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Research article

Canopy volume removal from oil and gas development activity in the upper Susquehanna River basin in Pennsylvania and New York (USA): An assessment using lidar data

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ABSTRACT

Oil and gas development is changing the landscape in many regions of the United States and globally. However, the nature, extent, and magnitude of landscape change and development, and precisely how this development compares to other ongoing land conversion (e.g. urban/sub-urban development, timber harvest) is not well understood. In this study, we examine land conversion from oil and gas infrastructure development in the upper Susquehanna River basin in Pennsylvania and New York, an area that has experienced much oil and gas development over the past 10 years. We quantified land conversion in terms of forest canopy geometric volume loss in contrast to previous studies that considered only areal impacts. For the first time in a study of this type, we use fine-scale lidar forest canopy geometric models to assess the volumetric change due to forest clearing from oil and gas development and contrast this land change to clear cut forest harvesting, and urban and suburban development. Results show that oil and gas infrastructure development removed a large volume of forest canopy from 2006 to 2013, and this removal spread over a large portion of the study area. Timber operations (clear cutting) on Pennsylvania State Forest lands removed a larger total volume of forest canopy during the same time period, but this canopy removal was concentrated in a smaller area. Results of our study point to the need to consider volumetric impacts of oil and gas development on ecosystems, and to place potential impacts in context with other ongoing land conversions.

1. Introduction

Unconventional oil and gas (UOG) development (i.e. horizontal drilling into deep shale formations and/or stimulated with hydraulic fracturing) is changing the landscape in many regions of the United States (Meng, 2017; Allred et al., 2015). Recent advances in drilling technology for exploitation of "tight gas" locked in shale formations has opened up new areas of the U.S. to energy development and similarly is spurring interest in other shale plays globally (U.S. EIA, 2011). Land clearing necessary for development of well pads, new infrastructure for accessing drilling platforms (access roads), and infrastructure for transporting petroleum products (pipelines), have potentially become major new influences on forested landscapes. In areas such as the Marcellus shale play in Pennsylvania (USA), new areas opened up by unconventional drilling techniques, in combination with a long history of conventional oil and gas drilling, have elicited concern about the current and future footprint of energy development on the landscape (Dunscomb et al., 2014). However, the nature, extent, and magnitude of landscape change due to energy development, and precisely how this development compares to other ongoing drivers of land conversion (e.g. urban/sub-urban development, timber harvest) is not well understood.

Smith et al. (2012) reviewed landscape impacts from unconventional oil and gas development and discuss the similarity to and impacts from land clearing during forestry operations as compared to urban and suburban development. They concluded that land conversion for unconventional oil and gas activities likely has impacts intermediate between forest removal and urbanization. They concluded that canopy removal and road construction impacts are likely similar to timber harvest, but with impervious surface development similar to urbanization impacts. However, they did not consider how the *volume* of forest material removed by recent oil and gas development might compare to other forms of land conversion, a distinction with implications for

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wildlife habitat, evapotranspiration potential, carbon sequestration, and a host of other ecosystem services.

Unconventional oil and gas production has received much recent attention in the scientific literature as more scientists seek to understand the nature and potential impacts of energy development. Assessment of aquatic system vulnerability (Entrekin et al. 2011, 2015; Smith et al., 2012; Souther et al., 2014; Maloney et al., 2017), energy build out potential (Evans and Kiesecker, 2014), and potential risk to human populations (Meng, 2015) have all been recently examined. Studies on landscape impacts from recent oil and gas development are relatively few, including studies by Moran et al. (2015) in Arkansas, Preston and Kim (2016) in North Dakota, and Slonecker et al. (2012), and Slonecker and Milheim (2015) in Pennsylvania. These studies explicitly mapped and examined the spatial footprint of both conventional and unconventional oil and gas production, assessed habitat fragmentation effects, and assessed implications to wildlife, streams, drinking water intakes, and human populations. Klaiber et al. (2017) conducted a land use change analysis for the State of Pennsylvania using land cover change statistics from medium resolution National Land Cover Data summarized by Census tracts, and suggested that each additional well drilled impacted between 46 and 52 acres of core forest and increased patchiness, while consolidation of wells could potentially reduce that impact. Donnelly et al. (2017) assessed land change due to shale gas infrastructure in the Utica and Marcellus plays in Pennsylvania and found that, although overall only 1% of forest area had been impacted, "fragmentation affects are amplified by the pattern of infrastructure on the landscape". Other studies by Drohan et al. (2012) found that well pads developed for shale gas production in Pennsylvania were placed predominantly in previously agricultural land, but many of those placed in forested areas disturbed core forests. Although Drohan et al. (2012) did not explicitly examine forest removal effects from pipelines, in a follow-up study of Lycoming County, PA the authors found that pipeline clearings removed more forest area than well pads (Langlois et al., 2017). Models of potential future development predicted close to 450,000 ha of impacted forest (2% of the total area) from combined oil, gas, and wind turbine development throughout the Marcellus play by 2030 (Evans and Kiesecker, 2014; Dunscomb et al., 2014). Although unconventional oil and gas development occurs in shale plays across the United States, and is predicted to be a major future landscape influence (Trainor et al., 2016), many studies have focused on the Marcellus shale play in Pennsylvania because of the open availability of oil and gas permitting data provided by the State.

While most prior work on land cover change considers only the areal, or 2-dimensional, nature of forest loss, not all forests are equal in terms of standing volume. Adding in the height (z) dimension allows for estimating variability in forest structure and volume and potentially allows assessment of biomass or carbon storage potentially lost to development. Larger, older, and more structurally diverse forest canopies provide more diverse and higher quality habitats for interior forest animals, birds, and plants (Brittingham et al., 2014). Opening of interior forests exposes these areas to impacts from invasive plants, altered light and microclimatic regimes, and dust, noise, and vehicle impacts (Barlow et al., 2017). Since clearing for well pads, access roads, and pipelines are, for the most part, semi-permanent conversions (i.e. clearings are managed to prevent forest regrowth), forest volume that is removed can be considered to be permanently lost, at least for the anticipated lifespan of the producing well.

Measuring volumetric changes in forests over large landscapes has traditionally been difficult. However recent advances in lidar (light detection and ranging) remote sensing technology enables high resolution 3-dimensional mapping of forest structure, allowing quantification of canopy volume (Wulder et al., 2012). The result of mapping with a lidar system is a dense 3-dimensional "point cloud" of elevations from surface objects, including from multiple parts of the tree canopy. Lidar data, while useful for a host of application areas, have become especially useful in forestry for direct measurement of 3-dimensional metrics important for forest mensuration and habitat assessment such as tree and stand height, canopy structure and density, and stream shading (Dubayah and Drake, 2000; Lefsky et al., 2002; Vierling et al., 2008; Hudak et al., 2009; Zellweger et al., 2014; Bode et al., 2014). Volumetric measures of tree canopies can be directly converted to measures of biomass or carbon stocks and can be used to assess potential implications of forest loss on carbon sequestration and climate change impacts (Lefsky et al., 2002; Asner et al., 2011).

Studies employing lidar data to assess forest volume or biomass typically model allometric relationships between lidar canopy structural metrics and ground plot-based measures of tree basal area, height, cover, and crown characteristics and extrapolate forest volume to unsampled areas based on model parameter estimates applied to mapped lidar predictors (Jucker et al., 2017; Chirici et al., 2016; Chen et al., 2007b; van Aardt et al., 2006). Derivation of allometric relationships is typically constrained to local areas to account for environmental and species specific characteristics governing tree diameter-height relationships (e.g. site quality, soil nutrients, moisture availability). Because of this, development of forest volume or biomass relationships over large areas is challenging, but recent efforts have established the conceptual basis for regional estimates of biomass from standardized allometric equations using consistent tree diameter and height relationships within ecoregional types (Jucker et al., 2017; Ferraz et al., 2016). These efforts point to development of generalized 3-dimensional forest canopy volume assessments which would be timely considering the increasing availability of aerial lidar acquisitions often provided to the public for free.

In the absence of detailed field plot data to evaluate allometric relationships, models of forest canopy heights derived from lidar point clouds may still have utility for assessing landscape and habitat change over large areas. Tree and canopy top height measured from small footprint aerial lidar data has consistently been found to be reliably accurate and precise, often measured as accurately as tree heights measured from the ground (Chen, 2007a; Andersen et al., 2006). Assessing the difference between modeled canopy surface elevations and modeled ground elevations (i.e. a digital elevation model) provides measures of canopy height and height variability. When assessed over a given area (e.g. a ground area represented as a raster pixel), canopy height can be converted to an estimate of canopy volume. Chen et al. (2007) introduced the concept of "canopy geometric volume", which is defined as "the volume encircled by the outer surface of the crown" based on lidar surface –derived canopy height models and found that it explained a large portion of the variability in biomass in test areas. Véga et al. (2016) define this metric as the canopy inner volume (*CHMvi*), e.g. "characterizing the maximum 3D space occupied by trees" and report that this volume measure (and ratios with other canopy volume variants) is predictive of above ground volume, measured in field plots. While *CHMvi* is not in and of itself a measure of forest volume since it includes interstitial space under and in-between trees, it is highly correlated with above ground forest volume and biomass.

Assessment of changes in 3-dimensional habitat attributes is a new area of scientific investigation due in large part to the growing availability of aerial lidar acquisitions (Eitel et al., 2016). However, due to the often prohibitive acquisition cost, availability of repeat acquisition lidar data for change detection monitoring is rare. Therefore, methods that combine single-time period pre-disturbance lidar data with high resolution land cover mapping from post-disturbance aerial photographs or satellite imagery hold additional promise for temporal monitoring of forest canopy volumetric changes.

In this paper, we examine land conversion from oil and gas development in terms of total canopy volume change, as well as canopy volume change as a percentage of intact canopy volume prior to oil and gas development. For the first time in a study of this type, we use fine-scale lidar forest canopy data to assess the volumetric impact of land conversion from these activities. We compare and contrast canopy removal due to well pad development, access road construction, and