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Landsat time series analysis of fractional plant cover changes on abandoned energy development sites

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ABSTRACT

Oil and natural gas development in the western United States has increased substantially in recent decades as technological advances like horizontal drilling and hydraulic fracturing have made extraction more commercially viable. Oil and gas pads are often developed for production, and then capped, reclaimed, and left to recover when no longer productive. Understanding the rates, controls, and degree of recovery of these reclaimed well sites to a state similar to pre-development conditions is critical for energy development and land management decision processes. Here we use a multi-decadal time series of satellite imagery (Landsat 5, 1984–2011) to assess vegetation regrowth on 365 abandoned well pads located across the Colorado Plateau in Utah, Colorado, and New Mexico. We developed high-frequency time series of the Soil-Adjusted Total Vegetation Index (SATVI) for each well pad using the Google Earth Engine cloud computing platform. BFAST time-series models were used to fit temporal trends, identifying when vegetation was cleared from the site and the magnitudes and rates of vegetation change after abandonment. The time series metrics are used to calculate the relative fractional vegetation cover (RFVC) of each pad, a measure of post-abandonment vegetation cover relative to pre-drilling condition. Mean and median RFVC were 36% (s.d. 33%) and 26%, respectively, five years after abandonment, with one third of well pads having RFVC greater than 50%. Statistical analyses suggest that much of the high vegetation cover is associated with weedy invasive annual species such as cheatgrass (*Bromus tectorum*) and Russian thistle (*Salsola* spp.). Climate conditions and the year of abandonment also play a role, with increased cover in later years associated with a wetter period. Non-linear change at many pads suggests longer recovery times than would be estimated by linear extrapolation. New techniques implemented here address a complex response of cover change to soils, management, and climate over time, and can be extended to the operational monitoring of energy development across large areas.

1. Introduction/Background

Oil and gas development across the western United States has increased substantially in recent decades (Allred et al., 2015), including within the Colorado Plateau (Martinez and Preston, 2018). The Colorado Plateau is a high desert region of grasslands, shrublands, and woodlands and is home to a large number of world-renowned national and tribal parks and monuments (e.g., Grand Canyon, Zion, Bryce, Arches, Canyonlands, Monument Valley, and Mesa Verde). Energy development on the Colorado Plateau is of concern regionally due to potential environmental impacts, including water and air pollution, habitat fragmentation, dust emissions, and soil loss from erosion, all of which can have cascading impacts on human health (McKenzie et al., 2012), biodiversity (Butt et al., 2013), watershed hydrology (Painter et al., 2010), habitat quality (Brittingham et al., 2014), and recreational land uses (Copeland et al., 2017).

Nearly 100,000 wells have been developed on the Colorado Plateau (Fig. 1). Generally, vegetation and topsoil are removed across roughly 1–2 ha for the initiation of drilling (Buto et al., 2010; Google Earth Pro observation), and an approximately 1/3–1/2 ha rectangular area is leveled for the production phase of drilling (Martinez and Preston, 2018). In addition to the spatial footprint of oil and gas pads, there is an extensive network of pipelines, roads, and processing facilities in oil and gas development areas (Allred et al., 2015). Oil and gas sites are typically developed for a multi-year period of extraction and then when they are no longer productive, they are capped, reclaimed, and left to

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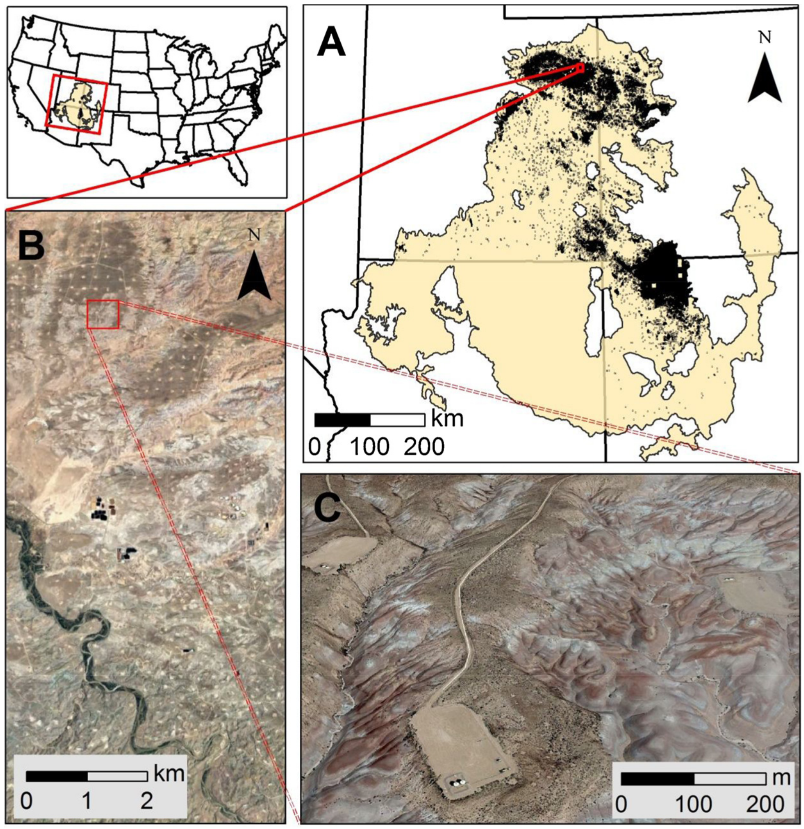

Fig. 1. Location map of the Colorado Plateau ecoregion; ecoregion detail (A) with individual well sites identified by a black dot; Google Earth Pro aerial photography showing the footprint of oil and gas development at the landscape scale as small light colored patches (B); Google Earth Pro close-up of well pads and roads (C).

recover (collectively termed "plugged and abandoned").

The U.S. Bureau of Land Management (BLM) publishes the Surface Operating Standards and Guidelines for Oil and Gas Exploration and Development on federal lands, with specific instructions for reclamation and abandonment (USDI-BLM and USDA, 2007). These call for the return of original topsoil and landform where practicable, with an overall effort to set the stage for ecosystem restoration, including the natural vegetation, hydrology, and resulting erosion control. Reclamation done on BLM lands is considered successful when a self-sustaining and diverse native plant community is established with enough density to control erosion and prevent non-native plant invasion, and restore wildlife habitat or forage production. The operator is not responsible for long term recovery but is responsible for implementing the short-term measures that help ensure that the long-term objectives will be met after natural processes take their course. However, management of plugged and abandoned wells on the Colorado Plateau has been shown to be challenging (Nauman et al., 2017), likely due to inherent challenges of reclamation and restoration in drylands, uncertainty over the operational definition of reclamation success (i.e., the quantification of "self-sustaining and diverse"), and insufficient resources to monitor and evaluate reclamation practices and successes at a large and growing number of well sites regionally. As a result, many abandoned sites are not undergoing a natural recovery and are instead experiencing little vegetation regrowth or regrowth dominated by undesirable non-native plants that thrive in disturbed areas, such as cheatgrass (*Bromus tectorum*) and Russian thistle (*Salsola* spp.) (Schwinning et al., 2008; Nauman et al., 2017).

Natural resource managers and energy industry reclamation specialists require a monitoring strategy to assess reclamation success over large areas and within various time frames. Remote sensing has a long history of being used for the monitoring of land cover change over time (Singh, 1989; Kennedy et al., 2010), including the measurement of recovery from mining (Almeida-Filho and Shimabukuro, 2002). Image-based techniques are varied, and range from simple vegetation index-based time series using the Normalized Difference Vegetation Index (NDVI; Tucker, 1979) to slightly more complex approaches such as change vector analysis (Lambin and Strahler, 1994) and multiple end-member time series using spectral mixture analysis (Adams et al., 1995; Elmore et al., 2000). Shortwave infrared information can be especially useful for capturing total vegetation cover in arid lands (Asner and Lobell, 2000; Hagen et al., 2012), accounting for both the photosynthetically active green vegetation and the non-green vegetation that might be considered as brown vegetation (Okin, 2010) or non-photosynthetic vegetation (NPV; Roberts et al., 1993). The Soil-Adjusted Total Vegetation Index (SATVI; Marsett et al., 2006), makes use of information in the two Landsat shortwave infrared bands, along with the red band, and has been found to perform particularly well as a total vegetation metric across semi-arid rangelands of the western United States (Hagen et al., 2012). It was found to accurately predict percentage of bare ground across a variety of vegetation communities on the Colorado Plateau, often performing best in a comparison of a variety of vegetation indices for each community (Poitras et al., 2018), and has also been successfully used to track vegetation cover changes after disturbance in other semi-arid regions (Villarreal et al., 2016). These studies make it clear that SATVI has substantial merit for time series analysis of vegetation cover across large arid regions.

Landsat 5's Thematic Mapper, with a 28 year record (1984–2011), provides consistent spectral information over a sufficiently long time period to evaluate vegetation change for a large number of well pads with varying abandonment dates. This 28 year period of images yields spectral information pre-dating site development (drilling) for many wells, allowing for extraction of baseline spectral characteristics of the site prior to disturbance. Given the extent of the Colorado Plateau (366,000 km^2), the large number of well sites, and the large quantity of