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Developing and validating indicators of site suitability for forest harvesting residue removal

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ABSTRACT

The increasing demand for forest biomass, notably from primary residues of harvested trees for the production of bioenergy, has raised concerns because of potential adverse effects on forest soil productivity. Our aim was to develop and validate spatially explicit planning indicators of site suitability for harvesting residue removal based on mapped forest site properties for four large case study areas located across Canada, each containing field studies on the impact of harvesting residue removal. Sustainability was assessed relative to the baseline scenario of conventional stem-only harvesting, to investigate the incremental effects of the removal of residues associated with whole-tree harvesting in typical operational conditions in Canada. Using information from scientific literature and guidelines from various jurisdictions, eleven planning indicators were developed, from which nine were related to the loss of soil fertility risk and two to erosion risk. Planning indicators were tested for redundancy and validated using response indicators of stand growth and nutrition from field studies. Several relationships between mapped soil properties and the empirical response of stands to harvesting residue removal were found. Planning indicators based on concentrations of organic C, total N and total P in the top 30 cm of the mineral soil best explained stand responses to harvesting residue removal. Despite caveats, the methodology used here demonstrates an approach for developing and empirically testing planning indicators of site suitability for harvesting residue removal. As more information on the impact of this practice becomes available from field studies, it can be used to refine and further validate the indicators.

1. Introduction

Bioenergy in general, and that derived from forest biomass in particular, has a high potential for increasing the proportion of renewable energy produced over the next 50 years at a global scale (Chum et al., 2011). Over recent years, this has led to an interest in the use of primary residues from harvested trees. Primary residues, or harvesting residues, are defined as trees or tree parts that are by-products of forest harvesting operations and not used by traditional wood-processing industries such as timber and pulp (Röser et al., 2008). In Canada, it is estimated that approximately 20 Tg y^{-1} of harvesting residues, mainly tree tops and branches produced during clearcutting, could be available for use as feedstock for bioenergy (Dymond et al., 2010).

However, the increasing demand for forest biomass, and related pressure on forest ecosystems, has also triggered a debate on the sustainable production of biomass (reviewed in Lamers et al., 2013). One concern related to removal of harvesting residues is the potentially adverse effects on soil productivity (defined as the capacity of a soil to sustain a growing forest) due to increased extraction of nutrients and organic material and increased soil physical disturbance relative to conventional stem-only harvesting (Johnson, 1994; Burger, 2002; Raulund-Rasmussen et al., 2008).

A number of jurisdictions and certification systems have developed guidance in the form of regulations, best management practices or recommendations for ensuring that soil productivity is maintained when removing harvesting residues (Stupak et al., 2007; Abbas et al., 2011; Evans et al., 2013). There is growing

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scientific knowledge about the impacts of harvesting residue removal on soil productivity that can inform forest management policy. However, existing scientific information is often site-specific and disjointed, making generalizations for wider applicability difficult, although synthesis analyses have been conducted (e.g., Thiffault et al., 2011; Wall, 2012; Ponder et al., 2012). This is why current guidance often relies on local expert knowledge. Variations in ecological, geographical and geopolitical conditions within and between jurisdictions can thus lead to corresponding variations in guidance (Stupak et al., 2008). There is therefore no consensus on how best to predict impacts of harvesting residue removal on soil productivity, and therefore on how to define *planning indicators* so that managers can identify suitable sites for harvesting residue removal. There is also no consensus on how best to measure impacts on soil productivity after harvesting residue removal using *response indicators*, which monitor the ecosystem response and validate whether the planning indicator correctly assessed site suitability and allowed soil productivity to be maintained. More importantly, there has been little attempt so far to empirically validate whether assessment of site suitability given by planning indicators is indeed reflected in the field in the response of soil productivity to harvesting residue removal. As underlined by McBride et al. (2011), there is a need for a set of indicators that represent the realized environmental effects of bioenergy systems.

Sets of standardized and accepted planning and response indicators are needed to plan, evaluate and compare forest management activities to ensure sustainable use of resources in the context of adaptive management (Kneeshaw et al., 2000). In the case of harvesting residue removal, such indicators are crucial for establishing and monitoring sustainable forest biomass supply chains, and allowing learnings from on-going trials and field tests to be applied to other sites, which will, in turn, strengthen the scientific credibility of the developing forest bioenergy sector (Van Dam et al., 2008; McBride et al., 2011). Planning and response indicators need to be underpinned by a solid scientific basis; have to be clear, objective and easy to apply; and need to be based on readily available or easily measurable parameters (Kneeshaw et al., 2000; Hall, 2002; Rempel et al., 2004; Heink and Kowarik, 2010). To inform management policy decisions at the regional and national scales and to identify the quantity of forest land from which harvesting residues may be available, planning indicators that allow the identification of suitable sites for harvesting residue removal should also be made spatially explicit, i.e., displayed across landscapes using maps or other geographic information system (GIS) tools (e.g., Brierley et al., 2004; Kimsey et al., 2011).

These types of indicators are particularly important for Canada because the forest bioenergy sector is nascent, biomass supply chains are not yet stable, and governance schemes are quickly evolving. On the other hand, Canada has had a rigorous forest research program for many decades that includes development of indicators of ecosystem function and studies on the ecological impacts of forest management (Kneeshaw et al., 2000). In particular, a number of field trials have been established across the country to study the effects of harvesting residue removal from whole-tree harvesting on soil productivity relative to the effects of conventional stem-only harvesting. In most trials, whole-tree harvesting was conducted in order to reflect regular operational conditions, which leave behind a proportion of residues. The average level of residue removal in whole-tree operations in Canadian forests is estimated to be around 50–70% of residues (E. Thiffault unpublished data). Empirical data were collected at intervals up to 20 years after treatment depending on the trial (Titus et al., 2008). Post-harvest aboveground stand biomass and tree foliar nutrition, which are recognized as proxies for forest soil productivity (Fisher and Binkley, 2000), have been measured across the trials. These trials therefore provide a foundation of scientific knowledge that can be used to develop planning indicators for harvesting residue removal for the protection of forest soil productivity, and to validate them using field-based measurements of ecosystem response.

The overall aim of this project was to develop spatially explicit planning indicators of site suitability for harvesting residue removal, and validate them using response indicators. Site suitability is defined here as the capacity of a site to sustain a level of harvesting residue removal equivalent to typical operational conditions in Canadian forests (i.e., an average of 50–70% of available residues) without decline in soil productivity. Sustainability of harvesting residue removal was assessed in view of its potential additional pressure relative to stem-only harvesting. Stem-only harvesting was therefore set as the baseline or reference scenario, in order to reveal the additional effects of the bioenergy system, i.e., additional biomass removal (McBride et al., 2011; Efroymson et al., 2013).

Specific project objectives were: (i) to identify from the literature a range of planning indicators of site suitability; (ii) to spatially apply these planning indicators to four case study areas across Canada and to produce maps comparing the spatial patterns of the different indicators; (iii) to validate planning indicators using response indicators based on empirical measurements of growth and foliar nutrition from experimental trials; and (iv) to identify the best sets of indicators. Overall, these objectives were used to test the hypothesis that site properties and tree measurements can be used to rate and validate site suitability for forest harvesting residue removal.

2. Methods

2.1. Study areas

Four case study areas across Canada were delineated in British Columbia, Ontario, Quebec and Nova Scotia so that each encompassed a cluster of long-term forest residue removal field trials set up in the past decades by various agencies (Table 1). The boundaries of case study areas followed those of Canadian Ecological Land Classification System ecoregions (Ecological Framework of Canada, 2012), except for Quebec where only the northernmost half of the ecoregion was studied (Fig. 1).

The British Columbia study area is Ecoregion 209 in the Thompson-Okanagan Plateau. The mean annual temperature of the major valleys is approximately 6 °C with a mean annual precipitation that ranges between 250 and 300 mm in the major valleys to over 1000 mm in subalpine and alpine forests. Plateau regions receive about 400–600 mm. The subalpine forests are principally composed of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and lodgepole pine (*Pinus contorta* Dougl. ex Loud.). Lower elevations support forests of lodgepole pine mixed with some trembling aspen (*Populus tremuloides* Michx.), white spruce (*Picea glauca* (Moench) Voss), and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco.). Valley bottoms support principally Douglas-fir and ponderosa pine (*Pinus ponderosa* Dougl. ex P.&C. Laws.). The region has a gently rolling surface covered mainly by glacial deposits largely derived from basic volcanic rocks.

The Ontario study area is Ecoregion 94, which surrounds Lake Nipigon. Mean annual temperature and precipitation are approximately 1.5 °C and 750 mm, respectively. The dominant vegetation is mixed forest, characterized by stands of white spruce, black spruce (*Picea mariana* (Mill.) B.S.P.), balsam fir (*Abies balsamea* (L.) Mill.), jack pine (*Pinus banksiana* Lamb.), trembling aspen, and paper birch (*Betula papyrifera* Marsh.). Dry sites are dominated by jack pine with secondary quantities of black spruce. This ecoregion is underlain by the acidic, Archean bedrock of the Canadian Shield.