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Research article

An enhanced approach for the use of satellite-derived leaf area index values in dry deposition modeling in the Athabasca oil sands region

Mervyn Davies [a], Sunny Cho [b, c, *], David Spink [b], Ron Pauls [b], Michael Desilets [a], Yan Shen [a], Kanwardeep Bajwa [a], Reid Person [a]

[a] *Stantec, Calgary, AB, T2A 7H8 Canada*
[b] *Cumulative Environmental Management Association, Air Working Group, Fort McMurray, AB, T9H 4A4 Canada*
[c] *Government of Alberta, Alberta Environment and Parks, Edmonton, AB, T6H 4T8, Canada*

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A B S T R A C T

In the Athabasca oil sands region (AOSR) of Northern Alberta, the dry deposition of sulphur and nitrogen compounds represents a major fraction of total (wet plus dry) deposition due to oil sands emissions. The leaf area index (LAI) is a critical parameter that affects the dry deposition of these gaseous and particulate compounds to the surrounding boreal forest canopy. For this study, LAI values based on Moderate Resolution Imaging Spectroradiometer satellite imagery were obtained and compared to ground-based measurements, and two limitations with the satellite data were identified. The satellite LAI data firstly represents one-sided LAI values that do not account for the enhanced LAI associated with needle leaf geometry, and secondly, underestimates LAI in winter-time northern latitude regions. An approach for adjusting satellite LAI values for different boreal forest cover types, as a function of time of year, was developed to produce more representative LAI values that can be used by air quality sulphur and nitrogen deposition models. The application of the approach increases the AOSR average LAI for January from 0.19 to 1.40, which represents an increase of 637%. Based on the application of the CALMET/CALPUFF model system, this increases the predicted regional average dry deposition of sulphur and nitrogen compounds for January by factors of 1.40 to 1.30, respectively. The corresponding AOSR average LAI for July increased from 2.8 to 4.0, which represents an increase of 43%. This increases the predicted regional average dry deposition of sulphur and nitrogen compounds for July by factors of 1.28 to 1.22, respectively. These findings reinforce the importance of the LAI metric for predicting the dry deposition of sulphur and nitrogen compounds. While satellite data can provide enhanced spatial and temporal resolution, adjustments are identified to overcome associated limitations. This work is considered to have application for other deposition model studies where dry deposition represents a significant fraction of total deposition.

1. Introduction

Alberta's oil sands represent the world's third largest proven reserve of crude oil and are found in three regions: the Athabasca oil sands region (AOSR), which is the largest, the Cold Lake oil sands region both of which are located in northeastern Alberta; and the Peace River oil sands region which is located in north central Alberta, Canada. (Alberta Energy, http://www.energy.alberta.ca/LandAccess/pdfs/OSAagreeStats.pdf). There has been a dramatic increase in the rate of oil sands development and an associated growing public interest and concern regarding the health and environmental effects due to oil sands development including those related to sulphur and nitrogen compound deposition (Royal Society of Canada (2010)).

In the AOSR, the dry deposition of sulphur and nitrogen compounds represents a significant fraction of total sulphur and nitrogen deposition (Laxton et al., 2010; Davies et al., 2012; Vijayaraghavan et al., 2014). Deposition of these compounds is a regional concern in terms of potential acidification and nitrogen eutrophication effects on aquatic and terrestrial ecosystems (Whitfield et al., 2010; Weider et al., 2010; Percy et al., 2012). An Acid Deposition Management Framework (http://cemaonline.ca/index.php/cema-recommendations/ozone-management) and an Interim Nitrogen Management Framework (http://cemaonline.ca/index.php/cema-recommendations/interim-nitrogen) have been

* Corresponding author. Government of Alberta, Edmonton, AB T5J 1G4 Canada.
E-mail address: sunhee.cho@gov.ab.ca (S. Cho).

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established to address these issues. Modeling and monitoring programs associated with these Frameworks require estimates of nitrogen and sulphur deposition. CALPUFF model sensitivity runs conducted in 2009 assessed the effect of different model inputs on predicted potential acid input and ambient SO_2, NO_2 and NO_X concentrations in the AOSR (Golder Associates, 2010). The model sensitivity work recommended that regional acid deposition modeling use 2.5 km Moderate Resolution Imaging Spectroradiometer (MODIS) land use and leaf area index (LAI) values for 5 seasons. Consistent with this recommendation, CEMA commissioned studies to compare satellite and filed LAI measurements for dominant land cover classes in the AOSR (Bourque and Hassan, 2008; 2011).

Models used to estimate dry deposition use leaf area index (LAI) as the metric to quantify the amount of vegetative surface that is active in dry deposition processes (Hicks et al., 1987; Wesely and Hicks, 2000; Zhang et al., 2001; 2003; Zhang and He, 2014). There are different definitions for LAI depending on leaf type and the intended use of the LAI measurement (e.g. radiation interception versus stomatal diffusion) with the general definition being based on some measure of leaf area or leaf projection in the canopy per unit of underlying horizontal ground area (; Smith et al., 2000; Asner et al., 2003). The LAI depends on the vegetation canopy properties that vary with land cover type and with season and site (Jose and Gillespie, 1997; Li et al., 2011).

In terms of dry deposition modeling, LAI is a key parameter for both stomatal and nonstomatal uptake. Because in the AOSR seasonality extremes and variability strongly affect LAI values, higher temporal and spatial resolution data for LAI is desirable for the dry deposition modules within atmospheric chemical transport models. Also, consistency of input parameters and/or meteorological variables (e.g., roughness length, soil moisture, canopy wetness, and many boundary layer micrometeorological variables) between the dry deposition module and its host model is preferred (Carey, 2008; Wu et al., 2012). In addition to dry deposition, surface features also influence surface energy balance and atmospheric turbulence which affect dry deposition processes. For these reasons, surface cover characteristics need to be determined for different land/vegetation types in the model domain.

Numerous methods are available to estimate LAI (Price and Baush, 1995; Qi et al., 2000; Wykoff, 2002; X. Zhang et al., 2003; Breda, 2003; Jonckheere et al., 2004; Hasegawa et al., 2010) which are broadly categorized as ground-based and remote sensing. Historically in the AOSR the inferential modeling of dry deposition of nitrogen and sulphur compounds has been based on air quality models that use LAI look-up tables specific to the vegetation type and the associated season. Satellite data has the advantage of providing geophysical information such as LAI on a near real-time basis (Narasimhan et al., 2005; Sakamoto et al., 2014). Bourque and Hassan (2008 & 2010) conducted studies to identify deficiencies and information gaps regarding LAI determination. MODIS based LAI data and field-based measurements at 75 sites representing six major forest vegetation types in the AOSR were used. Subsequently Davies et al. (2012) and Vijayaraghavan et al. (2012) identified the following two factors that needed to be addressed when using satellite LAI data in deposition modeling: 1) satellite data represents one-sided LAI but for deposition, the reactive surface of conifer forests is proportionally greater than that for broadleaf forests. A conifer adjustment needs to account for needle leaf geometrical considerations that differ from those for broadleaf vegetation types (Chen and Cihlar, 1996; Running et al., 1986; Stenberg, 1996; Wang et al., 2014); and 2) for high latitude, winter-time condition, satellite data underestimates LAI. This underestimation has been varyingly attributed in numerous studies to low sun angles, low data capture, understory influences, incomplete atmospheric corrections, or change in needle properties (e.g., Tian et al., 2002; Myneni et al., 2002; Chen et al., 2006; Yang et al., 2006a; 2006b). Collectively, the item 2) considerations are referred to as "spectral limitations".

This paper outlines the approach and resultant LAI modeling protocol that was developed to address the LAI metric and satellite LAI estimation issues identified in previous studies and the significant seasonal vegetation cover variability in the AOSR. The approach used in this study to adjust LAI values, which was based on regional ground-based measurements and a focus on LAI measurements that would best reflect the underlying process being modeled (i.e. dry deposition through stomatal diffusion) may have application in other dry deposition modeling and determination situations.

2. Methodology

2.1. Site description

This study focuses on improving the LAI and land cover data for the AOSR. The AOSR is within the Boreal Plains Ecozone with both upland and wetland ecosites and a variety of vegetation covers (Percy et al., 2012; Beckingham and Archibald, 1996). The selected AOSR Study Area for this study has a nominal east-west extent of 504 km (126 4-km grid cells) and a nominal north-south extend of 756 km (189 4-km grid cells) (Fig. S1 (a)) in northeastern Alberta, Canada. The Lambert conformal projection was used to account for the curvature of the earth resulting in the Study Area representing a surface area on the earth that is 396,333 km^2.

2.2. Description of data

2.2.1. Land cover classes

Land cover classes are required to adjust the satellite LAI values for different vegetation canopy types. The boreal plains ecozone supports a mixture of upland and lowland vegetation. Specifically, the region is characterized by forests of black spruce, white spruce, balsam fir, jack pine, aspen, poplar, and white birch (Beckingham and Archibald, 1996). Due to differing drainage patterns, soil types (Lamoureux et al., 2012), sun exposure, and transitional forest fire zones; vegetation cover throughout the region is non-uniform and forest canopy heights may vary from less than 10 m to more than 30 m, depending on these conditions and the tree types present. Stand densities can also vary significantly with 13 jack pine biomonitoring sides established in the AOSR in the 1970s having stand densities ranging from 150 to 6400 stems >10 cm DBH.ha^{-1} (Addison, 1980). The southern boundary of the Study Area is located outside the boreal forest zone, and is dominated by cropland and grassland. The Earth Observation for Sustainable Development (EOSD) initiative by the Canadian Forest Service, in partnership with the Canadian Space Agency, developed a Land Cover Classification (LCC) system and land-cover map for the forested area of Canada (Wulder and Nelson, 2003). The base resolution of the land-cover data is 30 m. The EOSD product is based upon data from the early 2000s, and despite the temporal difference between the land cover class (2000) and the LAI data (2010); it is an acceptable product for this assessment.

The EOSD LCC scheme is comprised of 26 classes and a subset of 17 classes are used for this study. Table S1 shows the relationship between the two LCC schemes and the relative coverage on a 30 m resolution. The land cover data were resampled to a 0.5 km resolution. The land cover class for each 0.5 km grid cell is based on the dominant land cover for that grid cell. Even though there may be several land cover classes in each grid cell, the grid cell is analyzed on the basis of the dominant land cover. Table 1 shows relative coverage for each new land cover class on a 0.5 km resolution. On