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Effects of Fire Severity and Woody Debris on Tree Regeneration for Exploratory Well Pads in Jack Pine (*Pinus banksiana*) Forests

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Abstract: Restoring anthropogenic footprints to pre-disturbance conditions or minimizing their long-term impacts is an important goal in conservation. Many footprints, particularly if left alone, have wide-ranging effects on biodiversity. In Canada, energy exploration footprints result in forest dissection and fragmentation contributing to declines in woodland caribou. Developing cost effective strategies to restore forests and thus conserving the woodland caribou habitat is a conservation priority. In this study, we compared the effects of wildfire and local variation in the amount of residual woody debris on natural regeneration in jack pine on exploratory well pads in Alberta's boreal forest. Specifically, we investigated how footprint size, fire severity (overstory tree mortality), ground cover of fine and coarse woody debris, and adjacent stand characteristics (i.e., height, age, and cover), affected tree regeneration densities and height using negative binomial count and linear models (Gaussian), respectively. Regeneration density was 30% higher on exploratory well pads than adjacent forests, increased linearly with fire severity on the exploratory well pads (2.2% per 1% increase in fire severity), but non-linearly in adjacent forests (peaking at 51,000 stems/ha at 72% fire severity), and decreased with amount of woody debris on exploratory well pads (2.7% per 1% increase in woody debris cover). The height of regenerating trees on exploratory well pads decreased with fire severity (0.56 cm per 1% increase in fire severity) and was non-linearly related to coarse woody debris (peaking at 286 cm at 9.4% coarse woody debris cover). Heights of 3 and 5 m on exploratory well pads were predicted by 13- and 21-years post-fire, respectively. Our results demonstrate that wildfires can stimulate natural recovery of fire-adapted species, such as jack pine, on disturbances as large as exploratory well pads (500–1330 m^2) and that the type and amount of woody debris affects these patterns.

Keywords: jack pine; *Pinus banksiana* Lamb.; exploratory well pad; well pad; fire; woody debris; forest gap; boreal forest; reforestation; restoration

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1. Introduction

Anthropogenic disturbances in forests have risen worldwide [1,2] to the point that 70% of the world's forests are within 1 km of an open forest edge [3]. In boreal regions, the largest anthropogenic contributors to forest disturbance are related to the natural resource sectors (timber, minerals, oil, and gas) [4]. Many of these disturbances can be quite small in size, ranging from 3–50 m wide. Yet, even the smallest of disturbances can accumulate to levels of concern for biodiversity [5].

Large parts of the boreal forest, as well as the world's forest, are dominated by pine (*Pinus* spp.). The most widely distributed pine species in boreal Canada is jack pine (*Pinus banksiana* Lamb.) [6]. Jack pine is a fire-adapted species whose seeds are released in mass after wildfires, from their serotinous cones [7–9], dispersing distances 2–3 times their parent tree height [10]. While wildfires can result in much socioeconomic and ecological damage, it is a natural ecosystem process that has been largely ignored for its potential to rejuvenate and restore smaller (<50 m wide) clear-cut disturbances. [11,12]. In Alberta, Canada where energy exploration is a key driver of local forest disturbance, jack pine forests were observed to be regenerating post-fire on narrow seismic lines used for energy exploration [13]. However, seismic lines have a small forest gap width (3–12 m) suggesting that distance to seed is not limiting. Nevertheless, other footprints, such as exploratory well pads (20–40 m), are often larger and thus may have less access to jack pine seeds following a fire.

Exploratory well pads are small clearings (~500–1330 m^2) connected by seismic lines used to determine subsurface lithosphere characteristics in the exploration stage of oil and gas development. Over 50,000 energy wells were established each year over the past two decades in North America where hydrocarbon deposits are found [14]. In the boreal forest of Alberta, Canada, energy exploration and development is especially common making it a major source of forest disturbance [15]. These sites are expected to be reclaimed to pre-disturbance or ecologically equivalent conditions [16]. Many disturbances from oil and gas exploration have delayed forest regeneration, particularly in treed peatlands and upland jack pine forests [13,17–19]. These persistent forest clearings have led to "winners and losers" in the local animal community [20], with deer (*Odocoileus virginianus*) and wolves (*Canis lupus*) proliferating, largely at the expense of woodland caribou (*Rangifer tarandus caribou*) [21–23]; therefore, the restoration of disturbed areas has become a priority for woodland caribou conservation [24].

Loss of woody debris has been suggested as a factor contributing to delayed restoration of vegetation on well sites [25–29]. The creation of exploratory well pads results in the initial removal of vegetation to provide a level foundation for operation. This can result in little to no residual woody debris for some sites, while other sites can have high amounts of residual woody debris depending on: the vegetation present when cleared, the machinery used, and the operator's instructions/preferences. Woody debris on exploratory well pads does not accumulate after initial reclamation as it does in adjacent forests due to the lack of trees [28]. As a consequence, woody debris application has been recently used in some reclamation efforts by the oil and gas industry. Although few studies have evaluated the benefits of residual woody debris or their application, early results suggest that woody debris applications can: control erosion, provide a long-term storage/supply of organic matter and nutrients, regulate soil temperature and light, increase water content, create microsites for regeneration, and enhance diversity [25–29]. However, the amount of woody debris can be important. A study of mixed wood forest with trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* Moench. Voss) found that a ground cover from 1 to 30% woody debris was optimal, with too much being detrimental to native plant species' diversity and abundance [27].

The woodland caribou recovery strategy by the Species At Risk Act (SARA) requires 65% of each caribou range to be in an undisturbed state, from both anthropogenic and natural disturbances [24]. Long-term habitat restoration, coupled with short-term conservation strategies, such as controversial predator culling, may be the only way to prevent the localized extinction of caribou [30,31]. Long-term restoration focuses on re-creating pre-disturbance levels of forest structure to impede wolf predation [32]. Many restoration techniques can be prohibitively expensive over larger scales of practice, exceeding $CAD 12,500 per km [19,33,34]. The examination of low-cost and effective solutions to forest recovery is therefore a priority [13,19,35,36].

The objectives of this study are to examine how wildfire severity and residual woody debris affect tree recovery patterns (density and height) on exploratory well pads in jack pine forests. Specifically, we ask: (1) what are the patterns of tree regeneration density between adjacent forests and the interior of exploratory well pads post-fire? (2) how does density and height (only on exploratory well pads) change as a function of stand variables (fire severity, forest canopy cover, basal area, stand height, and stand age at the time of fire), ground layer woody debris cover, and well pad size? We hypothesize that increasing fire severity in the surrounding forest should increase tree regeneration of jack pine in not only adjacent forest stands, but also on exploratory well pads because fire is required for mass seed release and is known to recruit trees on similar but smaller footprints of seismic lines [13]. We also hypothesize that woody debris provides microsites for tree establishment and survival, but reduces colonizable surface area at higher levels of debris [27]. Stand variables (i.e., forest canopy cover, basal area, stand height, and stand age at the time of fire) that increase sunlight and seed availability will further benefit tree regeneration, but is secondary to fire severity [13]. Finally, we predict that tree regeneration height will depend on factors influencing sunlight, such as stand variables (forest canopy cover, basal area, and stand height), the surface area (gap size) of the exploratory well pad, competition from the regenerating trees (density dependence), and the amount of woody debris.

2. Materials and Methods

2.1. Study Location

This study was carried out near McClelland Lake in the Richardson area (57°30′ N, 111°20′ W), approximately 100 km north of Fort McMurray, Alberta, Canada (Figure 1). Sample sites are west and northeast of McClelland Lake. The study sites are on the Athabasca Sand Plain in jack pine-dominated forests. The soil in the area is dry and sandy with a thin organic layer. The study area is within the southern parts of the Richardson fire that occurred in the late spring (May/June) of 2011, burning over 700,000 ha [37]. Fire severity in these jack pine stands is inherently uneven, resulting in a mosaic of post-fire stand conditions (height, basal area, severity, etc.) [13,38].

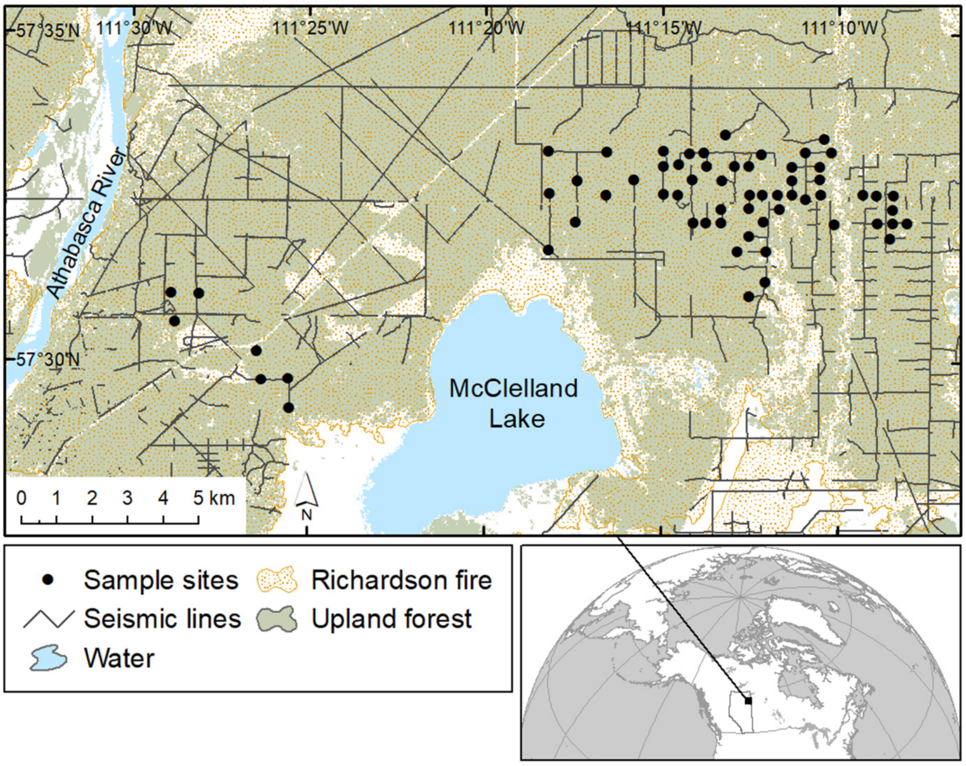

Figure 1. Location of the study area in the Richardson area of northeast Alberta, Canada (bottom right with Alberta boundary in grey). On the top: the location of sample sites (exploratory well pads and adjacent forest controls, black circles) along seismic lines and the southern boundary of the Richardson Fire (orange outline and dots). Note that fire severity could significantly vary between sites close together and locations of samples largely reflects location of jack pine-dominated stands.

Exploratory well pads selected for study were established in the years 2005–2006 and planted shortly after (~2009) at approximately 3000 stems per hectare with jack pine before the 2011 Richardson fire. All sites were sampled ~9 growing seasons post-fire in August of 2019 (Figure 2).

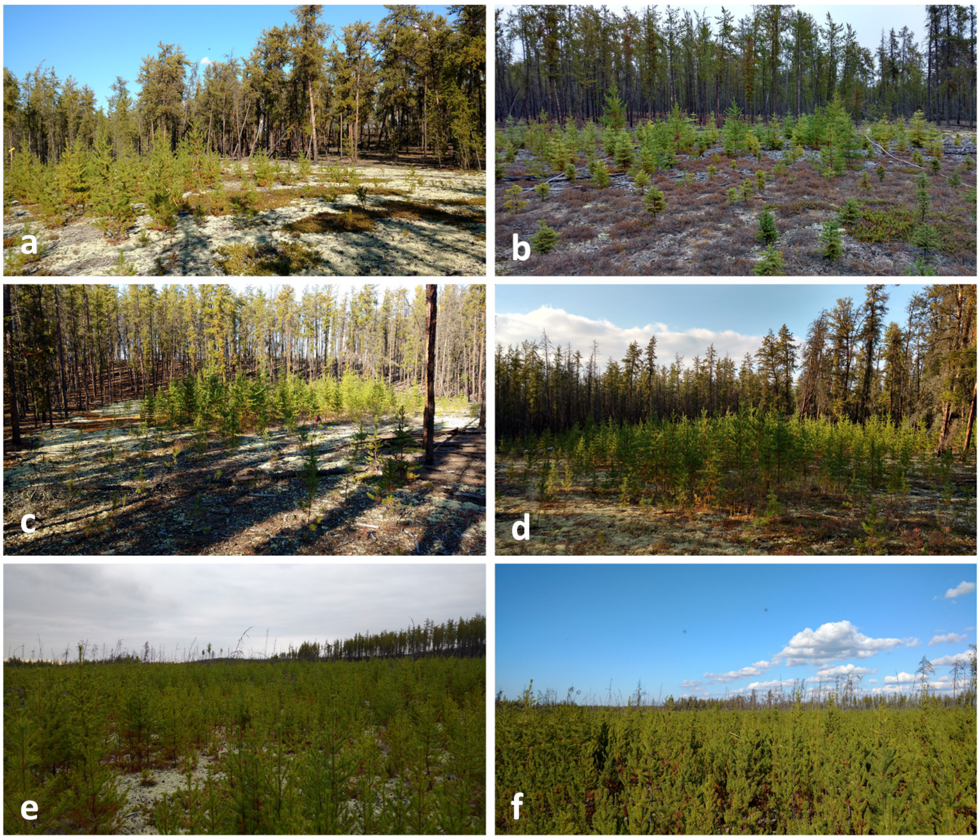

Figure 2. Examples of exploratory well pads and adjacent forest stands seven growing seasons post-fire (2017, two-years prior to sampling). Fire severity low (**a**,**b**) to moderate (**c**,**d**) to high (**e**,**f**) from top to bottom. All photographs by Angelo T. Filicetti.

2.2. Data Collection

We sampled 63 exploratory well pads and their adjacent forest stands for a total of 126 plots (63 pairs). Sites were limited to jack pine-dominated forests with the aim to include a range of fire severity as measured by percent overstory tree mortality. All sites were separated by a minimum distance of 380 m with nearby sites often having different fire severities.

For the adjacent forest we used a single 30 m transect to sample trees, matching prior work in the area [13,39]. For exploratory well pads we separated the transect into two 15 m transects (Figure 3) to better sample the area of the exploratory well pad and avoid edge effects from the periphery since the shapes and sizes of the exploratory well pads vary (generally square but sometimes more rectangular). We expect edges to be responding more than the center of well pads, and thus chose to be conservative in representing responses since the centers should be the slowest to recover. The adjacent forest plot was placed 25 m from the edge of the exploratory well pad into the adjacent forest. The adjacent forest plot always ran parallel to the closest of the four sides of the exploratory well pad edge (Figure 3). The location of the adjacent forest plot was chosen at random, with the condition of having a 50 m buffer from any obvious landscape change (a seismic line, large hill, change in fire severity, etc.). The adjacent forest plots were used as controls for the plots on the exploratory well pads.

In each belt transect we measured the density of tree and shrub seedlings. For estimating the percent of ground cover of woody debris, we used ten 1 m^2 quadrats placed every 3 m on alternating sides of the transect (Figure 3). Woody debris cover was separated into 2 sub-categories, fine woody debris (<7 cm diameter) and coarse woody debris (≥7 cm diameter). We collected additional information on stand characteristics in the adjacent forest, including: the basal area using a 2-factor metric prism from the transect midpoint

(15 m); stand height from representative trees using a Haglof Vertex IV; stand age at the time of fire, estimated by collecting dendrochronological tree cores at a height of 130 cm; and canopy cover using a spherical densiometer. Fire severity is most often measured as the below and/or above ground loss of organic material from fire [40]. For this study we used overstory tree mortality as a proxy for fire severity, which was effective in relating tree recovery patterns post-fire on seismic lines [13,36]. Specifically, we recorded fire severity as the percent of overstory tree mortality in the forest stand post-fire similar to other studies [13,39–41]. Higher severity (mortality) correlates with the amount of serotinous cone opening and seed release [13,40] and on seismic lines tree regeneration [13,36]. Finally, we collected the heights of ten representative regenerating trees per exploratory well pad.

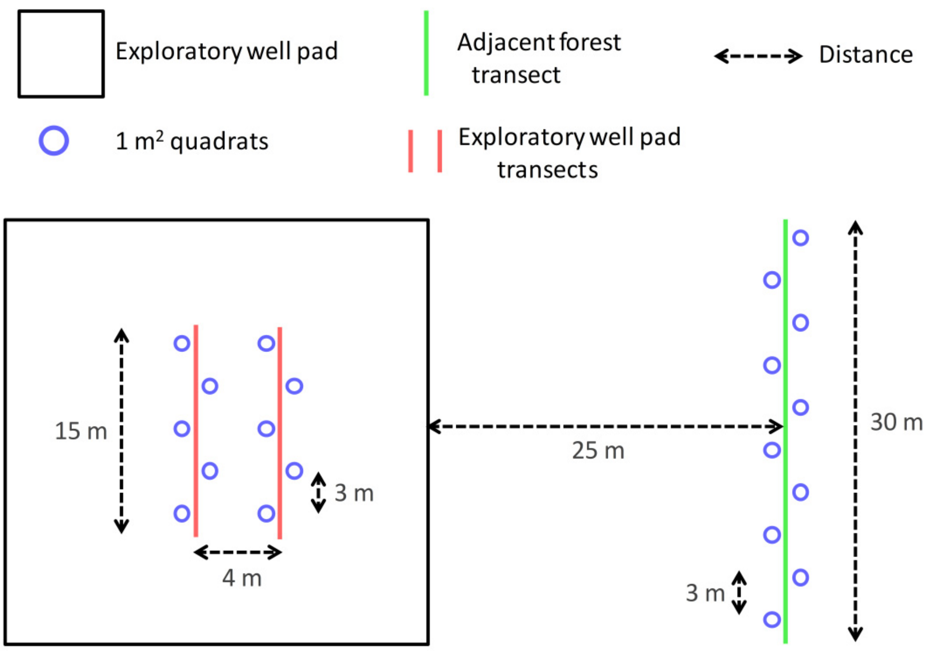

Figure 3. Plot design used to measure tree regeneration density, tree height, and woody debris cover at each site. The exploratory well pad (black square) contains two transects (pair of red lines) in the center of the patch for a total length of 30 m. The adjacent paired forest transect (green line) was placed 25 m away from and parallel to the exploratory well pad edge and was 30 m in total length. Tree density was measured within 1 m wide belt transect, while height was collected from ten representative trees on the exploratory well pad. The 1 m^2 quadrats (blue circles) spaced 3 m apart on alternating sides of the transect were used to measure woody debris ground cover.

Because trees were planted on the exploratory well pads prior to the wildfire and may have survived, we verified our ability to distinguish natural regeneration to that of previously planted trees by examining growth forms and the spatial distribution of trees on the well pad. The spacing of planted trees was much more uniform and wider than natural regeneration post-fire and planted trees had substantially different growth form and size. To test our ability to distinguish planted seedlings from natural regeneration, we excavated a sub-sample of individuals to examine their root system for soil plugs. We also confirmed the age of the planted seedlings by counting growth rings from cross sections, all matching the years since the planting occurred (2009). This also confirmed tree planting at ~3000 stems/ha. Because we were interested in natural regeneration on exploratory well pads post-fire and not the fate of planted trees, we excluded planted trees on the exploratory well pads, although we acknowledge that this ignores the effects of competition on natural regeneration. However, only a minority, <1%, of regenerating trees were dead due to the early nature of post-fire stand development and thinning (~9 growing seasons post-fire). At each site, we outlined the extent of the exploratory well pad with at least four GPS locations (spatial resolution of 2–3 m) to calculate the area (m^2) of the exploratory well pad.

2.3. Analysis

We first visualized the effects of fire severity and plot type (exploratory well pad or forest) on tree regeneration density by plotting regeneration density across ordinal categories of fire severity. Although fire severity categories were used to visualize data, all statistical analyses used its original continuous form.

Negative binomial count models (nbreg command in STATA 15.1/SE; [42]) were used to assess responses in tree regeneration density (stems per 30 m^2) to predictor variables that included stand variables (fire severity, forest canopy cover, basal area, stand height, and stand age at the time of fire), ground layer woody debris cover (woody debris, fine woody debris, coarse woody debris), and area of exploratory well pads. For tree regeneration heights, we used generalized linear mixed effects models (xtreg command in STATA 15.1/SE; [42]), with a Gaussian distribution and an identity link function since height was normal in shape across the more recent ages of regenerating trees. We related linear changes in tree regeneration height to the same predictor variables as above with the inclusion of tree regeneration density (density dependence) as an additional factor. The site was used as a random effect to account for the 10 replicates of tree regeneration heights taken per plot (exploratory well pad). Model assumptions were examined for independence, normality of response variables, presence of outliers, and correlations ($r > |0.7|$) among predictor variables. Model selection followed a forward selection, retaining significance of $p < 0.05$, of the hypothesized predictor variables.

When examining collinearity among predictor variables, two variables were highly correlated and, therefore, excluded from being included in the same model. Correlated predictor variables, from highest to lowest were fire severity with forest canopy cover (Pearson correlation, $r = -0.81$, $p < 0.001$), fire severity with tree regeneration density ($r = 0.62$, $p < 0.001$), forest canopy cover with tree regeneration density ($r = -0.54$, $p < 0.001$), and adjacent stand age at the time of fire with adjacent stand height ($r = 0.51$, $p < 0.001$).

3. Results

3.1. General Results

Stand characteristics varied, but generally the overall plant community was similar among sites (xeric jack pine forests). Fire severity ranged from 0 to 100% (mean of 49.8, SE = 4.5), stand age at the time of fire ranged from 17 to 132 years (mean of 62, SE = 1.7), stand height ranged from 6.1 to 23.1 m (mean of 15.4, SE = 0.5), basal area ranged from 0 to 32 m^2/ha (mean of 10.1, SE = 0.9), and forest canopy cover ranged from 0 to 100% (mean of 37, SE = 3.6) (Table 1). Jack pine (*Pinus banksiana* Lamb.) was the most common tree or shrub sampled in the study plots representing 80% (n = 10,975) of all stems and 97% of all regenerating trees. Following jack pine, the next most common trees or shrubs sampled were 4.9% prickly rose (*Rosa acicularis* Lindl.), 4.5% raspberries (*Rubus idaeus* L.), 3.7% Saskatoon (*Amelanchier alnifolia* (Nutt.) Nutt. ex M. Roem.), 2.6% pin cherry (*Prunus pensylvanica* L. f.), and 2.4% trembling aspen (*Populus tremuloides* Michx.). The remaining 1.9% were other tree and shrub species each representing less than 1% of the stems sampled. Stands that had experienced high fire severity showed high regeneration density of jack pine to the near exclusion of other species. Average regeneration height on exploratory well pads ranged from 22 to 407 cm (mean of 212, SE = 3.8). Although exploratory well pads differed in size (500 to 1330 m^2), most were near the average size of 791 m^2 (SE = 27).

Characteristics of the adjacent forest stands differed significantly among sites (Table 1). It was apparent that the stands that experienced higher fire severities had higher tree regeneration densities in both exploratory well pads and adjacent forests. Noticeably, although less clear, was the tendency of exploratory well pads to support higher tree regeneration densities than the adjacent forests (Figures 2 and 4). On average, exploratory well pads have 1.3-times higher tree regeneration than adjacent forests (Table 1). In all scenarios, excluding adjacent forests that experienced the lowest fire severities, tree regeneration densities were higher than those planted at 3000 stems/ha (Figures 2 and 4).

Table 1. Stand characteristics for 63 exploratory well pads sampled in the Richardson area of northeast Alberta, Canada following fire. Tree regeneration density is shown for both exploratory well pads (n = 63) (excluding the planted 3000 stems/ha in exploratory well pads) and paired adjacent forest plots (n = 63).

Stand Variable	Minimum	Median	Maximum	Mean (S.E.)
Fire severity (overstory mortality)	0	45	100	49.8 (4.5)
Stand age at the time of fire (years)	17	62	132	62 (1.7)
Stand height (m)	6.1	15.9	23.1	15.4 (0.5)
Basal area (m^2/ha)	0	10	32	10.1 (0.9)
Forest canopy cover (%)	1	36	100	37 (3.6)
Tree regeneration density (stems/ha)				
Exploratory well pad	1000	17,333	136,667	27,542 (3465)
Adjacent forest	0	11,333	115,000	21,148 (3315)
Exploratory well pad				
Tree regeneration height (cm)	22	214	407	212 (3.8)
Well pad area (m^2)	500	729	1330	791 (27)

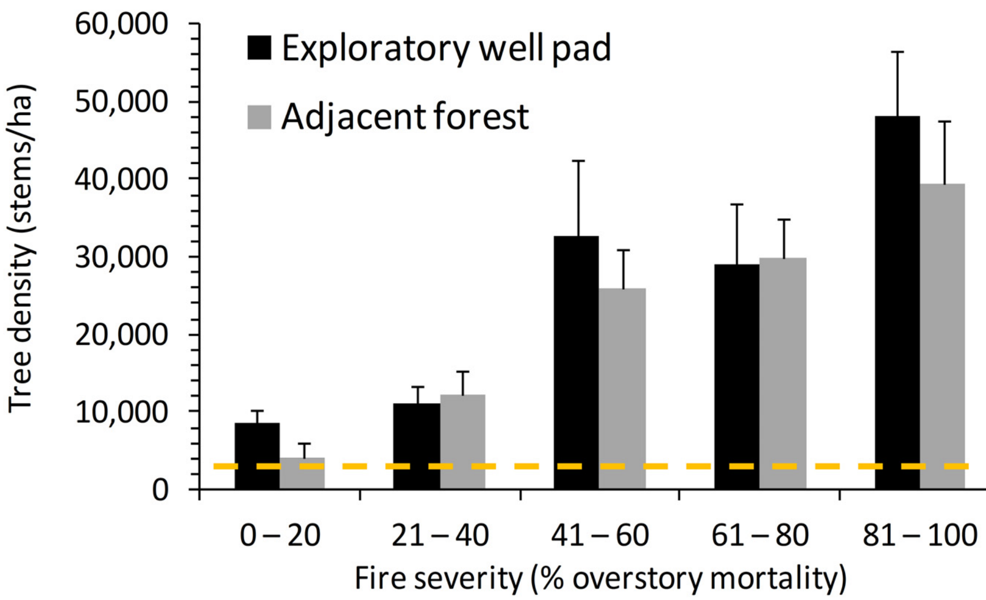

Figure 4. Mean and standard error (error bars) of natural tree regeneration density as a function of fire severity (overstory mortality) at 20% intervals for both exploratory well pads (black) and adjacent forests (gray). Note, the orange dashed line represents the number of planted stems per hectare on exploratory well pads (3000 stems/ha).

3.2. Tree regeneration Density in Forest Stands

Tree regeneration density in forest stands ranged from 0–115,000 stems/ha with a mean of 21,148 stems/ha (Table 1). Tree regeneration density in forest stands depended on fire severity with no other predictor variable significantly explaining regeneration patterns (Table 2). The relationship with fire severity was non-linear (quadratic), where tree regeneration density increased substantially to a maximum at ~72% fire severity after which tree regeneration decreased. Specifically, average tree regeneration density was predicted to be 800 stems/ha at 0% fire severity, peaking at 51,000 stems/ha at 72% fire severity, and declining to 27,000 stems/ha at 100% fire severity (Table 2 and Figure 5a,b).

Table 2. Model parameters predicting tree regeneration density and height based on final model variables of fire severity, woody debris cover, and coarse woody debris cover. Shown with model coefficient (β), standard error of the coefficient (S.E.) and significance (*p*). The number "2" is superscritped to represent a squared term.

Response Variable	β	S.E.	*p*
A. Tree regeneration density (forests only)			
Intercept	0.889	0.397	0.025
Fire severity	0.115	0.022	<0.001
Fire severity ^{2}	−0.001	<0.001	<0.001
B. Tree regeneration density (exploratory well pads only)			
Intercept	3.398	0.173	<0.001
Fire severity	0.022	0.002	<0.001
Woody debris cover	−0.028	0.007	<0.001
C. Tree regeneration height (exploratory well pads only)			
Intercept	209.340	8.890	<0.001
Fire severity	−0.564	0.133	<0.001
Coarse woody debris cover	22.179	2.976	<0.001
Coarse woody debris cover ^{2}	−1.179	0.223	<0.001

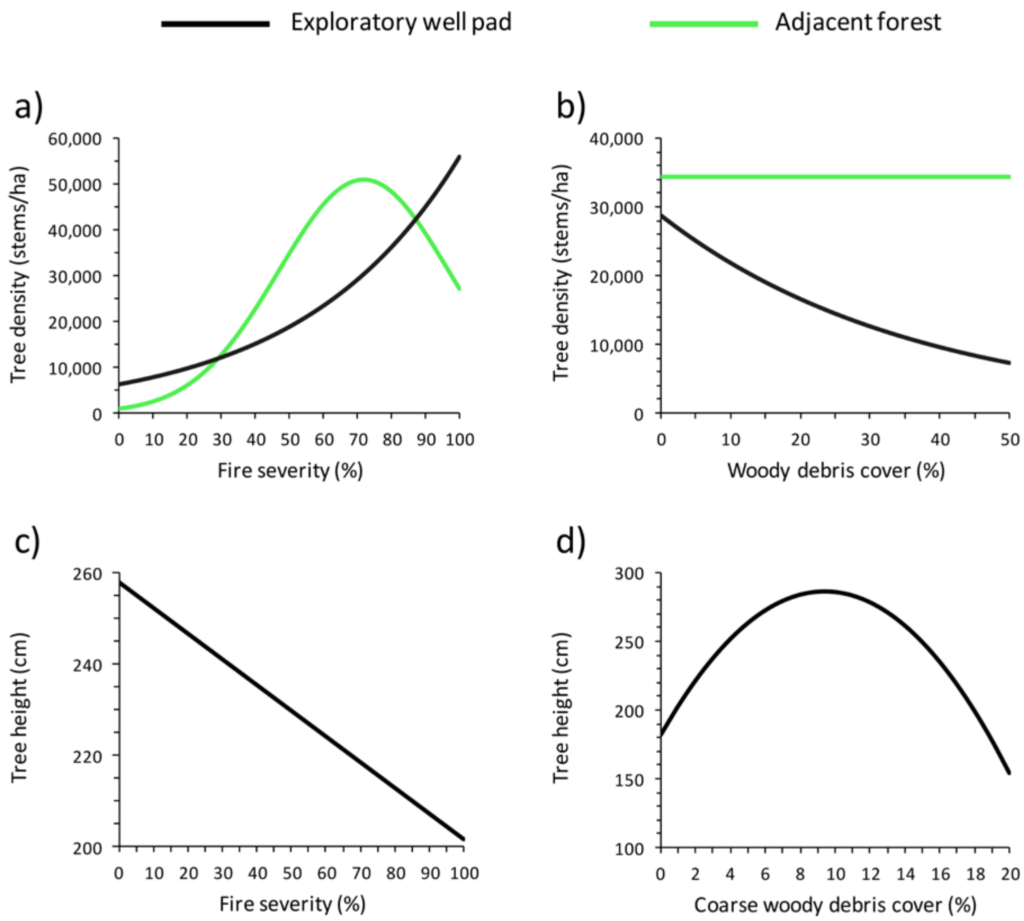

Figure 5. Predicted amounts of tree regeneration density (**a**,**b**) and tree regeneration height (**c**,**d**) with changes in predictor variables of fire severity (**a**,**c**), woody debris cover (**b**), and coarse woody debris cover (**d**).

3.3. Tree Regeneration Density on Exploratory Well Pads

Tree regeneration density on exploratory well pads ranged from 1000–136,667 stems/ha with a mean of 27,542 stems/ha (Table 1). Specifically, tree regeneration density depended on fire severity and woody debris cover increasing by 2.2% per 1 unit (%) increase in fire severity and decreased by 2.7% per 1 unit (%) increase in woody debris cover (Table 2 and Figure 5a,b).

3.4. Tree Regeneration Height on Exploratory Well Pads

Tree regeneration height on exploratory well pads ranged from 22–407 cm (mean of 212 cm) ~9 ng seasons post-fire (Table 1) and thus averaging 23.6 cm/year of growth. Tree regeneration height on exploratory well pads was dependent on fire severity and coarse woody debris cover (Table 2). Tree regeneration height decreased by 0.56 cm per 1 unit (%) increase in fire severity (Table 2 and Figure 5c). The relationship with coarse woody debris cover was non-linear (quadratic), where tree regeneration height increased to a maximum height at 9.4% coarse woody debris ground cover after which height decreased. Model predictions suggested that coarse woody debris ground cover of 2–17% would increase tree regeneration heights post-fire above the average observed in this study (Figure 5d). Specifically, the average predicted tree regeneration height was 182 cm at 0% coarse woody debris ground cover, peaking at 286 cm at 9.4% coarse woody debris ground cover, and then decreasing to 154 cm at 20% coarse woody debris ground cover (Table 2 and Figure 5d).

4. Discussion

Findings here show different post-fire patterns in tree regeneration densities between adjacent forests and exploratory well pads. Post-fire regeneration on exploratory well pads averaged ~10-times the density of restoration treatments planted at 3000 stems/ha. Regeneration density was negatively related to the amount of woody debris ground cover, while regeneration height was non-linearly related to coarse woody debris ground cover peaking at 9.4%.

4.1. Tree Regeneration Density in Forest Stands

Tree regeneration density in post-burned jack pine stands was strongly related to fire severity. Jack pine, a fire-adapted and dependent species, comprised 80% of the total tree and shrub vegetation and 97% of all regenerating trees. Although fire overall supported high regeneration densities, regeneration density declined when fire severity was above 72%. Similar findings were made in nearby jack pine-dominated forests, having a non-linear (quadratic) relationship with fire severity, although here young stands (<30-years) were found to regenerate at much lower levels than older stands (>60-years) [38]. This decrease of tree regeneration density at sites of more severe fires may be due to cones/seeds being burnt by the more severe fire [43]. Regardless, even at 100% fire severity tree regeneration densities were predicted to be ~27,000 stems/ha which is more than enough for healthy forest renewal following wildfire.

4.2. Tree Regeneration Density on Exploratory Well Pads

Patterns in tree regeneration differed on exploratory well pads compared to adjacent forest stands. Tree regeneration on exploratory well pads was positive and linearly related to fire severity, while tree regeneration patterns in the adjacent forest stands were non-linear (quadratic) with fire severity. Indeed, post-fire tree regeneration on exploratory well pads increased exponentially to increases in fire severity. Results show patterns of tree regeneration on exploratory well pads reached a maximum density at 100% fire severity, while adjacent forest stands reached a maximum regeneration density at 72% fire severity. These differences may be due to seed/cone destruction at higher fire severities in interior forests. Perhaps the lack of neighboring trees and/or interweaving branches overhanging the exploratory well pad alters the fire behavior along the forest edge of the exploratory well pad. Wildfires above the exploratory well pad may have lower residency times, and/or less fuels, etc. Therefore, the canopy overhanging the exploratory well pad may experience fire behaviors that are less destructive to seeds/cones. Changes in fire behavior on other exploratory oil and gas disturbances have been reported in the forests of northeast Alberta. Wildfires often skip seismic lines, which are narrower than exploratory well pads, leaving residual unburned vegetation not found in adjacent forests [36,44].On exploratory well pads, regeneration density was negatively related to the amount of woody debris. We predicted a non-linear relationship where lower levels of woody debris would provide favorable microsites [25–29], but at high levels woody debris would limit the colonizable area for trees [27]. Yet, even low levels of woody debris adversely affected tree regeneration density suggesting that favorable microsites were not limiting after this fire, but only acted to reduce total colonizable area. Regardless, even at 50%, woody debris cover tree regeneration density was predicted to be ~7200 stems/ha which is suitable to renew forest conditions that are common to these jack pine forests.

Interestingly, the surface area of exploratory well pads, stand variables (forest canopy cover, basal area, stand height, and stand age at the time of fire), nor possible interactions between these were significantly related to tree regeneration density. This suggests that the gap sizes of exploratory well pads are not large enough to limit seed dispersal, recruitment (establishment) or survival nine growing seasons post-fire. Others have estimated the dispersal distance for jack pine seed is roughly 2–3-times the parent tree height [10] with jack pine starting to develop seeds as early as five-years of age when in good conditions [45,46]. Seed dispersal distance may be larger on exploratory well pads as some exploratory footprints, such as the connecting seismic lines, are known to increase wind speeds and dispersal in other plants [47,48]. Other potential seed sources on exploratory well pads include the cones within the residual woody debris left post-construction, five years pre-fire, although viability of these seeds may be low. Nevertheless, adjacent forest height averaged 15.4 m which would provide dispersal to 30 m or more (2-times the stand height). With edges on each side of exploratory well pads, exploratory well pads as large as 60 m per side (or an area of 3600 m^2) would be suitable for seed dispersal. This is larger than the maximum patch size of disturbance studied here (1330 m^2). Formally active well pads that are being reclaimed are larger in size being up to 1 ha in size and may have seed dispersal limitations in their center.

Lastly, we would expect initial rates of post-fire regeneration on exploratory well pads to be even higher if the planted stems (3000 stems/ha) were never planted since they locally competed for space post-fire. A study in nearby forests found two-times the regeneration density of jack pine post-fire on seismic lines which received no plantings or treatments [13].

4.3. Tree Regeneration Height on Exploratory Well Pads

Tree regeneration height on exploratory well pads was negatively related to fire severity. Although we predicted that fire severity would be negatively related with canopy cover (we observed a Pearson correlation of -0.81), and that less canopy cover would be associated with higher light levels which in turn would result in taller regenerating trees [6,46], this prediction was not supported. The negative relationship between tree regeneration heights on exploratory well pads to fire severity was likely related to intra-specific competition from high tree regeneration rates at higher fire severities, as well as smaller amounts of planted trees pre-fire. Similar to results in tree regeneration density, the exploratory well pad surface area, stand variables (forest canopy cover, basal area, stand height, and stand age at the time of fire), nor possible interactions were significantly related to tree heights. This suggested that the gap sizes of exploratory well pads were not narrow enough to limit sunlight for growth, where sunlight is often the limiting factor for growth in jack pine [6,46].

Tree regeneration height on exploratory well pads was predicted to have a non-linear (quadratic) relationship with coarse woody debris. Models predicted an increase of tree regeneration height until 9.4% coarse woody debris ground cover and decreasing above this. Increases in coarse woody debris could reduce tree density by limiting colonizable surface area [27], resulting in higher growth rates (discussed above) by reducing density dependence [46] and/or from beneficial microsites (supply of nutrients, protection from wind, capture and maintain moisture) [25–29,46]. It is widely agreed that too much coarse woody debris can be detrimental, although the exact amount and mechanisms may differ depending on specific site and wood characteristics [25–29]. Too much coarse woody debris could result in among other things over-shading, interception of moisture, or encouraging mold or pests [25–29]. Oddly, the inclusion of either fine woody debris or total woody debris was not significant. It is possible that fine woody debris does not limit colonizable area or benefit microsites as effectively as coarse woody debris does. Certainly, these patterns may change depending on time since post-fire.

With an average growth rate of 23.6 cm/year for the nine post-fire growing seasons, regenerating trees here should reach 3 and 5 m in ~13 and ~21 years, respectively. Tree heights of 3 and 5 m in the boreal forests of Canada are often used for assessing initial functional recovery, in particular, slowing down animal movements [18,49,50]. Obtaining tree heights of 3 and 5 m within a 15- and 23-year period would be considered quite successful, but of course this first requires fire to start the regeneration and growth process.

5. Conclusions

Planting 3000 stems/ha on exploratory well pads should be suitable for restoring forested conditions and restoring woodland caribou habitat, but where possible waiting for wildfire may provide an effective alternative strategy. Jack pine is both shade-intolerant and fire-adapted, therefore, plantings in jack pine-dominated forests may not be the most effective use of restoration dollars, and this is particularly the case if a wildfire is likely. Although predicting the timing of wildfires is difficult, estimates of fire return intervals for boreal forests are known and climate change is expected to result in larger, more frequent, and higher severity wildfires [51,52]. The majority of exploratory well pads that experienced a wildfire had much higher (~10-times) tree regeneration densities than reclamation plantings (3000 stems/ha).

Although amount of woody debris post-fire can increase regeneration densities and heights in reclaimed exploratory well pads, higher amounts of woody debris were detrimental to tree regeneration. Residual coarse woody debris from 2–15% increased tree regeneration height for the first nine growing seasons post-fire. Given observed heights and growth rates, post-fire heights of 3 and 5 m on exploratory well pads are predicted by 13 and 21 years, respectively.

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