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Monitoring ecosystem reclamation recovery using optical remote sensing: Comparison with field measurements and eddy covariance

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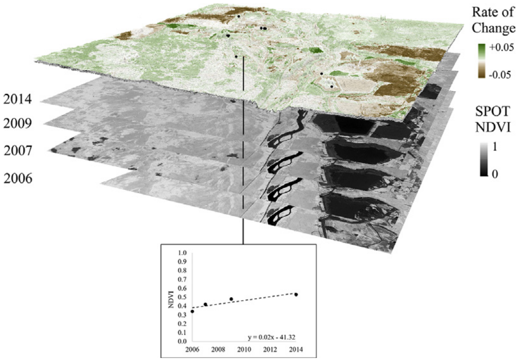
HIGHLIGHTS

- Remote sensing vegetation indices are compared with indicators of ecosystem function at sites.
- Simple ratio corresponds with variations in vegetation structure at 15 sites.
- Normalised difference vegetation index compares with stand productivity at sites.
- Time series remote sensing data provides useful indicator of change for monitoring.

GRAPHICAL ABSTRACT



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ABSTRACT

Time series remote sensing vegetation indices derived from SPOT 5 data are compared with vegetation structure and eddy covariance flux data at 15 dry to wet reclamation and reference sites within the Oil Sands region of Alberta, Canada. This comprehensive analysis examines the linkages between indicators of ecosystem function and change trajectories observed both at the plot level and within pixels. Using SPOT imagery, we find that higher spatial resolution datasets (e.g. 10 m) improves the relationship between vegetation indices and structural measurements compared with interpolated (lower resolution) pixels. The simple ratio (SR) vegetation index performs best when compared with stem density-based indicators ($R^2 = 0.65$; $p < 0.00$), while the normalised difference vegetation index (NDVI) and soil adjusted vegetation index (SAVI) are most comparable to foliage indicators (leaf area index (LAI) and canopy cover ($R^2 = 0.52–0.78$; $p > 0.02$). Fluxes (net ecosystem production (NEP) and gross ecosystem production (GEP)) are most related to NDVI and SAVI when these are interpolated to larger $20\ \text{m} \times 20\ \text{m}$ pixels ($R^2 = 0.44–0.50$; $p < 0.00$). As expected, decreased sensitivity of NDVI is problematic for sites with LAI > 3 $\text{m}^2\ \text{m}^{-2}$, making this index more appropriate for newly regenerating reclamation areas. For sites with LAI < 3 $\text{m}^2\ \text{m}^{-2}$, trajectories of vegetation change can be mapped over time and are within 2.7% and 3.3% of annual measured LAI changes observed at most sites. This study demonstrates the utility of remote sensing in combination with field and eddy covariance data for monitoring and scaling of reclaimed and reference site productivity within and beyond the Oil Sands Region of western Canada.

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1. Introduction

The Athabasca Oil Sands Region (AOSR) of Alberta, Canada underlies 142, 200 km^2 of boreal mixed wood uplands, peatlands, and water, of which 3.4% of the region is considered suitable for mining (total Mineable Surface Area). As of December 2012, 667 km^2 has been mined. Bitumen extraction from large, open pit mines requires the removal of peat and mineral soils to a maximum total depth of up to 80 m, while overburden is removed to a maximum depth of up to approximately 40 m. Once bitumen has been extracted from the mineral soils, the salvaged unmined surface peat and mineral soils are used to cap tailings materials and other unsuitable mine waste deposits. Salvaged materials are used for reclamation of landscape units representative of the pre-disturbance landscape (Daly et al., 2012; Carrera-Hernández et al., 2012). Further, both upland and wetland ecosystems will be present on the post-mining landscape, where the reclamation goal is to ensure equivalent end land use capability of both.

The Government of Alberta requires that all surface mines, oil wells and linear disturbances are reclaimed to equivalent land capabilities similar to undisturbed Boreal ecosystems (Alberta Environment and Parks, 2017). To address this, government, industry and academic partners have devised methods to reclaim and revegetate sites. Often the successional stages of ecosystem development are bypassed or accelerated through the planting of donor peat, seeds, shrubs, and trees (where required) (Daly et al., 2012; Faubert and Carey, 2014; Wytrykush et al., 2012). The goal is for reclaimed land areas to mimic local undisturbed boreal ecosystems, such that ecological equivalence is reached in less time then would occur naturally (Nwaishi et al., 2015; Gingras-Hill et al., in press).

Despite ongoing reclamation and best practices assessments for numerous forestland and peatland areas in the AOSR, prescriptive guidelines for peatland reclamation are not provided, and there remains no standard for the evaluation of reclamation success (Graf et al., 2009; Foote, 2012; Wood et al., 2015). Further, meaningful monitoring outcomes of reclaimed ecosystem trajectories can be expensive due to the length of time required to ensure long-term sustainability of ecosystem function and natural self-design (Mitsch and Wilson, 1996). Some metrics used within a functional framework to quantify long-term success include: the hydraulic properties of ecosystems, including groundwater storage, runoff and evapotranspiration fluxes (Petrone et al., 2007; Pouliot et al., 2012; Carrera-Hernández et al., 2012; Nicholls et al., 2016; Ketcheson et al., 2016; Scarlett et al., 2017; Strilesky et al., 2017), microbial activity, and nutrient dynamics (Farnden et al., 2013; Nwaishi et al., 2015; Wood et al., 2015). Nwaishi et al. (2014) propose a multi-disciplinary approach to quantifying ecosystem functional trajectories beyond vegetation community structure and biotic conditions, including interactions between biotic and abiotic components of the ecosystem. However, they warn that the presence of indicator vegetation species may not adequately represent the equivalent functional analogues found in the natural environment. Therefore, understanding the ecohydrology of sites and surroundings, and the nutrient cycling required to maintain successional trajectories, should be incorporated into monitoring frameworks. Arguably, surface revegetation cover, type and trajectories (Phillips et al., 2016; Renault et al., 2000) may provide proxy indicators of spatially varying ground water storage, nutrient distribution related to soil organic matter (Huang et al., 2015), and salinity (Phillips et al., 2016). Therefore, the spatial variability of plant condition over time may be used as an additional indicator, validated by fluxes of mass (water, CO_2) and energy exchange (Carey, 2008; Wood et al., 2015; Strilesky et al., 2017; Petrone et al., 2015).

Optical remote sensing methods have been proposed as a potentially low-cost, high efficiency method for the assessment of ecosystem condition and change trajectories over time within the AOSR (Gillanders et al., 2008; Nwaishi et al., 2015). Long-term changes have focused on general trends in disturbed, reclaimed and natural (undisturbed) ecosystems within or in close proximity to mining activities (Latifovic and Pouliot, 2014). Some studies using remote sensing are based on per-pixel trends in vegetation and/or water indices or transformations (Brown et al., 2000; Latifovic et al., 2005; Gillanders et al., 2008). Others have focused on classification methodologies for identifying disturbance and fragmentation (Meddens et al., 2008; Powers et al., 2015). Detection of reclamation trajectories using remote sensing requires that data are of high temporal (Kennedy et al., 2007; Gillanders et al., 2008; Huang et al., 2009), spatial (Komers and Stanojevic, 2013; van Rensen et al., 2015) and spectral resolution (Chowdhury et al., 2017). Individually, these ensure that: a) temporal variability of growth or mortality trends can be captured in time series data over long periods (Kennedy et al., 2007); b) pixel areas are small enough to capture small features in the landscape (Komers and Stanojevic, 2013); and c) greater numbers of discrete electromagnetic wavelengths observe differences in species and water content (Phillips et al., 2016), respectively. Despite these requirements, there is no one system that delivers all three adequately. While remote sensing indices provide an indicator of vegetation growth and/or disturbance/loss or decline over time (Gillanders et al., 2008), we are not aware of studies that have evaluated the use of remote sensing data using field plot measurements and long-term ecosystem productivity within AOSR reclamation sites. To address this need, the following study provides a unique application of standard remote sensing vegetation indices derived from high spatial resolution, multi-temporal SPOT 5 imagery. These are compared with indicators of ecosystem function determined from plot mensuration and growing season eddy covariance data within a comprehensive dataset of 15 reclaimed and reference sites. Sites have been hydrologically classified as wet, 'fresh' and dry based on Pojar et al. (1987); Straker et al. (2015) and site soil surveys (Table 1). Wet sites are defined as those that do not experience a growing-season water deficit and do not require substantial withdrawal of water from soil storage due to the presence of groundwater table at the rooting zone. Fresh sites are defined as those sites that do not experience a growing-season water deficit, but do require water withdrawal from soil storage to meet actual evapotranspiration demands. Finally, dry sites are defined as those sites that experience a water deficit where potential evapotranspiration exceeds precipitation during the growing season in an average year (Pojar et al., 1987; Straker et al., 2015). The objectives of this study are to: a) quantify the relationships and differences among vegetation spectral indices, in situ field measurements of vegetation productivity and gas flux indicators, including NEP, gross ecosystem production (GEP) and evapotranspiration (AET), over a period of years; and b) determine how differences in wet, fresh and dry reclaimed and reference site productivity is manifested within remote sensing data. Following Nwaishi et al. (2015), we answer the question: can subtle variations in vegetation change related to biomass accumulation and hydro-ecology at reclaimed sites be accurately quantified and assessed over time using optical remote sensing data?

2. Study area

Study sites used in this study are within the AOSR in the western half of the Boreal Plains ecoregion (WBP) in north-central Alberta, Canada (Fig. 1), north of the City of Fort McMurray (herein "Fort McMurray" sites) and east of the smaller Peace River Oil Sands (herein "Utikuma" sites). The climate of the region is sub-humid, where potential evapotranspiration (PET) exceeds precipitation (P) during most years (Marshall et al., 1999; Devito et al. 2005). Approximately 76% of annual P falls as rainfall during the growing season from May to August, coinciding with highest evaporative demand (Petrone et al., 2007). Carrera-Hernández et al. (2012) found that dry periods over the last century are more frequent and last longer than wet periods, potentially increasing the sensitivity of boreal ecosystems to disturbance. Mean annual (1981–2010 30-year normal) air temperature is 1 °C at Fort McMurray and cumulative P is 419 mm. Wabasca (nearest long-term