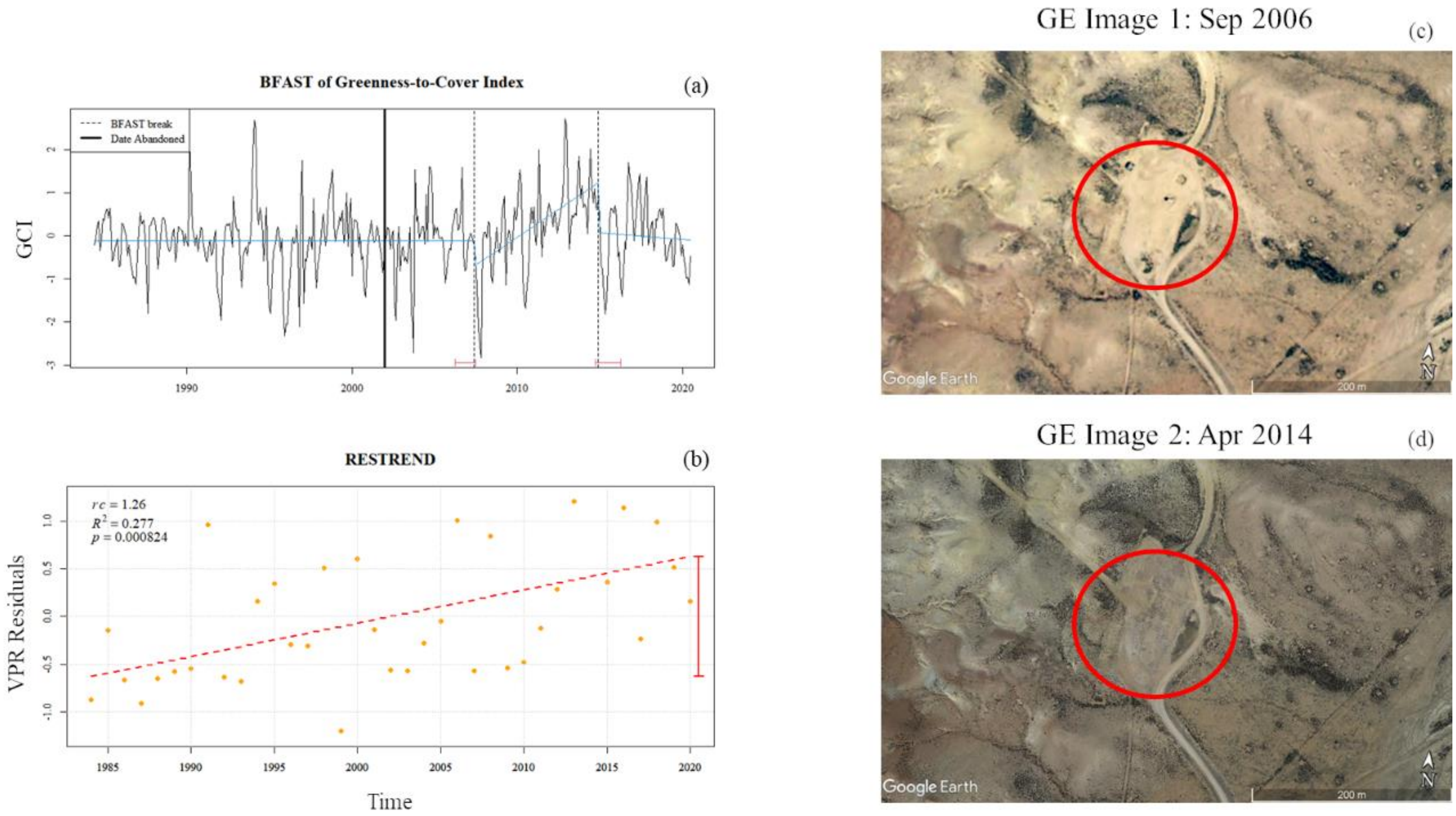

Figure 3.8: Example of well pad with an inaccurate abandonment date as documented by the Colorado Oil and Gas Conservation Commission (COGCC). Results for well pad 05-081-05488 (identifier for COGCC) for each step of the TSS-RESTREND methodology and Google Earth (GE) images that correspond with breaks in the well pad's GCI time series, as identified by BFAST. Red circle indicates location of well pad in the GE image. P-value is for the most significant break in the vegetation – precipitation (VPR) relationship, as determined by the Chow test.

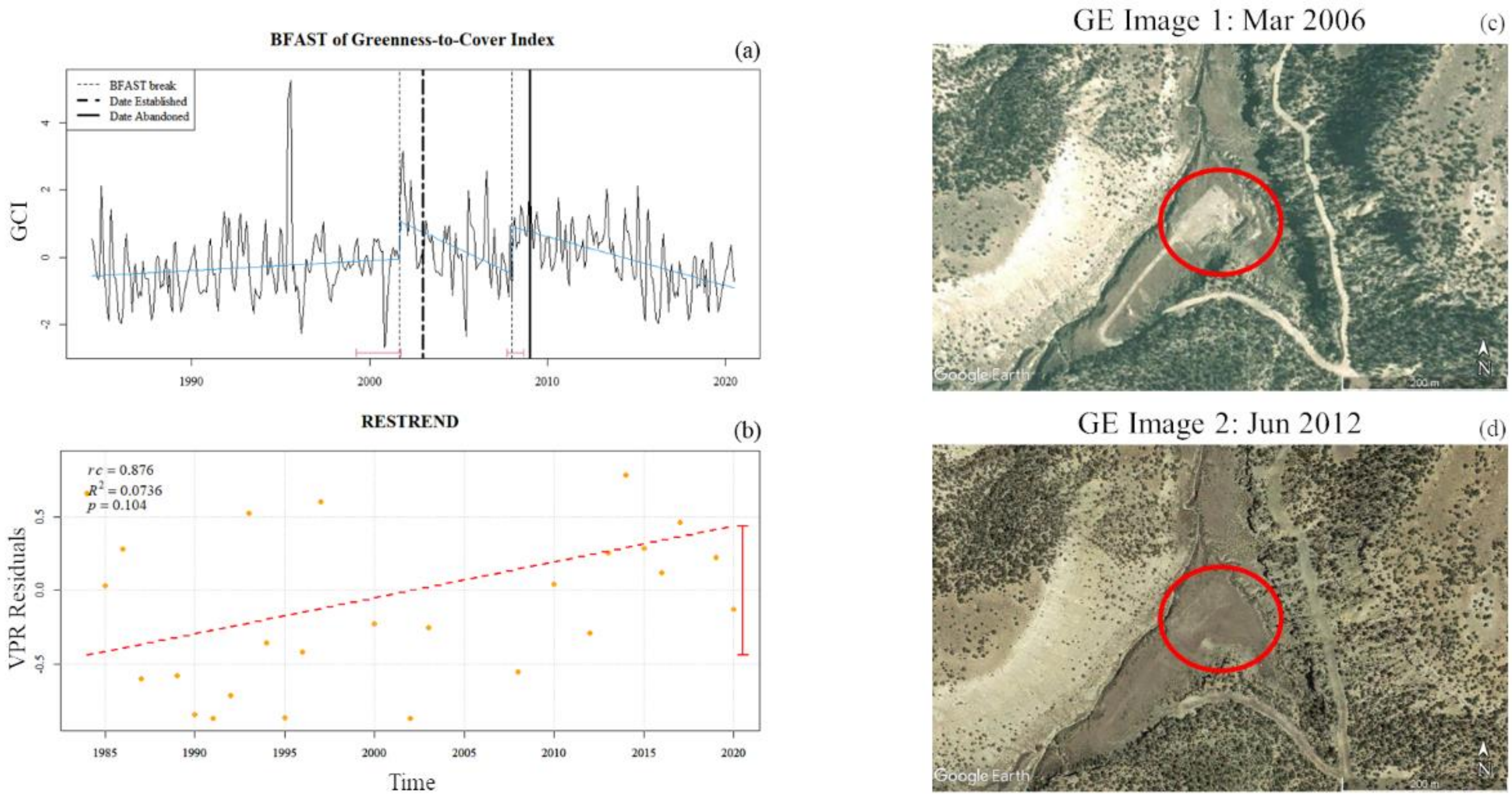

Figure 3.9: Example of well pad with plant community recovery after reported abandonment date. Results for well pad 05-103-10370 (identifier for COGCC) for each step of the TSS-RESTREND methodology and Google Earth (GE) images that correspond with breaks in the well pad's GCI time series, as identified by BFAST. Red circle indicates location of well pad in the GE image. P-value is for the most significant break in the vegetation – precipitation (VPR) relationship, as determined by the Chow test.

Chapter 4: Using Plant Traits in a 20-year Chronosequence to Determine Land Potential of Reclaimed Well Pads in Western Colorado

Introduction

Public Land Management of oil and gas Development

On US public land, oil and gas development is primarily administered by the Bureau of Land Management (BLM) which oversees approximately 99 million surface ha of public land and 283 million subsurface ha. Approximately 5 million subsurface ha produces oil and gas in profitable quantities (Bureau of Land Management, 2021; U.S. Department of the Interior, 2017). US federal land management agencies, like the BLM, are required to manage for multiple natural resource uses without permanent impairment of the productivity of the land and the quality of the environment, commonly referred to as the multiple-use mandate (Haskell, 1976). The unique nature of oil and gas development (i.e., vast network of discrete disturbances from well pads, pipelines, and connecting access roads) challenges this mandate, and plant community recovery has been observed still occurring 50-100 years after well pad abandonment, if at all (Di Stéfano et al., 2021; Rottler et al., 2018). Additionally, US federal land management agencies lack a common environmental and legal framework that clearly communicates to private drilling companies the expected outcomes of reclamation activities of lands damaged during development (Di Stéfano et al., 2021). This has put US federal land management agencies in a contentious, and often litigious, environment with private drilling companies to manage oil and gas development.

Oil and gas reclamation is the process by which lands damaged by oil and gas development are re- paired and desired ecosystem services are restored (USDI and USDA, 2007). Steps in reclamation include: 1) removal of all equipment, 2) site preparation (e.g., recontouring of landscape), and 3) revegetation (Di Stéfano, 2021). The reclamation process typically takes 3-5 years because vegetation and soil processes need sufficient time to establish, and monitoring data are needed to determine if a site is on a trajectory toward meeting reclamation success criteria. Reclamation success criteria can include requirements such as soil stabilization and establishment of a self-perpetuating native plant community resistant to invasive plant species (Di Stéfano et al., 2021). On US public land, a combination of federal and state land managers determine whether a site meets the success criteria and if a private drilling company can be released from environmental liability.

Reclamation success criteria vary widely across states and BLM field offices but have a common theme of trying to recover the desired post-reclamation land potential of a site (Bureau of Land Management, 2021). Land potential refers to the types and amounts of vegetation that can occur at a site given the circumstances and available resources (e.g., soil nutrients, climate conditions) and is slow moving in time (i.e., does not change drastically year-to-year) (Duniway et al., 2010). Post-reclamation land potential describes the altered soil and vegetative outcomes that can be expected on a highly disturbed site whose plant community and natural soil horizonation were completely lost during development and reclamation (Di Stéfano et al., 2021). Field offices differ extensively in how they define and measure post-reclamation outcomes, making the evaluation and interpretation of post-reclamation trends inconsistent and difficult to compare across management boundaries.

Post-Reclamation Trends

Oil and gas development across the western US occurs in regions characterized by an arid climate where precipitation is low and often unpredictable (Nauman et al., 2017; Noojipady et al., 2015; Waller et al., 2018). Because climate is a dominant influencing factor on reclamation outcomes, the dry climate of the western US compounds the complexities and difficulties of reclamation, making it difficult to put a site on a pathway to plant community recovery (Waller et al., 2018). For example, well pads abandoned during multiyear droughts have decreased plant community recovery and may require reseeding, whereas well pads reclaimed during wet periods experience more rapid recovery (Waller et al., 2018). Additionally, changes in timing of precipitation affects the composition of plant communities. For example, higher than average winter precipitation followed by multiple dry years increases the risk of exotic species invasion after a disturbance where a plant community had been completely removed such as what has occurred on a reclaimed well pad (Villarreal et al., 2019).

The expected outcome of reclamation, particularly for reseeding, is to restart and accelerate successional processes, provide resources to allow desired plants to outcompete invasive plant species, and prevent soil erosion (Fowers, 2015). In reality, current reclamation practices have not proved sufficient in facilitating plant community recovery and many reclaimed oilfields continue to be highly degraded landscapes (Di Stéfano et al., 2020; Nauman et al., 2017; Rottler et al., 2018; Sylvain et al., 2019). Observed outcomes from development or reclamation failure include habitat degradation, increased susceptibility to invasive plant species, and altered landscape hydrology, and impacts which often impair or inhibit other important ecosystem values and permitted uses such as livestock grazing, wildlife habitat, and recreation (Allred et al., 2015; Di Stéfano et al., 2021; Walker et al., 2007; Waller et al., 2018; Yu et al., 2015).

Seeded plant species in reclamation are typically native perennial grasses and forbs that will meet the multiple management needs of the field office and perform desired ecosystem services. Seeded species though are often not the same species from before disturbance or surrounding area, and it is unclear if this mismatch leads to permanent alternative successional trajectories for reclaimed well pads (Farrell et al., 2021; Rottler et al., 2018; Waller et al., 2018). More specifically, while seeded species may meet reclamation requirements for vegetation, they often differ in trait-based characteristics of vegetation from the previous plant community, such as the pad being seeded with mesic plants when xeric plants dominated previously, resulting in structurally different plant communities compared to the surrounding area (Lupardus et al., 2020). Additionally, shrubs are not typically included in seed mixtures and recruitment from the surrounding area is slow or does not occur, causing vegetation structural differences to persist decades after drilling companies are released from environmental liability (Fowers, 2015; Rinella et al., 2016). These vegetation structural differences have management implications for sensitive wildlife such as the Greater sage grouse (*Centrocercus urophasianus*) who have lost large amounts of intact and suitable habitat (e.g., sufficient vertical cover from predators) to energy development (Kirol et al., 2020).

Post-reclamation soils are often physically and biologically different than soils from surrounding areas, being characterized as nutrient poor and having a decreased ability to retain water within the soil profile (Di Stéfano et al., 2021; Fowers, 2015). These characteristics are a result of soil mixing during the construction and subsequent reclamation following abandonment of a well pad (Di Stéfano et al., 2021). The topsoil is first scraped and stored in preparation for pad establishment and drilling of the well. Later during reclamation, stored topsoil will be respread over the pad in preparation for reseeding. In spite of the outsize effects of soil on vegetative reclamation outcomes, soil characteristics and processes are often treated as secondary to the typical reclamation focus on vegetation composition and cover (Rinella et al., 2016; Rottler et al., 2019). The lack of attention to soil outcomes coupled with soil mixing, can result in soil legacy effects on well pads that persist decades after reclamation is completed (e.g., higher bulk density, nutrient poor) (Janz et al., 2019).

Evaluating Post-Reclamation Trends

There have been many studies on post-restoration plant community dynamics using chronosequences that compare traits within and between plant communities of different "ages" since restoration completion (e.g., Carter and Blair, 2012; McKone et al., 2021).The chronosequence approach seeks to quantify changes in community structure over a specified amount of time by using space-for-time design where sampling sites of increasing age is a substitute for sampling an individual site over time (Claassens et al., 2011; Willand et al., 2013). A technique used in chronosequence analysis to characterize plant community change is the community weighted means (CWM) method that quantifies patterns in the plant-trait-environment relationship by selecting traits that affect plant response to environmental change and determine their influence on ecosystem function at a specified site using linear-constrained ordination (Funk et al., 2017; Jing et al., 2019; Šmilauer and Lepš, 2014; Violle et al., 2007). In the CWM method there is an assumption of low variability within a plant species for each trait so that the relative dominance of individual traits on a site's ecosystem function can later be evaluated using a method such as a principal components analysis (Funk et al., 2017; Jing et al., 2019). In other words, the assumption is that variation in plant traits is greater between species than within an individual species. The plant traits' values are aggregated using a matrix of species composition (e.g., LPI data) and table of species attributes (e.g., from NRCS database) to characterize ecosystem processes and function at a broader community or landscape scale, or in our case, reclamation age (Zelený, 2018). More specifically, the mean of species attributes for each reclaimed well pad are weighted by the relative abundance of species in the pad with those attributes (Zelený, 2018). The null hypothesis when using CWM derived values is that the aggregated trait values remain the same for all environmental conditions, meaning that no group of traits is indicative of plant community change (e.g., shift to native plant community) in response to environmental change (e.g., reseeding during reclamation) (Šmilauer and Lepš, 2014).

Objectives

The objective of this paper was to identify plant and soil influences on post-reclamation potential and provide an objective and standardized approach to reclamation monitoring and evaluation in an area of high management concern. I compared plant community and soil traits at different reclamation ages and evaluate which traits are reliably indicative of a reclaimed well pad's altered land potential. To accomplish this comparison, I conducted the study in an area experiencing a high amount of oil and gas development, in Colorado where there is a robust regulatory framework and history of wide-spread reclamation (Mayer, 2019). Additionally, I chose a study area dominated by sagebrush because the preservation of this vegetation type is a federal management priority for the maintenance of intact sage grouse habitat (Chambers et al., 2017) and to reduce variability caused by comparing across different vegetation types.

Study Area

I conducted this study within the western portions of the BLM's White River and Little Snake Field Offices in northwestern Colorado, USA. This portion of the field offices covers approximately 2 million ha (40.3°N 108.3°W) with 385,000 ha having an active or pending oil and gas lease with the BLM (Fig. 4.1, BLM Colorado State Office, 2021). Mean annual precipitation of Dinosaur, CO (central location in study area), from the period between 1981 and 2010, was 289 mm with a mean annual snowfall of 889 mm

(U.S. Climate Data, 1981). Approximately 90% of the study area is public land that is predominantly managed by the BLM and the other 10% is privately owned.

The major vegetation type for this area is Inter-Mountain Basins Big Sagebrush (*Artemisia tridentata* Nutt.) Shrubland (Lowry et al., 2005). The study area is also characterized by perennial herbaceous cover such as Indian ricegrass (*Achnatherum hymenoides* (Roem. & Schult.) Barkworth), bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Á. Löve], and Sandberg bluegrass (*Poa secunda* J. Presl]. The principal parent material for the study area is residuum and/or colluvium weathered from shale or sandstone (Soil Survey Staff, 2021). The most prevalent use of the area is energy extraction because the study area is an important source of oil shale deposits of which the BLM issues and manages permits for their extraction (Taylor, 1987). Management of these permits includes reviewing drilling applications, monitoring compliance with extraction regulations, and evaluating the success of well pad reclamation. See DiStefano et al. 2021 for a review of current reclamation regulations and management.

Methods

Sampling Design

I used a stratified random sample to select 40 out of the total 979 reclaimed pads in the BLM Northwest District Office of Colorado. All 40 pads had big sagebrush as the dominant vegetation, were classified into three different aridity classes (Table 3.1), and then binned within four different times since reclamation (i.e., five, ten, fifteen, and twenty years; reclamation age). Of the total 979 reclaimed pads, 46.4% had big sagebrush SWReGAP cover classes. Aridity index value of all sagebrush dominated pads were acquired from the Global Aridity Index (Trabucco and Zomer, 2019) and were classified into groups using three quantiles, as identified by the *summary* function in the *base* package in R version 4.0.2 (R Core Team, 2021). Aridity values of less than 1,777 were classified as dry, values between 1,777 and 2,248 were semi-dry, and values greater than 2,248 were wet (Table 4.1).When collecting field data, 4 of the well pads were inaccessible because of road conditions so only 36 of the 40 had field data sampled.

Pad Sampling

I sampled each well pad between May and August, 2021 and collected foliar vegetation cover, vegetation height, species richness, and soil characteristics data following the BLM’s Assessment, Inventory, and Monitoring (AIM) program protocols (Herrick et al., 2017). Foliar cover was collected using the line-point intercept (LPI) method on three parallel 25m transects at each pad spaced 12.5m apart. Along each transect I recorded vegetation canopy intercepts against a 2mm pin lowered vertically through the plant canopy to the ground. Intercepts were recorded by species and soil surface every 0.5m for a total of 50 LPI points per transect and 150 LPI points per well pad. Plot-level cover by species and functional group (i.e., shrubs, perennial grasses, non-native invasive plant species, and total foliar cover) was calculated by dividing the number of intercepts for each species or group by the total number of possible intercepts in the plot (n=150). I recorded vegetation height every 2.5m on each transect for the tallest herbaceous and woody plant within a 15cm radius from the transect. For species richness, I recorded all species that occurred within a 30m radius from plot center during a 15-minute search.

I calculated species diversity for each well pad using the Shannon-Wiener (H′) and Simpson (D) indexes. Shannon-Wiener index values range from 0.0 to 5.0, with diversity increasing as the values increase, with typical values between 1.5 and 3.5 (Shannon, 1948). Simpson's index values range from 0.0 to 1.0, with diversity increasing with the value (Simpson et al., 1949). Shannon-Wiener is sensitive to species richness (number of species) than Simpson's, but values from Simpson's reflect a site's species evenness and are more heavily weighted towards the most abundant species (Nagendra, 2002; Spellerberg and Fedor, 2003). Species richness between reclamation ages was also compared.

Soil characteristics were determined from three 15cm deep soil excavations at the center of each transect with a total of three soil samples per well pad. I collected ~25-50g samples from each excavation which were later analyzed in a lab for soil pH and electrical conductivity (EC) (Burt, 2011). Soil texture was determined using the hand texturing method described in Herrick et al. (2017). Bulk density was calculated using the photogrammetry-based method described in Whiting et al., (2020), where photos of the soil clod were captured at multiple angles to determine soil volume which was then used to derive soil bulk density (BD). Soil clod photos were acquired by placing a soil clod on a turntable and photographing the clod every 10° as the turntable was rotated, until a full rotation was completed. Agisoft Metashape version 1.7.3 was used to align the overlapping clod photos and construct a stereo model of the soil clod using structure from motion techniques (Westoby et al., 2012). On the turntable, marked control points defining a Cartesian plane of fixed dimensions were used to scale the stereo model for accurate measurements. The stereo model was rendered as a 3D mesh and volume of the mesh was computed.

Plant Traits

A set of plant traits considered sensitive to changes caused by development and plant colonization ability post-reclamation were selected for analysis of the LPI data (Lupardus et al., 2020)(Table 4.1). Traits of each plant species recorded were acquired from the PLANTS database of the Natural Resource Conservation Services (NRCS) (USDA NRCS, 2022). I also checked the database for expected variability in selected traits within plant species to satisfy the assumption that a trait is consistent for an individual plant species, allowing for the relative influence of that trait to be evaluated on overall plant community structure.

Statistical Analyses of Community Traits

In this study I used a chronosequence of 20 years (2000-2020) of reclaimed pads to detect community structural changes over time by comparing community aggregated vegetation traits and soil characteristics across each of four reclamation age classes (i.e., five, ten, fifteen, and twenty years since reclamation). The CWM for each well pad was then calculated from of an individual well pad’s soil characteristics (pH, EC, and BD), LPI cover of each plant trait, and the species-by-trait matrix (Table 4.1). The CWMs were derived using the *cwm* function in the R package *weimea*.

Principal Component Analysis (PCA) is often used to detect and interpret patterns in complex ecological phenomena (Forkman et al., 2019). PCA is an ordination method that condenses multivariate data into descriptive axes (i.e., principal components [PC]) that describe the variance between points (e.g., well pads) (Forkman et al., 2019). The PCs are created based on the linear correlation of points' attributes (e.g., plant traits) and then used as orthogonal axes to project the magnitude of differences between the points based on the attributes (Wildi, 2013). The resulting transformation of the multivariate data is quantified by eigenvalues which reflect the relative importance or magnitude of a PC and eigenvectors which describe the direction of the PCs. The first few PCs explain the most variation and are typically used to interpret variation while the last PCs are considered "noise" explaining little of the variation between points (Wildi, 2013).

Principal coordinates analysis (PCoA) is also an ordination method like PCA but instead of focusing on shared variance of points, PcoA calculates distance or dispersion between points with measures such as the Bray-Curtis dissimilarity index (Anderson and Willis, 2003; Bray and Curtis, 1957). Additionally, PCA does not test a statistical hypothesis while PcoA determines whether the response of Y (e.g., plant traits) can be predicted by X (e.g., reclamation age)(Anderson and Willis, 2003; Wildi, 2013). Both ordination methods have been used to evaluate and describe the influence of environmental variables on community structure (Dray et al., 2006; Wildi, 2013).

The Bray-Curtis dissimilarity index that I used in the PCoA has commonly been used in ecological studies to quantify composition dissimilarity between 2 sites based on counts (e.g., LPI points) for each plant species (Beals, 1984). Bray-Curtis values range 0.0 to 1.0 where a value of zero means complete similarity (i.e., shared all species with similar cover) and a value of 1.0 means complete dissimilarity (i.e., no species in common) (Bray and Curtis, 1957). The index assumes that sites are of equal size so that differences in cover can be fairly compared, and the well pads I sampled were on average, 30 m^2(Bray and Curtis, 1957).

In this study, I used the CWM of each well pad as input to PCA and PCoA analysis to evaluate variation between reclamation ages and the influence of plant and soil traits on reclamation ages' differences. More specifically, CWMs quantified the influence of traits within a reclaimed pad, then using the CWMs in a PCA test allowed us to look at causes of variation within a reclamation age while PCoA helped us evaluate the driving causes of variation between reclamation ages. Data for calculating the CWM of each reclaimed well pad did not need to be standardized because vegetation cover (%) data is used to derive the weighted means. Data was standardized for the ordination methods using *scale* function from the *base* R package, because not all traits have the same unit such as soil bulk density (g*cm^{-3}) versus maximum vegetation height (cm). If the data was not standardized, a trait such as maximum vegetation height could appear to have an outsized influence on community structure because values are much larger compared to other traits causing us to reject the null hypothesis that a trait has no influence on community structure (Type I error). I used the Bray-Curtis dissimilarity index as the distance measure for PCoA because I was evaluating compositional differences between reclamation ages. In the end, I used the differences within and between reclamation ages to determine which plant and soil traits may be indicative of a plant community's post-reclamation land potential.

All statistical analyses were conducted using R version 4.1.1 (R Core Team, 2021). The PCA test was conducted using the *princomp* function of the *stats* R package and the PCoA was calculated with the *betadisper* functions from the *vegan* R package (Oksanen et al., 2020). I calculated the Bray-Curtis dissimilarity index using the *vegdist* function also from the *vegan* R package (Oksanen et al., 2020).

Results

Soil Characteristics

I did not observe a significant difference in soil pH and bulk density between reclamation ages. Soil texture was also consistent across all sites, typically with the texture of sandy clay loam and/or sandy clay. The mean for soil pH across reclamation ages was 7.49±1.25 (Fig. 4.2) and 1.64±0.49 g*cm^{-3} (Fig. 4.3) for bulk density. I did observe a significant decrease ($\alpha = 0.05$) in soil electrical conductivity between the reclamation ages of 5 years and 15 years (Fig. 4.4). The mean soil EC at 5 years was 4.03±2.21 dS*m^{-1} and 0.74±0.61 dS*m^{-1} at 15 years. Differences between other reclamation ages were not significant for electrical conductivity.

Diversity Indices

I found that plant community diversity declined with time since reclamation completion and was reduced at 15 years, compared to earlier reclaimed pads at 5 years (Fig. 4.5-6). The mean Simpson's diversity index was 0.17 at 5 years and 0.12 at 15 years, indicating a decrease in species evenness (i.e., a few plant species dominated at 15 years). The mean Shannon-Wiener's diversity index was 0.50 at 5 years and 0.33 at 15 years. Because all Shannon-Wiener diversity values were below the typical range of 1.5-3.5 (Shannon, 1948), this indicates a low overall amount of plant diversity across reclamation ages.

Plant Community Traits

When looking at individual variables, there was an overall increase in native perennial plant canopy cover (%) (Fig. 4.7-8) coupled with a decrease in introduced annual plant canopy cover (Fig. 4.9-10) with age since reclamation. I observed the greatest difference in these plant variables for reclamation ages 5 years and 15 years. At 5 years, the mean native canopy cover was 49.3±37.9%, mean perennial canopy cover was 49.3±37.9%, mean introduced canopy cover was 50.2±37.1%, and mean annual canopy cover was 50.7±37.9%. At 15 years, the mean native canopy cover was 83.5±22.5%, mean perennial canopy cover was 90.4±15.8%, mean introduced canopy cover was 13.3±21.7%, and mean annual canopy cover was 9.63±15.8%.

From the PCA, PC 1 explained 41.2% and PC 2 explained 17.3% of the total variance in plant community traits across reclamation ages. I found that the greatest contributing variables to PC 1 were plant duration (annual/native), status (introduced/native), and photosynthetic pathway (cool season/warm season) suggesting that PC 1 focuses on herbaceous cover (Table 4.1, Fig. 4.11). In contrast, PC 2 was most influenced by shrub cover, variable water preference, evergreen plant species, and maximum vegetation height suggesting that it's largely describing the presence of woody plants and vegetation structure (Table 4.1, Fig. 4.11). On the PC 1 and PC 2 axes, reclamation ages with the least amount of variation between each other were 10, 15, and

20 years, while 5 years was the most different from the other ages. I also observed in the first two PCA axes that the variance of 5 year well pads was largely influenced by the following variables: annual, introduced, warm-season, forbs, and xeric water preference. In contrast, variance at 15 years was characterized by the following variables: perennial, native, cool season, graminoid, and mesic water preference. At 20 years though, variance was not driven by one group of variables in the first two PC axes.

When looking at variance between reclamation ages in PCoA, 5 and 15 years exhibited the greatest dissimilarity between each other and had the least amount of variance within their reclamation age (Fig. 12). In contrast, 10 and 20 years exhibited the highest amount of variance between reclamation ages (i.e., wide dispersion) and also had a high amount of variation within their reclamation age.

Discussion

The lack of late successional species at later reclamation ages (i.e., 15 and 20 years) is consistent with other studies of the outcomes of oil and gas reclamation where reclamation practices were not leading to the re-establishment of late-successional ecosystems such as on big sagebrush rangelands (Monroe et al., 2020; Rottler et al., 2018). Additionally, the abundance and persistence of early successional vegetation, mostly perennial grasses without sagebrush, has also been found in other studies on the effects of oil and gas development on ecosystem structure (Ott et al., 2021; Walker et al., 2020). These studies have found that post-reclamation areas are dominated by early successional species (i.e., colonizers) because the species can easily colonize highly disturbed areas where soil nutrient cycling has been altered and water retention is low (Elsinger et al., 2022; Ott et al., 2021; Rottler et al., 2019).

The selected soil and plant characteristics described differences between reclamation ages and thus may be predictive of future successional change on well pads reclaimed from oil and gas development. For example, the decrease in soil EC over time suggests that sub-soil salts that were initially mixed and respread at the time of reclamation, are leaching down into the soil profile. Additionally, by focusing on individual plant characteristics (e.g., duration, water preference) I was able to discern what plant traits were most influential at different reclamation ages.

The most notable difference between reclamation ages was at 5 and 15 years. At 15 years, plant communities are dominated by native perennial plants and appear to be experiencing the full impact of previous reclamation actions (e.g., reseeding, salvaging topsoil). At 20 years though, the high variability on the PC axes 1 and 2 and dispersion in PCoA suggest that the “reclamation effect” may not have long-term viability. This loss in possible predictability of reclamation outcomes after 15 years is crucial in the context of reclamation evaluation where predictions of long-term outcomes (i.e., beyond 20 years) are made at 3-5 years since reclamation completion.

One possible explanation for the increase in plant community variability and decrease in species diversity at 20 years is that the original species seeded (e.g., Indian ricegrass [*Achnatherum hymenoides* (Roem. & Schult.) Barkworth]) during reclamation may not be persistent long-term and are being replaced by species well adapted to the local environment and conditions (e.g., fourwing saltbush [*Atriplex canescens* (Pursh) Nutt]). Seed mixes were not recorded in the publicly available records for the well pads sampled, so I was not able to fully evaluate this possibility. Additionally, later successional species (e.g., big sagebrush) were not observed at most of the sites, suggesting that complete plant community recovery may not be happening or occurs after 20 years (Rottler et al., 2018). Another explanation could be that reclamation practices were highly variable within the 20-year reclamation age leading to a wide variety of outcomes. However, most reclamation practices are not well documented in publicly available records (Curran et al., 2014; Di Stéfano et al., 2021), so I could not account for this possible circumstance. Additionally, the lack of sagebrush at 20-year reclaimed pads suggests that they are in persistent alternative states that may be a result of management, climate, or a combination of both (Lupardus et al., 2020; Waller et al., 2018).

By using a suite of indicators, rather than focusing on a single indicator, I could ascertain ecological dynamics of severely disturbed sites over time. Soil EC, plant duration, plant status, and photosynthetic pathway appear to be the most influential indicators for determining the altered land potential of reclaimed well pads. All these characteristics affect or are influenced by a reclaimed well pad's ability to cycle soil nutrients and retain water which determines the long-term plant community structure on the surface post-reclamation (i.e., land potential) (Di Stéfano et al., 2021; Elsinger et al., 2022; Ott et al., 2021). For example, native perennial communities dominated at 15-years even though introduced annuals were common at 5 years. This trend indicates that undesirable conditions at 5-years may not mean long-term reclamation failure but management inaction at this point will not lead to natural and spontaneous plant community recovery without proactive monitoring and management of invasive plants (Baasch et al., 2012).

One of the major limitations of this study was I was not able to screen well pads for variations in reclamation practices before field data collection. For example, some of the well pads were listed as reclaimed in the state Colorado Oil and Gas Conservation Commission (COGCC) database but once visited, it was clear reclamation had not been fully completed and/or equipment had been left behind. Additionally, the small number of well pads confined in a single region of Colorado may limit the applicability of these results to other areas where there are differences in vegetation, reclamation practices, and development intensity.

Conclusion

Restoring ecosystem services through reclamation on abandoned well pads is a delicate balance between active reclamation practices and natural plant community succession (e.g., recruitment of plant species from surrounding area) (Baasch et al., 2012). The soil and vegetative processes that lead to plant community recovery though are not well understood, making it unclear to reclamation managers which vegetative and soil characteristics are reliably indicative of desired reclamation outcomes (Di Stéfano et al., 2021). The lack of standard and quantitative monitoring indicators impedes the ability of land management agencies to measure reclamation success and progress towards the recovery of ecosystem services lost energy development.

Reclamation evaluations are completed with the assumption that appropriate reclamation actions will lead to plant community recovery, but our results suggest that plant community recovery may not always be sustained beyond 15 years. Longer-term data are needed to determine if conditions at well pads continue to be highly variable beyond 20-years regardless of reclamation practices and/or if other indicators become more influential to reclamation outcomes. Overall, using indicators of altered land potential could help improve understanding and management of the dynamics that form the highly disturbed landscapes created by oil and gas development, particularly in the absence of pre-disturbance information. Land potential is a useful concept for monitoring and evaluating reclamation outcomes because it makes clear what is being measured and why specific indicators are important to reclamation outcomes.

Tables

Table 4.1: Number of sampled well pads in each sampling strata, for a total of 40 well pads. Aridity classes are as follow: dry (aridity value < 1,777), semi-dry (1,777 < aridity value < 2,248), and wet (aridity value > 2,248) (Trabucco and Zomer, 2019)).

Time since Reclamation	Aridity class	Count
5	Dry	1
	Semi-dry	2
	Wet	0
10	Dry	3
	Semi-dry	6
	Wet	5
15	Dry	3
	Semi-dry	6
	Wet	4
20	Dry	4
	Semi-dry	5
	Wet	1

Table 4.2: Table of USDA NRCS plant traits tested in principal components (PC) analysis and their corresponding variable loadings for PC 1 and PC 2.

Trait	Trait Type	PC 1	PC 2
Annual	Duration	0.307	0.0935
Introduced	Status	0.291	0.0553
Warm Season	Growth Cycle	0.282	-0.0961
Forb	Functional Group	0.276	0.101
Xeric	Water Preference	0.276	-0.124
Seed	Reproduction	0.239	-0.0365
pH	Soil	0.0932	-0.158
EC	Soil	0.0647	-0.0582
Shrub	Functional Group	0.0244	-0.458
Variable	Water Preference	-0.0840	-0.469
Evergreen	Duration	-0.0947	-0.461
Max Veg. Height.	Vertical Structure	-0.163	-0.406
Rhizomatous	Reproduction	-0.257	0.125
Cool Season	Growth Cycle	-0.269	0.149
Graminoid	Functional Group	-0.269	0.188
Native	Status	-0.293	-0.0682
Mesic	Water Preference	-0.295	0.168
Perennial	Duration	-0.305	-0.0994

Figures

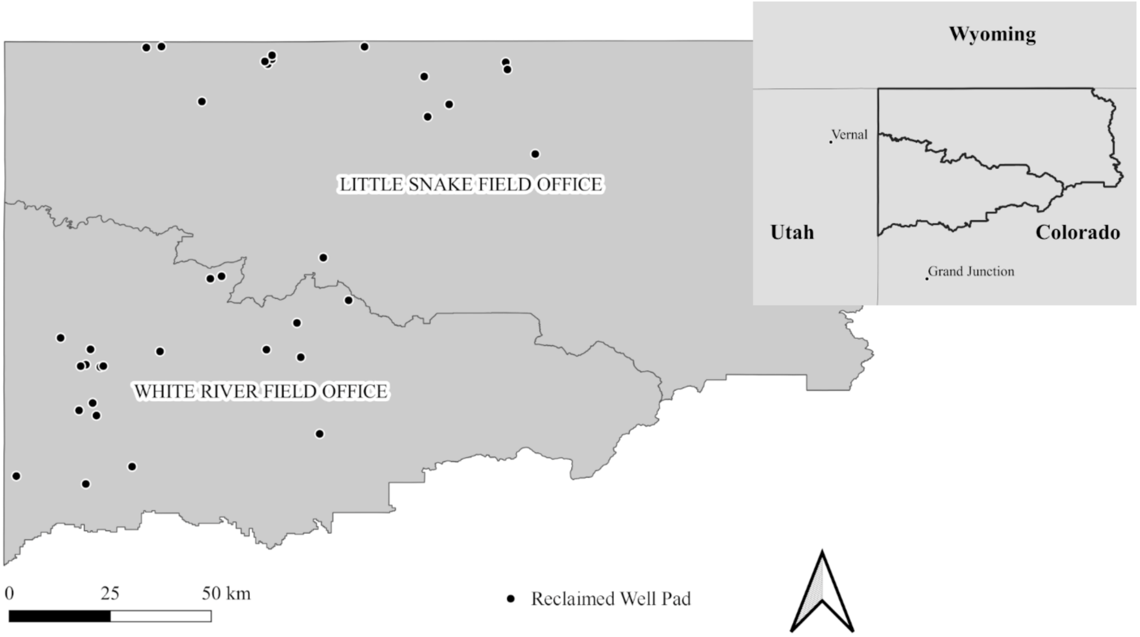

Figure 4.1: Locations of reclaimed well pads that were sampled (n=36).

Figure 4.2: Boxplots of soil pH values for each time period since reclamation completion (reclamation age).

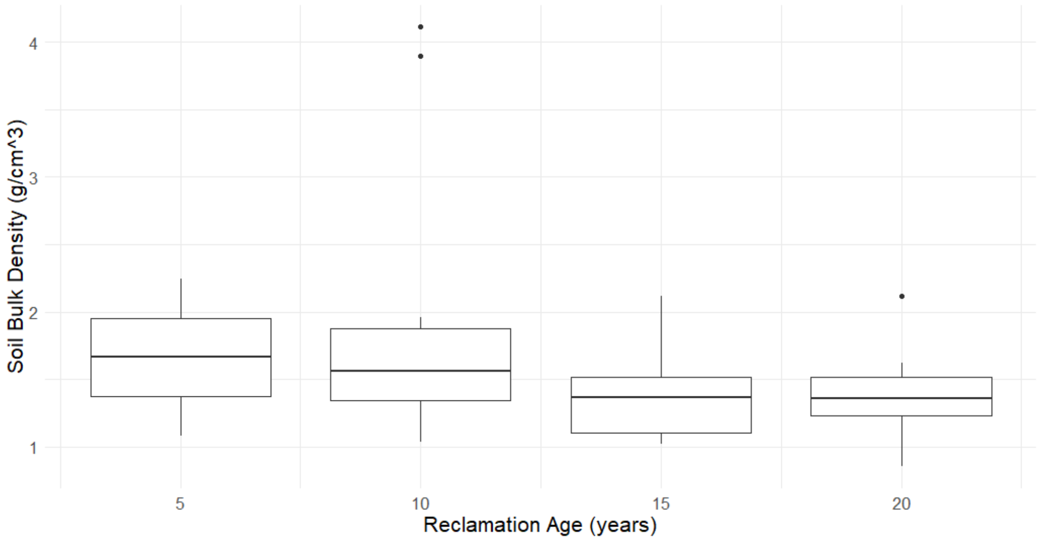

Figure 4.1: Boxplots of soil bulk density (g*cm^{-3}) values for each time period since reclamation completion (reclamation age).

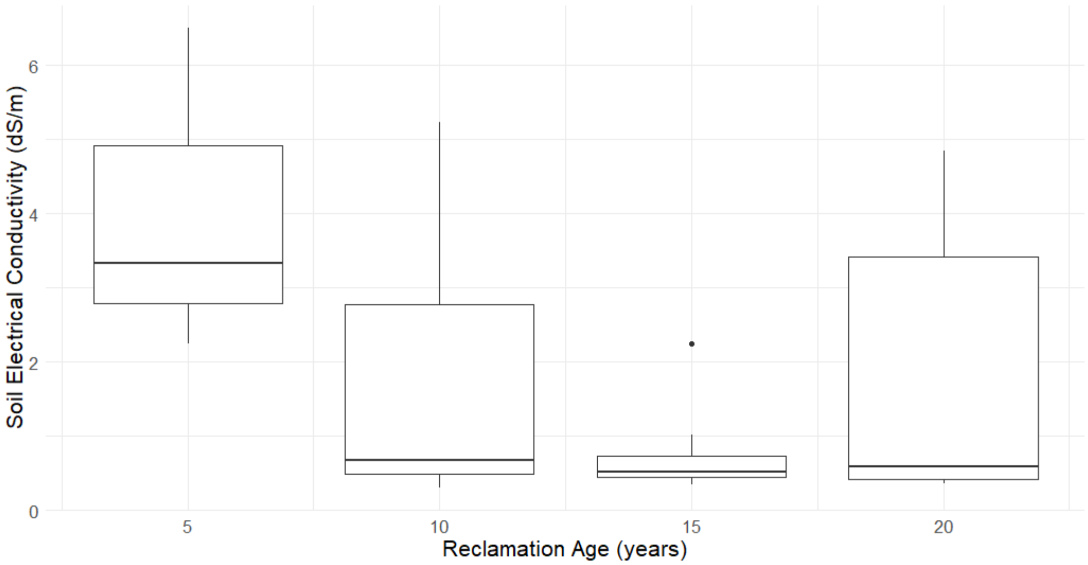

Figure 4.2: Boxplots of soil electrical conductivity (dS*m^{-1}) values for each time period since reclamation completion (reclamation age).

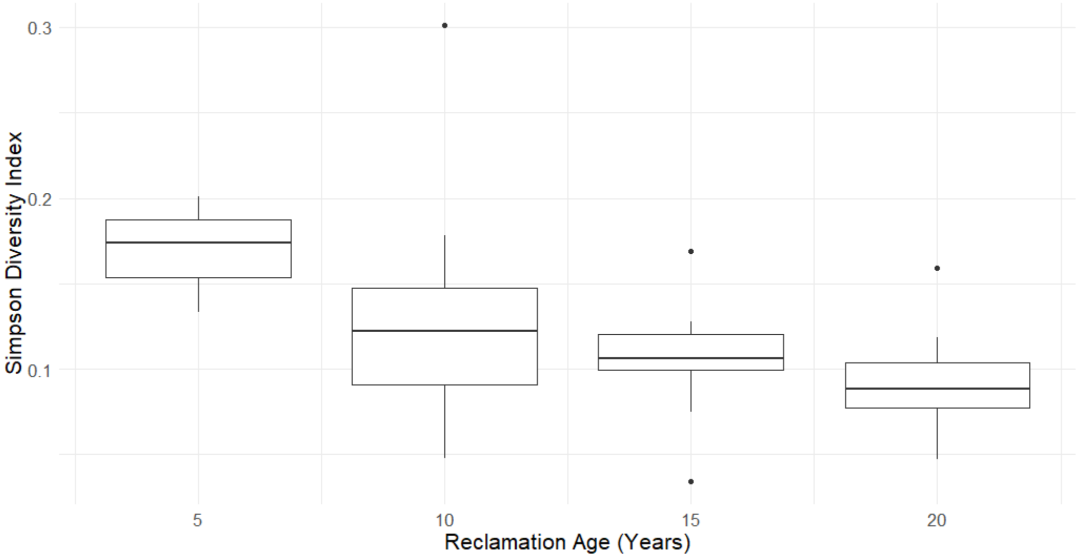

Figure 4.3: Boxplots of Simpson diversity index (0-1) values for each time period since reclamation completion (reclamation age).

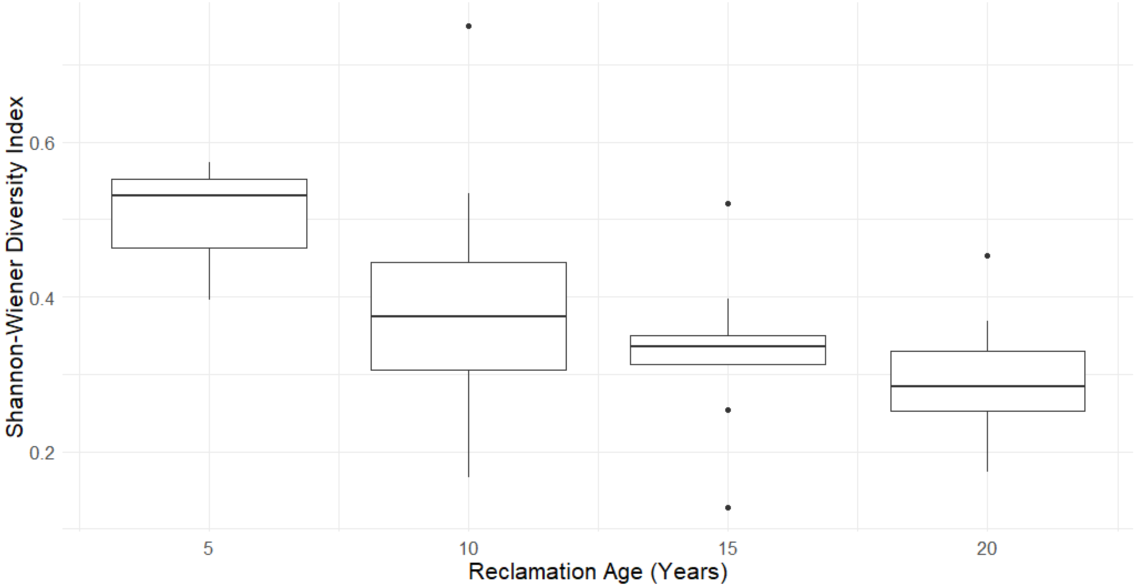

Figure 4.4: Boxplots of Shannon-Wiener diversity index (0-5) values on well pads for each time period since reclamation completion (reclamation age).

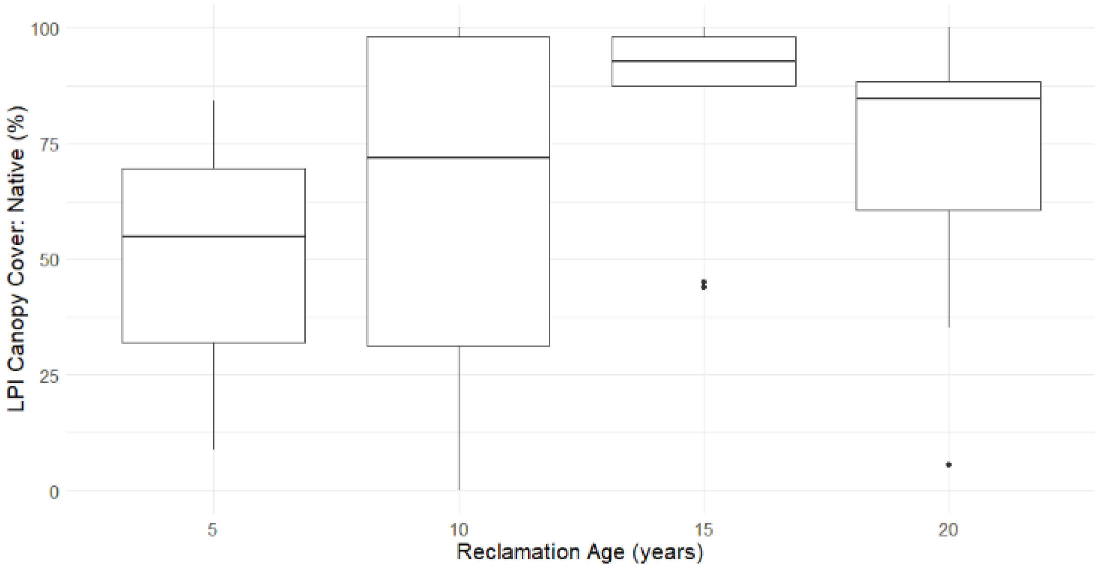

Figure 4.5: Boxplots of native plant canopy cover (%) on well pads for each time period since reclamation completion (reclamation age).

Figure 4.6: Boxplots of perennial plant canopy cover (%) on well pads for each time period since reclamation completion (reclamation age).

Figure 4.7: Boxplots of annual plant canopy cover (%) on well pads for each time period since reclamation completion (reclamation age).

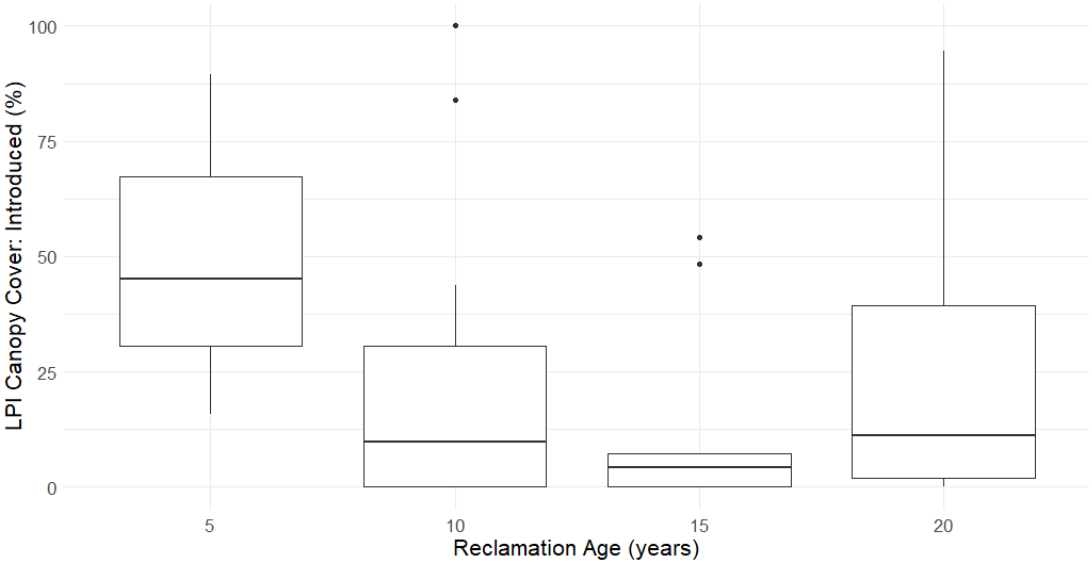

Figure 4.8: Boxplots of introduced plant canopy cover (%) on well pads for each time period since reclamation completion (reclamation age).

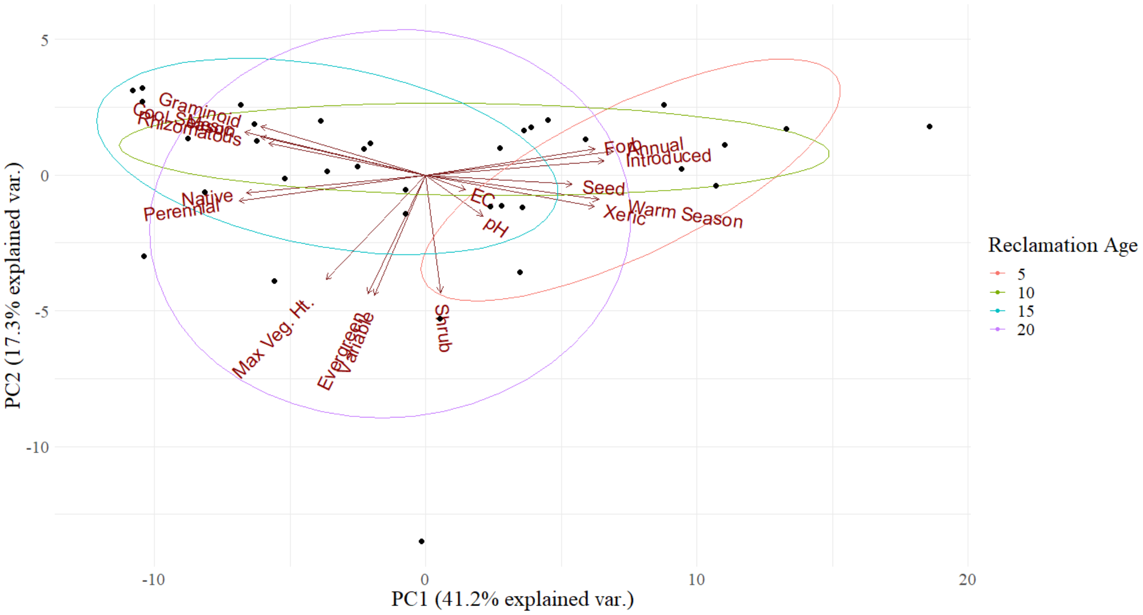

Figure 4.9: Principal components analysis on plant traits that affect reclaimed well pads. Arrows represent the relative influence of each plant trait. Circles represent the spread of each reclamation age with a 95% confidence interval

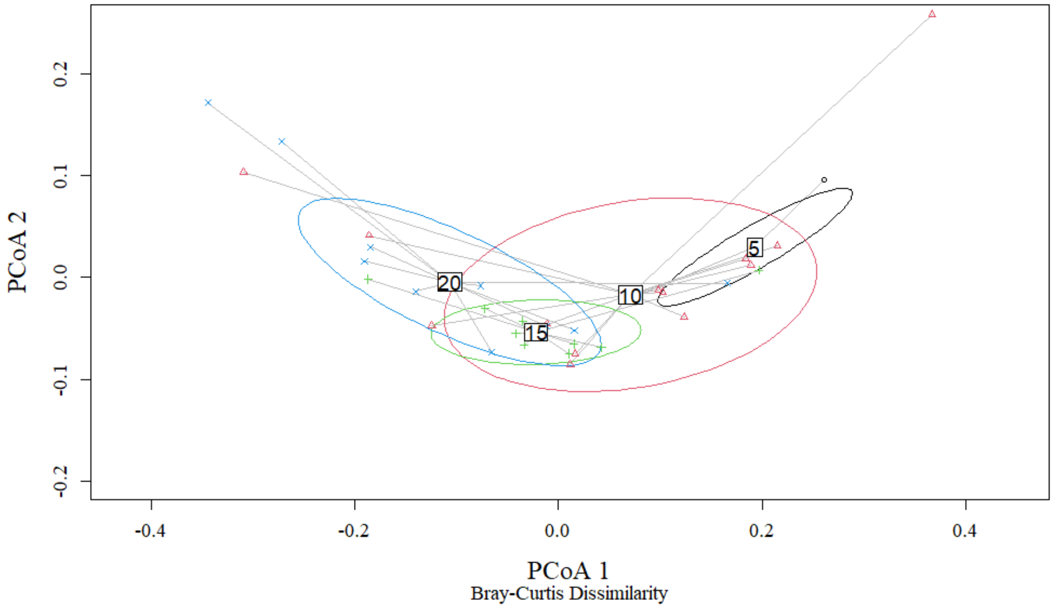

Figure 4.10: Variance for well pads across different time periods since reclamation completion (i.e., reclamation age) using the distance measure of Bray-Curtis

dissimilarity. Circles represent the spread of each reclamation age with a 95% confidence interval. Each point represents a single well pad.

Figure 4.8:Figure 4.9: Boxplots of perennial plant canopy cover (%) on well pads for each time period since reclamation completion (reclamation age).

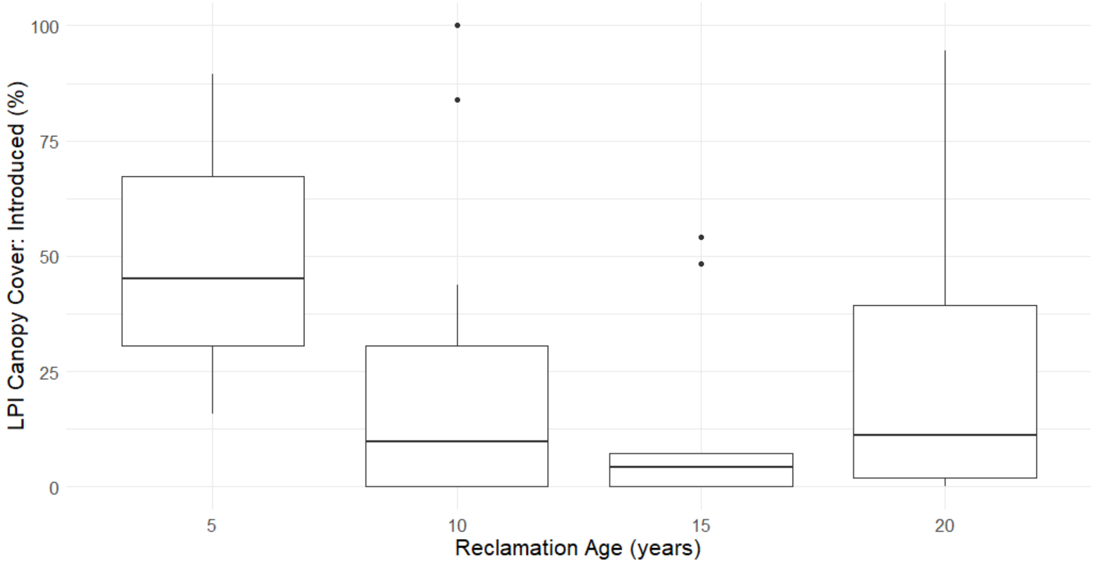

Figure 4.10: Boxplots of introduced plant canopy cover (%) on well pads for each time period since reclamation completion (reclamation age).

Figure 4.11: Boxplots of annual plant canopy cover (%) on well pads for each time period since reclamation completion (reclamation age).

Ch 5: Guidelines for Monitoring and Assessments Oil and Gas Reclamation on US Public Lands

Introduction

Oil and gas development on US public land largely occurs on Bureau of Land Management (BLM) land in arid regions of the western US where precipitation is low and often unpredictable (Noojipady et al., 2015; Waller et al., 2018) Because climate has an outsized influence on oil and gas reclamation outcomes, it is difficult to put a reclaimed site on a pathway to plant community recovery that regains ecosystem services vital to the multiple-use mandate of US public lands (Allred et al., 2015; Haskell, 1976; Waller et al., 2018). Withing this context, land managers of reclamation have the unique challenge of balancing reclamation practices with natural plant community succession when soil and vegetative processes affecting reclamation outcomes have not been well understood (Baasch et al., 2012; Di Stéfano et al., 2021). Additionally, reclamation guidelines within the BLM have been highly localized to each field office (FO), making it difficult to evaluate reclamation success over large landscapes (e.g., BLM district or state) or pass down knowledge on effective reclamation practices outside of an individual FO.

The expected outcome of reclamation, particularly for reseeding, is to restart and accelerate successional processes within the site’s plant community, provide adequate resources for desired plants to outcompete invasive plant species, and prevent soil erosion (Fowers, 2015). Multiple studies have found that focusing on individual traits of plant species within a community helps measure plant community change over time after restoration activities (Carter and Blair, 2012; Funk et al., 2017; Lupardus et al., 2020). Additionally, by using a group of indicators and plant traits, rather than a few or individual traits, a site’s land potential (i.e., the expected successional trajectory given current soil and vegetative conditions) can be predicted (e.g., Stiver et al., 2015). Using desired land potential as a guiding principle in reclamation also aids in areas where pre-disturbance information is minimal or non-existent.

In this chapter I outline plant and soil traits that are most influential on successional processes post-reclamation based on current literature and collected data. I make recommendations for what type of monitoring data would be needed to adequately measure the viability of plant and soil processes at the time of reclamation evaluation, when the BLM is considering releasing an operator from environmental liability of their previously drilled site. It is important to note that our recommendations should act as a guide and not an absolute standard. Expert opinion and judgement will always be needed and regional adjustments for local environmental conditions may be appropriate with strong scientific justification. The goal of our recommendations is to improve consistency and transparency in the reclamation evaluation process so that reclamation expectations can be more clearly communicated to operators and that by having standardized data, reclamation knowledge may be passed on to future generations of management.

Indicators and Data for Reclamation Evaluations

Predicting long-term outcomes from reclamation requires a basic understanding of the ecological processes that determine plant community structure (Lupardus et al., 2020). Because topsoil is scraped during pad establishment and re-spread at the time of reclamation, reclamation soils are physically and biologically different than the surrounding area. Reclamation soils are defined as being nutrient poor and susceptible to erosion which ultimately affects what species persist and thrive in a plant community (Rottler et al., 2019). Because of this, traditional assumptions about plant community recovery being complete at the time of a reclamation evaluation (i.e., 3-5 years after reclamation) cannot apply. Studies show that full recovery of plant community structure typically happens between 50-100 years after reclamation completion (Rottler et al., 2018). For these reasons, I recommend focusing on indicators that measure the key ecological processes that determine the altered land potential of a reclaimed well pad which are site water retention and nutrient cycling (Di Stéfano et al., 2021).

I found that the following indicators can be used to predict the successional trajectory of a reclaimed well pad: plant status (native/introduced), duration (annual/perennial), photo synthetic pathway (cool season/warm season), late successional plant species, noxious weeds, proximity to other development, soil electrical conductivity

(EC), soil pH, and soil bulk density (BD) (Table 5.1). The criteria I outline in table 1 for the land potential indicators have been determined by current reclamation and restoration literature to increase the likelihood of a stable native plant community and prevent widespread noxious weed invasion. It is important to note that abandoned well pads have been found to be vectors for noxious weed establishment but expecting zero presence of noxious weeds may not be practical considering the widespread occurrence of some noxious weeds in the western US such as cheatgrass (*Bromus tectorum*). Reclaimed well pads that would be considered heading towards complete reclamation failure would have higher than expected soil EC and bulk density, dominated by few native plant species, and/or only having xeric plant species where mesic plants are expected.

Setting Indicator Benchmarks

For example, in more arid regions of the western US, a higher EC and dominance of xeric plant species may be warranted because those characteristics are typical of plant community structure in those regions. As states earlier though, local investigation is necessary to determine if adjustments are truly warranted. References could include ecological site descriptions, historical monitoring data, and conferring with local experts (e.g., extension agents, soil scientists, natural resource specialists). Any indicator adjustments should be a collective effort that is discussed and agreed upon by multiple stakeholders to increase perceived fairness and trust between groups.

Reclamation Evaluation Steps

The following steps detail the process for implementing reclamation requirements and assessments based on land potential concepts. The steps are meant to act as a guide and reclamation managers will need to determine how best to apply these steps for their unique and local circumstances.

Step 1: Add Indicators to Reclamation Requirements (when possible)

Reclamation evaluations happen when an operator has submitted a Final Abandonment Notice (FAN) to the BLM. A BLM representative, often a Natural Resource Specialist (NRS), will then determine if the reclamation meets the requirements outlined in the Surface Use of plan of the initial Application to Drill (APD). For this reason, the indicators that I have recommended should not only be considered at the end of a well's life but should also be included in the APD to make the requirements legally binding and clear to the operator from the beginning. For older well pads where the APD has already been completed, the recommended indicators can still be used as a guide for evaluating reclamation outcomes.

Step 2: Compile Reference Information

When possible, I recommend that pre-disturbance soil and vegetation data be collected at a well pad to provide a baseline of comparison at the end of a well's life cycle. It should be noted that pre-disturbance or reference information should not be collected with the goal of being a strict standard but rather as a reference for where a well pad was in its successional trajectory before pad establishment. Other useful reference information could come from ecological site descriptions, nearby monitoring sites (e.g., BLM Assessment, Inventory, and Monitoring [AIM]), expert opinion, and experience.

A suitable tool for selecting reference sites for oil and gas reclamation is the Disturbance Automated Reference Toolset (DART), first described in Nauman et al., (2017), where reference sites are selected based on similarity in soil texture, topography, and geology. The goal of DART is to select areas with a similar ecological context where sites identified as similar would respond comparably to disturbance and an undisturbed site could be used as reference to identify recovery patterns for a disturbed site. Ultimately the expectation with DART is that the BLM and operators will have a common frame of reference to communicate reclamation expectations.

Step 3: Collect Monitoring Data

I recommend that soil and vegetation data for reclamation monitoring be collected following the BLM AIM protocols (REF) because it standardizes the format of the data, allowing for the availability of the collected data to be used for other management interests thus maximizing the use of BLM resources (Toevs et al., 2011). I did not find that a complete BLM AIM style plot is necessary to characterize plant community structure at reclaimed well pads because they are typically uniform in plant distribution and soil properties due to the drill seeding of vegetation and mechanical re-spreading of topsoil during reclamation. More specifically, measuring for vegetation height, gap intercept, 70 cm soil pit for soil characterization, and soil stability are not necessary but may be useful for addressing local management concerns.

I found that for smaller reclaimed sites (i.e., ~30m^2) a minimum of 2-3 transects should be used for collecting monitoring data. At larger reclaimed sites with multiple abandoned wells (made possible because of directional drilling) the BLM and operator should agree on the appropriate number of transects (i.e., >3 transects) for characterizing the plant community in its entirety on the reclaimed well pad (Grant et al., 2004). Additionally, the typical 25 m transect used in AIM may need to be reconsidered on larger reclaimed well pads (Herrick et al., 2017). Because seeding rows are typically parallel to one another, transects should be placed perpendicular to the seeding rows and parallel to each other which reduces the likelihood of sampling a single vegetation pattern not representative of the site (Herrick et al., 2017).

Vegetation and soil sampling methods should follow the AIM protocols with exceptions described below. Vegetation sampling methods should include line-point-intercept (LPI) for vegetation and soil surface cover, and plant species inventory. Vegetation height and canopy gap intercept may also be useful if soil erosion is a concern for the reclaimed well pad. I recommend that soil sampling methods diverge from the AIM protocol (i.e., soil characterization via a 70-cm pit and test of surface stability) to better characterize the unique nature of reclamation soils. Because reclamation soil is homogenous and artificially mixed, soil characterization from a 70 cm pit is unnecessary and a 50-100g collected soil sample from a depth of 0-15 cm (excluding litter) is sufficient for soil characterization on reclaimed rangeland topsoil (McIntosh et al., 2019). The 50-100 g soil samples are tested for soil pH and EC.

Step 4: Assess for Land Potential

Monitoring data should be summarized based on the indicators in table 1 and evaluated against the established benchmarks to determine a reclaimed well pad’s likely plant community successional trajectory (i.e., land potential). Describing the overall well pad’s condition as heading towards reclamation success or failure will require at least some professional judgement, particularly when some indicators may be within the parameters of the APD while others are not. The reasoning for any determinations should be clearly explained and recorded in the well pad's documentation, including the FAN. Photo monitoring of the reclaimed well pad may also be appropriate for documenting plant community change over time. An example of a reclamation evaluation is illustrated in figure 1.

Summary statistics for indicators derived from LPI should be calculated as a percentage of total vegetation cover based on each indicator described in Table 5.1 (e.g., percentage of total vegetation cover that is native plant species). Soil pH, EC, and BD can each be calculated as a mean from all soil samples (one sample per transect, n=2-3) from an individual well pad. Species inventory is the entire list of plant species observed on the well pad. If one of the plant species is identified as late successional or a noxious weed that should be noted in the species inventory. Additionally, all plant species in the inventory should be described by their status (native/introduced), duration (annual/perennial), and photosynthetic pathway (cool season/warm season). An example species inventory is described in figure 1. I also recommend a description of the surrounding area (e.g., land use, oil and gas development, location on landscape) be recorded to account for any possible off-site influences on reclamation outcomes.

Step 5: Storing and Sharing Reclamation Information

The vast majority of well pad documentation is still recorded in paper files stored in individual field offices, making it difficult to evaluate the efficacy of various reclamation practices and comparison of reclamation standards across regulatory boundaries (Di Stéfano et al., 2021). Some states such as Colorado have an online database of basic documentation on the dates and nature of actions taken on a well pad during its lifetime, but such documentation focused on the engineering and geological aspects of well pad management with little to no information on surface conditions. I recommend that surface reclamation actions and outcomes be recorded in a well pad's documentation and be made publicly available, particularly if surface conditions were a contributing factor to a FAN denial. I am aware that there are efforts to digitize some field offices’ well pad documentation and I encourage all field offices to do so to improve the sharing of reclamation information and knowledge across regions.

Discussion

Handling Disputes Between BLM and Operator

Quantitative data for reclamation evaluations are strongly preferred over qualitative data to decrease subjectivity and increase repeatability in reclamation evaluations (Veblen et al., 2014). Quantitative data also provides stronger support for management decisions when disputes on evaluations are made (Toevs et al., 2011). I recognize though that the collection of quantitative data rather than qualitative would demand a considerable shift in reclamation monitoring and evaluations and would require the commitment of increased resources and time towards evaluations by the BLM and private operators.

In the circumstance of a well pad having an undesirable land potential (i.e., FAN denial), open and willing communication between all parties will be necessary to promote community recovery and prevent well abandonment (i.e., creating an orphan well). As of 2022, there are over 130,000 wells on US public land lacking a legal owner, many of which were abandoned because an operator did not complete reclamation to the standards set by the BLM (BLM, 2022). The BLM does not have the resources to reclaim all orphaned wells so coordination with operators is crucial to meeting desired reclamation outcomes.

Allocation of Resources for Surface Reclamation

Most reclamation costs are understandably directed towards the plugging of the well to prevent pollution and seepage of oil or natural gas into water and soil resources, but surface reclamation is often treated as an afterthought and lacks the effort and time needed to bring about desirable reclamation outcomes (Di Stéfano et al., 2021). I recognize that implementing reclamation evaluations based on land potential and quantitative data will require a significant shift in practices, time, and financial resources but I find that it is warranted because of the increased scrutiny and pressure the federal government is under for past impacts and new drilling on public land (Davenport, 2022; DOI, 2022, 2021). In this contentious and often litigious environment, reclamation evaluations will need to be based on sound scientific information to manage and defend the BLM's actions surrounding oil and gas development on public land.

Conclusion

The guiding principle of reclamation should be to put a reclaimed well pad on a pathway towards a self-sustaining native plant community that provides the desired ecosystem services. If a plant community is designated as being unstable or having low resistance and/or resilience to likely disturbances (e.g., livestock grazing, wild horses), the BLM representative will need to coordinate with the operator on appropriate next steps. Actions may include requesting a re-completion of reclamation by the operator, weed removal (e.g., herbicide), application of mulch for soil stabilization, and continued monitoring of the site. Overall, the BLM and operators both need to be willing to make compromises in meeting reclamation standards and practices and come to agreed goals that alleviate the widespread loss of ecosystem services to oil and gas development on US public lands.

Tables

Table 5.1: List of soil and vegetative indicators recommended for reclamation from oil and gas development. All vegetative indicators require line-point-intercept (LPI) to be assessed and soil indicators are derived from soil samples collected at each transect. Together, these indicators influence the common reclamation goals of establishing a self-sustaining native plant community, stabilization of soils to prevent erosion, and putting a reclaimed well pad on a pathway to recovery.

Reclamation goal	Indicator	Description/Unit	Sampling method
Establish native plant community	Presence and cover of native plants	Canopy cover	Species inventory, LPI
	Presence and cover of perennial plants	Canopy cover	Species inventory, LPI
	Presence and cover of cool and warm season plants	Canopy cover	Species inventory, LPI
	Presence and cover of noxious weeds	Canopy cover	Species inventory, LPI
	Presence and cover of late successional species	Canopy cover	Species inventory, LPI
	Proximity to development	Distance (ft or m)	Plot characterization
Soil stabilization	Soil electrical conductivity (EC)	$dS*m^{-1}$	Soil sample
	Soil pH	0-7	Soil sample
	Soil bulk density (BD)	$g*cm^{3}$	Soil sample

Figures

Figure 5.1: Example of an oil and gas reclamation evaluation sheet based on our recommendations.

Name of operator:

Contact:

Location (lat/long):

Type of well:

Date reclamation completed:

Date evaluation completed:

Site description:

Management concern	Description
Proximity to other oil and gas development?	Y/N Approximate distance (ft or m):
Livestock grazing anticipated in the area?	Y/N Grazing allotment:
Other concerns?	Y/N

Soil:

Indicator	Value	Reference value *
Bulk density ($g*cm^{-3}$)		
Electrical conductivity ($dS*m^{-1}$)		
pH (0-7)		

* if available

Vegetation:

Plant functional group	Common name	Desirable Plant Species	Canopy cover (%)	Reference canopy cover (%) *
Graminoid		Y / N		
		Y / N		
		Y / N		
Forb		Y / N		
		Y / N		
Shrub		Y / N		
		Y / N		
Tree		Y / N		
		Y / N		

* if available

Plant species inventory:

Status: Introduced/Native
Duration: Annual/Perennial/Biennial
Photosynthetic pathway: Cool season/Warm season

Scientific name	Common name	Noxious weed *	Status	Duration	Cool season/ Warm season **	Late successional species **
		Y / N	I / N	A / P / B	C / W	Y / N
		Y / N	I / N	A / P / B	C / W	Y / N
		Y / N	I / N	A / P / B	C / W	Y / N
		Y / N	I / N	A / P / B	C / W	Y / N
		Y / N	I / N	A / P / B	C / W	Y / N

* refer to state noxious weed list

** refer to USDA plants database (https://plants.usda.gov/home)

Vegetation summary:

Indicator	Canopy cover (%)	Reference canopy cover (%)
Native plant cover		
Introduced plant cover		
Annual plant cover		
Perennial plant cover		
Warm-season plant cover		
Cool-season plant cover		
Late successional plant cover		

Summary:

Do the plant community and soils appear stable? Why or why not?

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