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Harvest residue removal and soil compaction impact forest productivity and recovery: Potential implications for bioenergy harvests

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ABSTRACT

Understanding the effects of management on forest structure and function is increasingly important in light of projected increases in both natural and anthropogenic disturbance severity and frequency with global environmental change. We examined potential impacts of the procurement of forest-derived bioenergy, a change in land use that has been suggested as a climate change mitigation strategy, on the productivity and structural development of aspen-dominated ecosystems. Specifically, we tested the effects of two factors: organic matter removal (stem-only harvest, whole-tree harvest, whole-tree harvest plus forest floor removal) and soil compaction (light, moderate, and heavy) over time. This range of treatments, applied across three sites dominated by aspen (*Populus tremuloides* Michx.) but with different soil textures, allowed us to characterize how disturbance severity influences ecosystem recovery.

Disturbance severity significantly affected above-ground biomass production and forest structural development with responses varying among sites. At the Huron National Forest (sandy soils), the removal of harvest residues reduced above-ground biomass production, but no negative effect was observed following whole-tree harvest at the Ottawa and Chippewa National Forests (clayey and loamy soils, respectively) relative to stem-only harvest. Maximum diameter and the density of stems greater than 5 cm DBH exhibited negative responses to increased disturbance severity at two sites, indicating that structural development may be slowed. Overall, results suggest that disturbance severity related to procuring harvest residues for bioenergy production may impact future productivity and development, depending on site conditions and quality.

1. Introduction

Forests have been suggested as a supply of alternative sources of energy feedstocks for offsetting fossil fuel consumption (Millar et al., 2007; Becker et al., 2009; Aguilar and Saunders, 2010; Buford and Neary, 2010); however, increases in demand for forest-derived bioenergy feedstocks could translate to an increase in harvest-related disturbance severity and frequency with associated ecological impacts (Berger et al., 2013). At the same time natural disturbance events (windthrow, fire, etc.) and stressors (e.g. drought) may also increase in frequency and severity as climate change progresses (Dale et al., 2001; Turner, 2010). Uncertainty regarding how ecosystems will respond to changes in disturbance, both natural and anthropogenic, poses a serious challenge to the development of long-term sustainable forest management and conservation strategies (Dale et al., 2001; Joyce et al., 2009).

Given the uncertainty surrounding ecosystem responses to potential increases in disturbance, sustainable forest management requires a better understanding of how disturbance severity affects forest productivity and successional development. Generally, forest development occurs more quickly on more fertile sites (Franklin et al., 2002; Larson et al., 2008; Ryan et al., 2008; Hardiman et al., 2011), but disturbance itself can degrade site quality through depletion of nutrients and changes in the understory environment (Stoeckeler, 1948; Thiffault et al., 2011). Also, increased disturbance severity or compound disturbance events may push ecosystems outside the range of natural variation (Paine et al., 1998; Lindenmayer et al., 2004). These changes in disturbance severity may favor the establishment and growth of dense understory layers (Royo and Carson, 2006) as has been observed in white spruce forests (Eis, 1981) and, to some extent, with trembling aspen (*Populus tremuloides* Michx.; Landhausser and Lieffers, 1998) in boreal regions. Such an understory can interfere with the establishment of tree species historically adapted to a site, thus slowing or changing forest developmental trajectories (Royo and Carson, 2006).

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Results from studies examining the effects of harvest residue removal to date have varied depending on site quality, time since disturbance, and forest type. In nutrient-poor forests, removal of harvest residues (i.e., slash) can reduce nutrient availability and tree growth (Walmsley et al., 2009; Helmisaari et al., 2011; Morris et al., 2014); however, negative effects may not be detected in some cases until 10–20 years following harvest (Egnell and Valinger, 2003; Helmisaari et al., 2011; Mason et al., 2012; Vanguelova et al., 2010). Findings from Long Term Soil Productivity (LTSP) study sites in boreal aspen and black spruce forests suggest that while tree densities may not respond negatively to the removal of harvest residues, tree height can be detrimentally impacted (Kabzems, 2012; Morris et al., 2014). Even where site productivity appears to recover, the reduction in above-ground biomass caused by initial post-harvest declines in site productivity can persist for over 30 years (Egnell, 2011). On richer sites the effects are more difficult to discern (Smolander et al., 2008, 2010; Roxby and Howard, 2013). Fully assessing ecosystem response to disturbance requires quantifying severity in terms of not only the death or removal of biomass, but also impacts to soil given the pervasive influence harvest-related soil disturbance may have on forest community development (Halpern, 1988; Roberts, 2007). The design of the LTSP study network allows assessing these different effects in a way applicable to bioenergy harvests.

Studies that consider impacts to soil, herbaceous biomass, shrub biomass, and other ecological response variables, will increase understanding of the potential long-term impacts that increased levels of feedstock harvests may have on ecosystem structure and function. For example, quantifying productivity in non-tree plant species concurrently with tree species can elucidate competitive interactions among different guilds and the processes behind community disturbance responses (Grewal, 1995; Royo and Carson, 2006). Additionally, the rate of post-disturbance structural development gives an indication of engineering resilience (hereafter 'resilience'; Larson et al., 2008), which represents the length of time required for a system to return to its pre-disturbance state (Holling, 1996). If disturbance severity influences species composition, structural development, and resilience, then anticipated impacts on future functions will vary similarly, as will the degree to which forest stands accommodate different management objectives (Schwenk et al., 2012).

We examined how aspen-dominated forests growing on three different soil textures across the northern Lake States region respond to a gradient of disturbance severity created through different combinations of biomass removal and soil compaction. We show how above-ground productivity and structure respond to experimentally-controlled variations of stand-replacing disturbance and that responses vary across a range of sites. The responses to differing disturbance severities are used to demonstrate how forests may respond to bioenergy feedstock procurement of differing severity and whether some sites may be more resilient to such practices. Because of potential nutrient losses and greater departure from natural disturbance, we hypothesized that above-ground productivity would decrease with increasing disturbance severity across all sites. We also expected that structural development following the most severe disturbance would lag behind less severely impacted stands because of lowered site quality, which is known to be directly tied to the rate of structural development (Franklin et al., 2002; Ryan et al., 2008). These hypotheses were tested using experimental sites associated with the LTSP network, established in the early 1990s. Three LTSP installations in the Lake States located within the Chippewa, Ottawa, and Huron-Manistee National Forests, provide the opportunity to assess how forests dominated by the same species but distributed across a landscape respond to different levels of disturbance severity over 15 years.

2. Methods

2.1. Study sites

The study includes three sites within the Laurentian Mixed Forest Province extending from northern Minnesota, USA to Lower Michigan, USA. Each site was dominated by aspen (*P. tremuloides* Michx.) prior to harvest. The Chippewa National Forest (Chippewa) installation (47°18′N, 94°31′W) occurs on silty loam Frigid Haplic Glossudalfs, receives approximately 64 cm precipitation each year, and is the most productive of the three sites (site index 23 m height at age 50 (SI_{50}) for aspen; Voldseth et al., 2011). Important species prior to harvest included aspen (Curtis Importance Value = 58%), sugar maple (*Acer saccharum* Marshall, 11%) and basswood (*Tilia americana* L., 9%). In terms of relative biomass, aspen maintained a similar dominance 15 years after harvest (52.0%). The Huron-Manistee site (Huron; 44°38′N, 83°31′W) has a SI_{50} of 19 m for aspen (Stone, 2001). Soils are sandy, classified as Frigid Entic Haplorthods and Frigid Typic Udipsamments and annual precipitation is approximately 75 cm (Voldseth et al., 2011). Before harvest important species in addition to aspen (57%) included big-toothed aspen (*P. grandidentata* Michx., 31%) and white pine (*Pinus strobus* L., 4%). Site-wide species composition was similar 15 years post-harvest with aspen (41.8%) and big-toothed aspen (34.1%) dominating, followed by red oak (11%). The Ottawa National Forest installation (Ottawa; 46° 37′ N, 89° 12′ W) occurs on clayey Frigid Vertic Glossudalfs. This site receives approximately 77 cm precipitation annually and has a SI_{50} of 17–18 m for aspen (Voldseth et al., 2011; Stone, 2001). Following aspen (50%), balsam fir (*Abies balsamea* [L.] Mill., 33%) and white spruce (*Picea glauca* [Moench] Voss, 14%) dominated prior to harvest. Aspen abundance was comparatively greater 15 years post-harvest (87.5%) with balsam fir (4.7%) and white spruce (0.01%) making up smaller components than pre-harvest levels.

2.2. Experimental design

The severity of disturbance has been quantified in terms of organic matter removal and soil compaction, two factors likely affected during the procurement of biofuel feedstocks from forests. These two factors, each with three levels, were crossed using a factorial design resulting in nine treatments examined over time.

The three organic matter removal levels are named according to the traditional harvest method they most closely resemble. These levels included: (1) stem-only harvest (SOH), in which shrubs and merchantable tree boles were removed leaving behind harvest residues (branches and non-merchantable tops); (2) whole-tree harvest (WTH) in which all aboveground portions of trees and shrubs were removed; and (3) whole-tree harvest plus forest floor removal (FFR) in which the forest floor was removed in addition to all above-ground woody biomass. Shrubs such as hazel (*Corylus cornuta* Marshall and *C. americana* Walter) often grow densely in this region and can inhibit tree regeneration, so they were removed from all treated plots at the time of harvest. WTH is a best approximation of the harvest practices associated with biomass feedstock procurement, given the focus of these harvests on removing materials, such as tree tops, and tree limbs which normally would be left on site after traditional harvests. Some states and countries have developed guidelines that recommend removal of only a portion of harvest residues for use in bioenergy production (i.e. MFRC, 2007); this study, as it was originally designed in the 1990s, only allows assessment of extremes within the range of residue levels that might be removed as bioenergy feedstocks.

The compaction levels included no additional compaction above normal levels associated with conventional harvesting (C0),