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Review and synthesis

Trends in post-disturbance recovery rates of Canada's forests following wildfire and harvest

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ABSTRACT

The recovery of forests following stand-replacing disturbance is of widespread interest; however, there is both a lack of definitional clarity for the term "recovery" and a dearth of empirical data on the rates of forest recovery associated with different disturbance types. We conducted a quantitative review of literature to determine recovery times following wildfire and timber harvest and to evaluate variation in recovery rates across Canada's diverse forest ecosystems. Recovery was assessed according to the rate of change associated with certain forest structural attributes that have traditionally been used as indicators of forest growth and productivity. The recovery of forest canopy cover, tree height, and stand basal area varied at rates that depended on disturbance type, forest biome, and ecozone. We found that, on average, it took 5–10 years, depending on factors such as location and species, for most forest ecosystems of Canada to attain a benchmark canopy cover of 10% after wildfire or harvest. Similarly, regenerating stands in Canada's boreal forests were capable of attaining average heights of 5 m within five to ten years after wildfire or harvest. Stands in the Boreal Plains ecozone post-harvest reached stand basal area, benchmarked at 10 m^2 ha^{-1}, faster than those in the Boreal Shield, attributable to differences in tree species composition and the rich mineral deposits of the Boreal Plains. Overall, recovery of canopy cover, tree height, and stand basal area was similar or more rapid following wildfire than harvest. Our review provides temporal benchmarks for gauging recovery times after disturbance. Building upon these temporal benchmarks, and conditioned by disturbance type, site conditions, and location, we present opportunities for using dense time series of remotely sensed data to inform on regional and national trends in forest recovery following disturbance.

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1. Introduction

Canada's forests are recognized globally for the important ecosystem services that they provide; however, these forests are dynamic in nature and subject to a wide range of natural and anthropogenic disturbances that vary in severity, extent, and frequency (Bergeron et al., 2001; Stocks et al., 2002; Boucher et al., 2009; Brandt et al., 2013). Disturbances such as wildfire and timber harvesting can directly impact forest structure and composition (Lavoie and Sirois, 1998; Brassard et al., 2008; Fleming et al., 2014), and indirectly impact soil properties (Certini, 2005), thereby altering ecosystem productivity and function. The ongoing nature of disturbances to Canada's forests (Brandt et al., 2013), combined with uncertainty related to climate change (Price et al., 2013), necessitates an improved understanding of forest dynamics and increasingly sophisticated and flexible management practices (Bergeron et al., 2004; Burton et al., 2006). Despite advances in knowledge and management practices, uncertainty remains in the rates of forest recovery associated with different disturbance types across the range of forest ecosystem conditions in Canada (Sturtevant et al., 2014). Forest recovery can also be understood from different perspectives, for instance silvicultural and ecological, with different assessment criteria and definitions present as a result.

Disturbances are relatively discrete events that disrupt the forest ecosystem and cause a change in the physical structure of vegetation, soil substrate, and resource availability (White and Pickett, 1985; Clark, 1990). Although disturbed forests will recover if left long enough, of interest is the extent and rate at which forests will return to pre-disturbance condition. Early studies of post-disturbance recovery in Canada's forests have largely focused on general descriptions of successional sequence (Black and Bliss, 1978; Bergeron and Dubuc, 1989), recovery of net primary production (Amiro et al., 2000), and advance regeneration (Gradowski et al., 2010; Spence and MacLean, 2012; Veilleux-Nolin and Payette, 2012). While these and other studies (Johnson, 1996; Greene et al., 1999; Chen and Popadiouk, 2002) have contributed to an increased understanding of post-disturbance stand dynamics, there remains a paucity of quantitative information and synthesis on rates of forest regrowth and the factors that influence the forest recovery process.

The nature and rate of forest recovery may depend on several factors relating to the nature and severity of disturbance, presence of biological legacies, and inherent productivity of the site (Johnson, 1996; Franklin et al., 2002; Chen et al., 2009; Ilisson and Chen, 2009a). Different disturbances contrast markedly in terms of biological legacies (Franklin et al., 2007), and forests faced with repeated perturbations tend to be less resilient (Payette and Delwaide, 2003). Rates of forest change following disturbances may ultimately depend on multiple interacting factors, such as disturbance history, pre-disturbance stand conditions, local site factors, regional species pool, and species life histories, among others (Foster et al., 1998; Harper et al., 2005; Mansuy et al., 2012; Girard et al., 2014). However, it is unclear how these factors interact to explain variation in rates of forest recovery. Some initial efforts have been made to better understand regional level variability of forest recovery across Canada's forested ecosystems (Goetz et al., 2006; Mansuy et al., 2012). A better understanding of forest recovery rates and patterns in different environmental and climatic conditions is necessary to understand the overall dynamics of Canada's forests and devise effective strategies for sustainable forest management.

Among the challenges encountered in characterizing rates of forest recovery is the absence of a universal definition of what is meant by the term recovery in a forest context. Because recovery involves the return of vegetation cover, terminologies such as "revegetation," "regeneration," and "regrowth" are often used, sometimes synonymously, to describe what happens to forests following disturbance. Some consider recovery as the reestablishment or redevelopment of forest biomass and canopy structure characteristics after the impact of a particular disturbance (Frolking et al., 2009). However, it is not entirely clear at what stage or condition a forest that has experienced disturbance can be described as returning to its function as a forest. In the context of these broader interpretations of forest recovery, for the purposes of this study, we are interested in the re-establishment and regeneration of vegetation at a site following a stand-replacing disturbance, specifically wildfire and timber harvest.

The Food and Agriculture Organization (FAO) defines a forest as an area of land greater than 0.5 ha in size with greater than 10% tree canopy cover, and trees that are capable of reaching a minimum height of 5 m (FAO, 2010). This includes young stands or temporarily unstocked areas that have not yet—but are expected to reach—a crown density of 10% and a tree height of 5 m (FAO, 2010). According to this definition of forest, it is possible to ascertain from early indicators whether a disturbed forest has recovered or is headed toward recovery. Therefore, the term recovery describes a long-term process, whose endpoint ultimately depends on one's interest or point of view (i.e., ecological, economic). In the context of this review, we consider a site to be regenerating or recovering if vegetation is reoccupying a site, if trees capable of reaching a certain height are re-establishing, and if there exists the potential of the trees to reach a given canopy cover.

Disturbance processes are increasingly well understood and systematically captured through remote sensing approaches (Frolking et al., 2009). The capacity of remotely sensed data to characterize vegetation recovery post-disturbance is increasing with the widespread availability of data and methods that enable dense time series analyses (Kennedy et al., 2014). Information on forest recovery is of interest from forest management, ecosystem services, and climate change perspectives (Anderson-Teixeira et al., 2013). While plot-based studies focused on the site-specific return of vegetation following disturbance have informed the forest management and ecological understanding of forest recovery (e.g., Drever et al., 2006), there is a need to bridge between the contexts offered by plot-based measurements and associated knowledge with emerging opportunities for large-area characterizations. Our objective in undertaking this review was to evaluate trends, derived from plot-based studies, in rates of forest regeneration following stand replacing disturbances, specifically wildfire and harvest, across the forested ecosystems of Canada. We focused specifically on quantifying the number of years required for forests to reach the benchmark values specified in the FAO definition of forests stated above, and the variability in regeneration among the represented ecological regions of Canada. We close with an outlook on opportunities to map and characterize recovery with time-series remotely sensed data.

2. Definitions

In accordance with widely acknowledged definitions, we refer to disturbance as any relatively discrete event in time that disrupts the forest ecosystem and causes a change in the physical structure of the environment, including vegetation, surface soil substrate, and resource availability (White and Pickett, 1985; Clark, 1990). As would be expected, wildfire predominates in more northern ecosystems of Canada, with anthropogenic activities preferentially located in proximity to settled areas and where forest productivity is highest (Andrew et al., 2012; Brandt et al., 2013). Across Canada's forested ecosystems, wildfire is a dominant natural disturbance factor that initiates new forest growth (Payette, 1992; Johnson, 1996; Stocks et al., 2002), with approximately 2 million ha impacted annually by wildfires (Stocks et al., 2002). Long term averages indicate approximately 1 million ha per year of timber is currently harvested in Canada (Masek et al., 2011). Harvesting is not the same as deforestation, as deforestation typically occurs when tree removal is associated with permanent land use change (i.e., forest to agricultural or residential uses that persist over time). The main cause of deforestation in Canada is the expansion of agricultural lands (Natural Resources Canada, 2008), which is estimated at approximately 50,000 ha/year, or 0.02% of Canada's forest area (Environment Canada, 2006; Leckie et al., 2015). Other disturbances such as insect infestation including spruce budworm, forest tent caterpillar, and mountain pine beetle, hurricane, flooding, and catastrophic wind blowdown also occur across Canada's forest regions and are widely studied (Royama et al., 2005; Burley et al., 2008; Kneeshaw et al., 2011). In this review, we focus on stand-replacing disturbances of wildfire and harvest.

In accordance with the aforementioned FAO definition of forest, we refer to a forest as recovered when the vegetation in a specified land area that has experienced a stand-replacing disturbance shows the potential to reach a tree canopy cover of more than 10% and a minimum height of 5 m. In this context and for the purposes of this review, we are interested in understanding how long it takes for a forest that has experienced disturbance to be considered forest again (using indicators of forest structure), and the dynamic recovery processes that characterize the transition from the disturbed state to the regenerated forest state. Forest recovery following disturbance can be determined from a variety of ecosystem attributes, such as growth and productivity, soil properties, forest structure, species composition, among others. Forest managers, however, typically rely on changes in forest structural attributes, such as aboveground biomass, stem density, and species composition, among other factors related to stand development. Field-based estimations of forest structural parameters are usually an expensive and time consuming endeavor. Hence, ecologists and forest managers have relied on long chronosequences of monitored study plots, applying a space-for-time substitution approach and often utilizing information on forest age or time elapsed since disturbance, supplemented with information on desired forest structure attributes, in order to characterize recovery. In this review, we have focused on several structural measures of recovery: canopy cover, tree height, and stand basal area. These attributes are most directly related to measures of ecosystem function and we examined their recovery by characterizing the time required to reach a benchmark value, according the FAO definition of forests cited above (i.e., 10% canopy cover, 5 m height, and 10 m^2 ha^{-1} basal area).

3. Forest recovery: regeneration mechanisms and stand development patterns

3.1. Natural regeneration after disturbance

Regeneration is basic to the continuation of forest following disturbance, and it is ordinarily accepted that most forests would regenerate given sufficient time. The ability of a forest to naturally regenerate following disturbances may depend on one or more sources: (1) regeneration of remnant individuals, (2) germination from the soil seed bank, (3) sprouting from cut or crushed roots and stems, and (4) regeneration from seeds from external sources (Timoney and Peterson, 1996; Turner et al., 1998; Greene et al., 1999; Chazdon, 2003; Chen et al., 2009). These regeneration modes play a crucial role in the determination of the speed and course of forest vegetation recovery and stand development patterns.

Regeneration from residual vegetation, defined as individual organisms or their propagules that survive a disturbance event, is critical to forest recovery (Chazdon, 2003). Regeneration of this form can be rapid or delayed depending on the nature of disturbance and extent of damage to surviving individuals and soil degradation. For instance, minor disturbances that cause minimal damage to residual vegetation, such as tree falls, create light gaps and free growing space, encouraging rapid regeneration and growth of suppressed shade-tolerant species (Kneeshaw and Bergeron, 1998). Regeneration from residual vegetation also involves vegetative recovery, i.e., sprouting of surviving stems or suckering from roots, as well as germination from aerial and soil seed banks, i.e., living seeds stored in disturbance killed trees and the soil. Many forest tree species, such as *Populus* and *Betula* species are able to regenerate vegetatively after disturbance (Chen et al., 2009; Ilisson and Chen, 2009a), making them adaptable to disturbance. The production of serotinous cones by some conifer species is a vital life-history adaptation to recurrent disturbances such as wildfire (Muir and Lotan, 1985). However, most seeds and cones of serotinous *Pinus* spp. and semi-serotinous *Picea mariana* are killed in high temperature fires, in which case their regeneration may depend on seed and cones from external sources.

3.2. Stages of forest recovery and stand development patterns

The processes of change following disturbance can lead to various stand structural stages (Oliver and Larson, 1996; Franklin et al., 2002). The stages are identified as stand initiation, stem exclusion, canopy transition, and gap dynamics stages (adopted from Chen and Popadiouk (2002)), which we viewed as corresponding to the phases of forest vegetation development following disturbance, namely the establishment and regeneration phase (stand initiation), young forest regrowth phase (stem exclusion), mature and transition phase (canopy transition), and old-growth phase (gap dynamics) (Figs. 1 and 2). As per previous studies, we also consider recovery as an ongoing process rather than a series of discrete stages. As such, the classification here is used to provide a heuristic of the paths and sequence of forest vegetation recovery following disturbance. We did not emphasize the successional pathways of canopy species composition as they have been

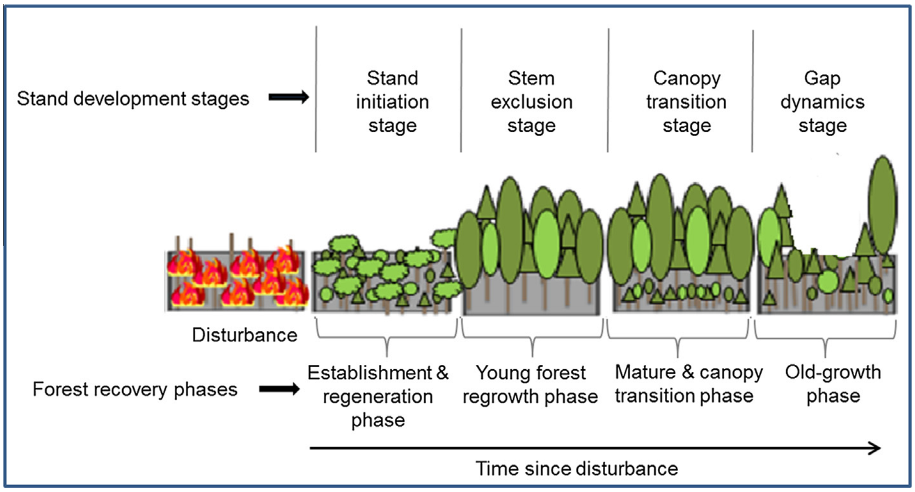

Fig. 1. Schematic stages of early to mature forest stand development following major disturbances (adopted from Oliver and Larson (1996)). The stages follow a sequence or phases of post-disturbance vegetation development indicative of forest recovery. The species composition, height structure, and time elapsed since disturbance at each stage vary with type of disturbance, dominant species, and site conditions.

described in detail elsewhere (Bergeron, 2000; Belleau et al., 2011; Taylor and Chen, 2011).

The *stand initiation stage* describes the regeneration of remnant vegetation by several means and the recruitment of new individuals. This stage lasts several years after disturbance. The process and pattern of the stand initiation stage can be categorized into two phases: the establishment and regeneration phase. The establishment phase represents the initial stand conditions immediately after disturbance. It is composed of organic substrates with exposed mineral soil, remnant trees, and ground vegetation that survived the disturbance. Depending on disturbance type, the landscape or regenerating stand at this stage is nearly barren of tree seedlings, or only scattered regeneration with no trace of seedling regeneration $\geqslant 2$ m in height. The regeneration phase is initiated by vegetative regeneration of damaged stems, stumps, and roots that survived the disturbance and *in situ* seeds from serotinous and semi-serotinous cones, as well as the recruitments of vascular understorey species that are well adapted for survival and rapid regeneration following disturbance. Regeneration is suggested to be rapid in the first 3 years following wildfire, with a more gradual return in later years (Greene et al., 1999; Ireland and Petropoulos, 2015). When assessed with vegetation indices from remotely sensed data vegetation indices, measured values may reach ~60% of pre-wildfire levels (Ireland and Petropoulos, 2015), indicating that there is sufficient live green vegetation at to be detected, and differentiated from recently disturbed sites, using appropriate remote sensing techniques. While there is active tree seedling regeneration at this stage, very few seedlings survive more than one year (Ilisson and Chen, 2009a,b). The establishment of tree seedlings is usually successful within the first 5 years after wildfire (Sirois and Payette, 1989; Galipeau et al., 1997; Gutsell and Johnson, 2002; Johnstone et al., 2004). At this time, the high cover of herbaceous species, especially grasses negatively affects recruitment and regenerating density of tree seedlings (Gartner et al., 2014). However, once established the seedlings and saplings of early successional tree species can outcompete shrub and herbaceous species that dominated the establishment phase. For some forest cover types, most of the herbaceous layer species tend to disappear almost completely within the first 10-year period after disturbance (Archambault et al., 1998; Kreyling et al., 2008a).

The *stem exclusion stage* typifies a young regrowth forest phase characterized by intense competition among regenerated species for available growing space and resources, and the lack of available growing space prevents further establishment of new stems. A prominent feature of this phase is that the smallest and weakest trees are eliminated, leaving the vigorous and more competitive individuals to use liberated resources (Luo and Chen, 2011). The trees that survived the competition continue to expand in size, leading to rapid canopy closure at a later phase (Chen and Popadiouk, 2002). Thus, the stand structure and vertical canopy stratification at this stage may not yet be comparable to the mature forest phase.

The *canopy transition stage* represents a mature forest phase characterized by vertical canopy stratification and crown closure through development of overlap among individual tree canopies (Chen and Popadiouk, 2002). It is also viewed as a transition between early, mid- or late-successional tree species, as shade-tolerant conifer trees from the understory and subcanopy strata begin to take over the main canopy. The duration of this stage may depend on when all of the individuals from the initial cohort die due to longevity or disturbance and their eventual replacement by a later cohort. Lastly, the *gap dynamics stage* represents an old-growth phase of forest development characterized by a mosaic canopy as a result of tree senescence. It is typically composed of sparse shade-tolerant species such as fir and spruce, and the large canopy gaps created become colonized by understory shrub and herb species, as well as shade-intolerant trees in direct response to available resources and growing space. In the absence of a major disturbance, emerging shade-intolerant species in the understory layer continues the process of new forest regrowth.

4. Factors that influence forest recovery

The rate at which a forest recovers from a disturbance is influenced by a wide range of factors that are related to local site conditions, regional climate, disturbance history, regional species pool, and species life histories (Harper et al., 2005; Mansuy et al., 2012; Spence and MacLean, 2012; Girard et al., 2014). Because recovery is an ongoing process, time since disturbance constitutes an important predictor of post-disturbance recovery of forest vegetation. A longer interval between disturbances will allow trees to become re-established. The relative contributions of these and other influencing factors are summarized below.

(a) The establishment phase

(b) The regeneration phase

(c) The young forest regrowth phase

Fig. 2. Photographic representation of the early phases of forest vegetation development indicative of recovery. From top to bottom: the establishment phase, the regeneration phase, and the young regrowth forest phase (photo credit: Alexandre Humes (top panel) and Zilong Ma (bottom two panels), Lakehead University).

4.1. Nature and severity of disturbance

Nature of disturbance (type, intensity, and frequency) constitutes an important determinant of post-disturbance vegetation dynamics because different disturbances vary in terms of their physical impact to soil and existing vegetation, and biological legacies (Foster et al., 1998; Franklin et al., 2007). As such, recovery is faster following disturbances that cause minimal damage to vegetation and leave much of the existing forest structure intact. For instance, recovery may be rapid following gradual mortality due to insect defoliation that affects a selective number of tree species compared with stand-replacing disturbance such as high intensity wildfire which potentially deprives a site of vegetation and initiates secondary-succession processes. It is widely acknowledged that disturbance severity determines the type of post-disturbance vegetation growing at a site (Johnstone and Kasischke, 2005; Ilisson and Chen, 2009a; Veilleux-Nolin and Payette, 2012), which may lead to different woody vegetation recovery patterns (Carleton and MacLellan, 1994). Frequency of disturbance is also important to forest vegetation recovery. The general successional path of Canada's boreal forest is largely dependent on wildfire cycle duration (Bergeron and Dansereau, 1993). Wildfire cycles shorter than the lifespan of the dominant species may lead to younger forests and the eventual replacement of the forest vegetation by non-tree vegetation, such as meadow, shrub, or tundra (Bergeron and Dansereau, 1993). Repeat wildfires reduce seed availability and alter substrate constraints on regenerating tree species (Brown and Johnstone, 2012). Hence, a shorter wildfire cycle may also not be sufficient for long reproductive tree species, such as black spruce, to reach sexual maturity and produce adequate seeds for eventual regeneration following the next wildfire.

4.2. Pre-disturbance forest composition and structure

Stand composition prior to disturbance constitutes an important determinant of post-disturbance recovery and regenerating patterns (Foster et al., 1998; Reyes and Kneeshaw, 2008; Chen et al., 2009; Ilisson and Chen, 2009b). Depending on intensity of disturbance, there is a high likelihood that dominant tree species at the time of disturbance will rapidly recolonize and dominate regenerating stands. Pre-disturbance species-specific basal area is also regarded as an important factor that influences regeneration density following disturbance (Chen et al., 2009; Ilisson and Chen, 2009b). Pre-disturbance forest composition can influence forest susceptibility or resistance to disturbances such as wind damage and subsequent regeneration. For example, stands dominated by early successional and shade intolerant species are most susceptible to wind damage (Rich et al., 2007), while at the same time most shade-intolerant species such as aspen and jack pine are capable of fast colonization after disturbance (Ilisson and Chen, 2009b). In low severity disturbances that create canopy gaps pioneer and opportunistic species may be expected to rapidly establish and potentially suppress pre-existing shade-tolerant species (Chen and Taylor, 2012). Using time series remotely sensed imagery and light detection and ranging (lidar) data, Bolton et al. (2015) also found that pre-disturbance structure (as captured with the lidar) was a strong indicator of post-disturbance conditions (using a chronosequence from the time series imagery).

4.3. Biological legacies, propagule availability, and species life history traits

There is widespread recognition of the role of disturbance in creating structural legacies that become key elements of post-disturbance stands (Franklin et al., 2002). The availability of *in situ* propagules, such as seeds and cones, and underground root systems that survived the disturbance largely contributes to rapid recovery and establishment of vegetation (see Section 3.1). In addition, proximity to seed source is important to natural regeneration after disturbance (Galipeau et al., 1997), and recovery is faster when seed bearers are present on site. For instance, at a site in Wood Buffalo National Park, harvested stands (clear-cut) were located beyond the effective dispersal of white spruce seed and this, combined with the destruction of advance growth and lack of residual growth, resulted in the failure of natural regeneration following harvest (Timoney and Peterson, 1996). Furthermore, the regeneration potential of remnant species can influence recovery. For instance, species that germinate solely by seeds may require suitable organic and mineral soil substrates for germination and may thus take a long time to become established, unlike those species, such as trembling aspen, white birch, balsam poplar, and white cedar that are able to regenerate vegetatively through root suckering, stem sprouting, or layering (Greene et al., 1999; Bergeron, 2000). Therefore, the presence of species with superior post-disturbance regeneration or those that are well adapted to recurring disturbances can influence the rates of recovery and species regeneration patterns following disturbance.

4.4. Climate and local site conditions

The prevailing climatic condition of an area influences forest regeneration following disturbance, and thus the rate of forest recovery. Regenerating stands are not immune to drought and may be even more sensitive to soil moisture deficits that occur in response to extreme temperatures and drying (Luo and Chen, 2013; Petrone et al., 2015). Hence, extremes in local climate, such as drought can impede forest regeneration. Previous studies indicate that slow forest regeneration is most likely to occur following wildfires that occur in dry years (Mansuy et al., 2012). In southwest Yukon for example, variation in precipitation (i.e., drought) resulted in the slow regeneration of spruce and aspen after wildfire (Hogg and Wein, 2005), suggesting that regenerating forests are vulnerable if the climate becomes drier under future global change (Luo and Chen, 2013). Forest vegetation recovery is also influenced by local site conditions, including topography and edaphic factors. Edaphic factors, such as parent material, surficial deposits, soil moisture, and organic matter accumulation influence seedling recolonization following disturbance, as well as the timing of forest developmental stages (Galipeau et al., 1997; Harper et al., 2005; Mansuy et al., 2012). For example, white spruce and balsam fir regenerating seedling densities after wildfire in southeastern boreal forests were found to be lower on clay deposits, but higher on till deposits (Galipeau et al., 1997). Soil deposits affect the rates of tree seedling establishment after disturbance, especially for species that are unsuited for very moist and wet site conditions, through their influence on the soil moisture regime. Till deposits, composed rich soil moisture and nutrient regime are generally associated with fast recovery and dense forest regeneration, compared with dry deposits that are unfavorable to regeneration (Mansuy et al., 2012).

5. Quantitative review of published studies

5.1. Literature search and data compilation

To facilitate a quantitative synthesis, we conducted a literature search (from ISI Web of Science, JSTOR, and SCOPUS databases for all available years) using disturbance type key terms, such as "wildfire," "harvest," "harvesting," "clear-cutting," on a concatenated string of the following words: disturbance type AND recovery AND resilience AND regeneration AND Canada to obtain relevant sources that reported on forest recovery or regeneration and related information in Canada's forest ecosystems. Retrieved articles were critically evaluated and judged to be eligible for inclusion when the following criteria were met: the paper made explicit reference to a specific stand-replacing disturbance event (wildfire or harvest) in an area located within the forest regions of Canada, with sufficient indication that the study stands originated from that particular disturbance(s); and, the paper communicates clear information on time since disturbance or stand ages and at least one response variable (canopy cover, height, or basal area), the numerical values of which were easily obtainable from the texts, tables, or figures. Data accessibility was critical as data in most studies were presented in formats that were not easily retrievable even with standard digitizing methods.

After interrogating all the relevant papers returned, we were able to retrieve adequate information from 28 studies published between 1985 and 2015. Reported data on forest structural attributes, including canopy cover, tree heights, and basal area were taken from original papers. To avoid duplication, data from the same study plots that were reported in different studies or sources were entered only once. The raw data were either extracted from published tables or obtained by digitizing data from graphs using SigmaScan Pro version 5.0 (Systat Software Inc.). The type of disturbance and time elapsed since disturbance (deduced from stand age where applicable) were recorded, as well as location of study, ecological zone (forest ecozones of Canada), forest biome (boreal and temperate forests), dominant tree species, and site type, where applicable. The final constructed dataset consisted of 717 observations with stand ages or time since disturbance ranging from 1 to 337 years (Appendix A1). The compiled data included wildfire and harvest events from seven different terrestrial ecozones across Canada (Table 1; Fig. 3). The majority of studies focused on stand-replacing wildfire ($n = 12$), followed by forest harvesting ($n = 10$), with 6 studies that include both wildfire and harvest (Appendix A1).

5.2. Estimation method

The response or indicator variables extracted in individual studies to inform on forest recovery included stand basal area, canopy cover, and tree height, with time since disturbance as an explanatory variable. The relationships between the indicator variables and time since disturbance were examined using a polynomial regression equation (up to the 3rd order) of the form:

$$y = b_0 + b_1 \cdot TSD + b_2 \cdot TSD^2 + b_3 \cdot TSD^3 \qquad (1)$$

where y is the response variable, TSD is time since disturbance, b_0 is intercept, and b_1, b_2 and b_3 are the slopes for the first-, second-, and third-degree terms, respectively.

As the majority of the studies retrieved did not provide sufficient information on variance for many of the response variables examined in this review, we resorted to an unweighted analysis in which the response effects were not weighted by sample size in order to include as many studies as possible. Data for each response variable were grouped by category, i.e., disturbance type (wildfire, harvest), forest biome (boreal, sub-boreal, taiga, temperate), and ecozones (Atlantic Maritime, Boreal Cordillera, Boreal Plains, Boreal Shield East, Boreal Shield West, Montane Cordillera, Taiga Shield East, Pacific Maritime).

Akaike Information Criterion (AIC) was used to determine the best fitted model among alternative polynomial regressions (linear, quadratic and cubic forms of untransformed and transformed functions, i.e., log (x) and exp (x) of the explanatory variable). The coefficients of the best fit model was then used to predict the time required to reach a benchmark value of the response variable indicative of recovery (i.e., 10% canopy cover, 5 m height, and 10 $m^2\ ha^{-1}$ basal area). For wildfire, the predictions were also made on a subset of the data (time since disturbance, $TSD \leqslant 100$ years) due to the range of the stand ages in the compiled

Table 1
Summary data of indicator variables of forest structural recovery grouped by time since disturbance, disturbance type, forest biome, and ecozone. The *n* indicates the number of observations for each data category.

Indicator	Disturbance	Biome	Ecozone	Time since disturbance Min–Max	Indicator variable Min–Max	No. of studies	*n*
Canopy cover (%)	Wildfire	Boreal	Atlantic Maritime	36.2	83.5	1	1
	Wildfire	Boreal	Boreal Shield	23.0–230.0	14.4–41.3	2	24
	Harvest	Boreal	Atlantic Maritime	41.5	79.4	1	1
	Harvest	Boreal	Boreal Shield	2.0–25.0	7.9–29.2	2	6
	Harvest	Temperate	Montane Cordillera	6.0–28.0	0–70.0	1	32
Tree height (m)	Wildfire	Boreal	Boreal Cordillera	43.0–44	0–9.8	1	1
	Wildfire	Boreal	Boreal Shield	20.0–337.0	2.1–15.4	2	90
	Wildfire	Boreal	Multiple[a]	6.0–65.0	3.6–15.1	1	106
	Harvest	Boreal	Boreal Plain	1.0–5.0	0.5–2.4	1	7
	Harvest	Boreal	Boreal Shield	8.0–80.0	5.6–9.2	2	14
Basal area (m^2 ha^{-1})	Wildfire	Boreal	Atlantic Maritime	36.2	23.7	1	1
	Wildfire	Boreal	Boreal Cordillera	43.0–44.0	0.9–6.7	1	10
	Wildfire	Boreal	Boreal Shield	2.0–323.0	0–75.0	6	152
	Harvest	Boreal	Atlantic Maritime	41.5	25.5	1	1
	Harvest	Boreal	Boreal Plain	4.0–28.0	0–60.0	1	13
	Harvest	Boreal	Boreal Shield	1.0–31.0	0.1–10.8	3	9
	Harvest	Temperate	Montane Cordillera	6.0–28.0	0–32.0	1	32

[a] Indicates observations from the various boreal forest ecozones of Canada, including the Boreal Shield, Boreal Plain, and Boreal Cordillera.

data (i.e., 1–337 years; Appendix A1). For harvest data, *TSD* was already ⩽100 years. All statistical analyses were performed using the 'Stats' package in R statistical software for Windows version 3.1.0 (R Development Core Team, 2013).

6. Results of estimated rates of recovery

6.1. Rates of forest recovery across Canada

With all data pooled together, our model results indicated an increase in canopy cover with increasing time since disturbance and high canopy cover in the order of 40% within the first 50 years (Fig. 4). Average tree height also increased up to 100 years post-disturbance, but tended to decrease after this period likely due to natural mortality of pioneer species, followed by the subsequent advance regeneration of understorey species (Fig. 4). Stand basal area also increased with time since wildfire but tended to decrease after more than 200 years, when natural senescence typically leads to more open stands. Rates of recovery for the various indicator variables were examined by predicting the time taken to reach a desirable state of recovery. Our model results showed that at as early as 5 years after disturbance, stands were predicted to reach a canopy cover of 42% after wildfire, and tree heights of about 5.4 m and 3.2 m after wildfire and harvesting, respectively (Table 2, Appendix A2); however, our model predictions are a product of the data observations available and the limited range of stand ages examined therein.

In order not to be overly influenced by single values in our sample, to acknowledge the uncertainty present, and to better uncover trends, we examined the recovery of the indicator variables by grouping observations into recovery time scales (i.e., 10-year epochs) according to the number of years following disturbance (Table 3). Based on our ten year epochal summaries, canopy cover for the first ten years after harvesting ranged from 0% to 12% (Table 3), but we had no comparable data for canopy cover post-wildfire. By 20–30 years after disturbance, recovery of canopy cover for wildfire and harvest had surpassed our defined benchmark of 10%. Recovery of canopy cover into the fourth decade after wildfire had reached 40–84%. Average tree heights ten years after disturbance were between 4.1 and 6.5 m for burned stands and 0.5 and 8.3 m for harvested stands. Similarly, tree height in post-fire stands 20–30 years after disturbance had a wider range from 2.1 to 10.9 m, compared with harvested stands, 5.6–8.8 m. Recovery of stand basal area proceeded more slowly for burned or harvested stands (ranging from 0 to 2.0 m^2 ha^{-1}) for the first 10 years after disturbance. Basal area recovery was between 4.8 and 42.2 m^2 ha^{-1} at 10–20 years after wildfire, whereas comparable basal area recovery for post-harvest stands was reached in 20–30 years after disturbance (Table 3).

6.2. Rates of forest recovery in relation to forest biome, ecozone, and disturbance type

Recovery time following disturbance was further grouped by type of disturbance, forest biome, and ecological zone in which the study data were located, and the time required to reach our defined benchmark values for recovery was estimated based on significant model terms (Table 4, Appendix A3). Between forest biomes, the results suggest that recovery of canopy cover (to a 10% cover benchmark) after harvesting in the boreal forest would take 5.7 years, compared with 7.8 years in the temperate forest biome. Recovery times varied among the different ecozones of Canada, with recovery of forest canopy to a benchmark value of 10% after harvesting taking an estimated 5.7 years in the Boreal Shield, but 7.8 years in the Montane Cordillera. Recovery of basal area after harvesting was twice as fast in the Boreal Plains (14.1 years) compared with the Boreal Shield (32.9 years), but this likely reflected the different tree species composition in individual studies. Wildfire and harvest were also associated with varying recovery times: recovery of basal area to our benchmark value in the Boreal Shield was twice as fast post-wildfire (16.9 years) compared to post-harvest (32.9 years), whereas tree height growth in the boreal forests was similar between wildfire and harvest: 4.1 m and 4.7 m, respectively (Table 4).

7. Discussion

In the absence of objective quantification of recovery in individual studies, we estimated rates of forest recovery based on forest structural attributes that have traditionally been used as indicators of forest growth and productivity. The results of our review suggest that post-disturbance recovery of Canada's forests has proceeded at varying rates, and moreover, that no more than five years are required for disturbed areas in most forested ecosystems of Canada

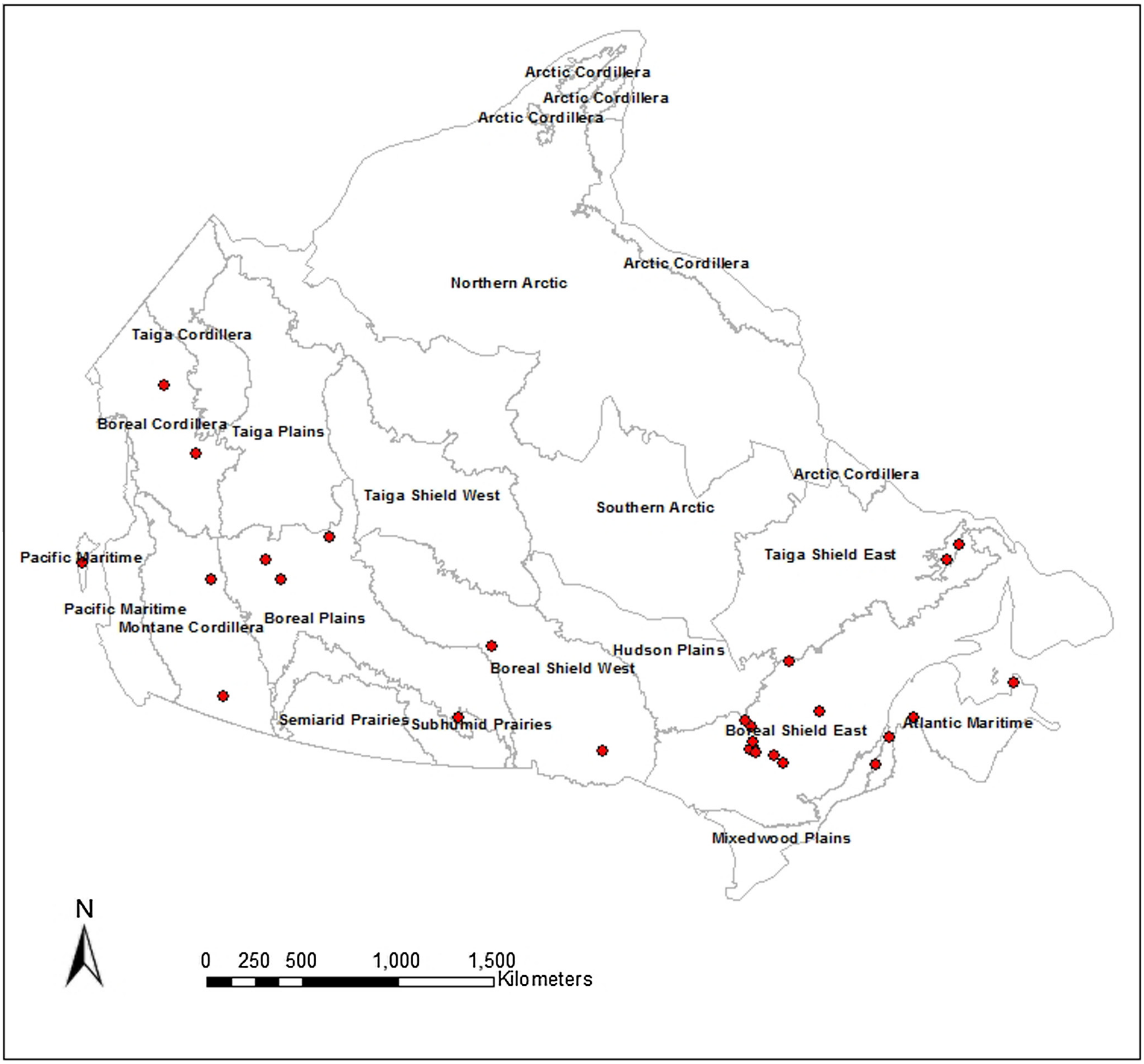

Fig. 3. Map highlighting the terrestrial ecological zones (ecozones) of Canada and the locations of the studies included in this study.

to attain a benchmark canopy cover of 10% after wildfire disturbance, compared to 10 years for harvest (Table 2). In addition, within that same 5-year time period, regenerating stands in Canada's boreal forests, most often dominated by fast growing shade-intolerant aspen and jack pine after fire, are capable of reaching a height of 5 m after wildfire or harvesting. These results suggest rapid recovery of Canada's forests, confirming previous reports of faster vegetation recovery after wildfire (Goetz et al., 2006; Jones et al., 2013; Ireland and Petropoulos, 2015). Stand basal area also showed signs of recovery early in the stand initiation and stem exclusion stages, corresponding to young forest regrowth conditions in many previous studies (Cogbill, 1985; Johnstone et al., 2004; Mansuy et al., 2012; Spence and MacLean, 2012), as well as a period of high net primary production (Amiro et al., 2000).

Recovery times increased with time since disturbance at rates that depended on disturbance type, forest biome, and ecozone. For instance, estimated recovery time for canopy cover after harvesting with regard to forest biome was shorter for the boreal forest than the temperate forest biome (Table 4). Conversely, recovery of basal area after harvesting was shorter in the temperate forest biome. Unlike the boreal forest, most of the data on temperate forest were obtained from studies conducted in high elevation mountain forests (Kreyling et al., 2008b). Hence, it remains unclear whether recovery of forest canopy cover in low elevation temperate forests differs from that in boreal forests.

Recovery of tree height after wildfire and harvesting (4.1 and 4.7 years respectively) was similar within the boreal biome, suggesting that the rate of forest recovery may be similar among forests located within similar biotic and abiotic settings. However, also within the boreal biome, recovery of basal area after harvesting was shorter in the Boreal Plains ecozone (14.1 years, Table 4) than after harvesting in the Boreal Shield ecozone (32.9 years). Although the variation between these two boreal ecozones was likely due to the range of stand ages examined and differences in tree species composition observed in individual studies (for instance, pioneer species such as pine and aspen in the Boreal

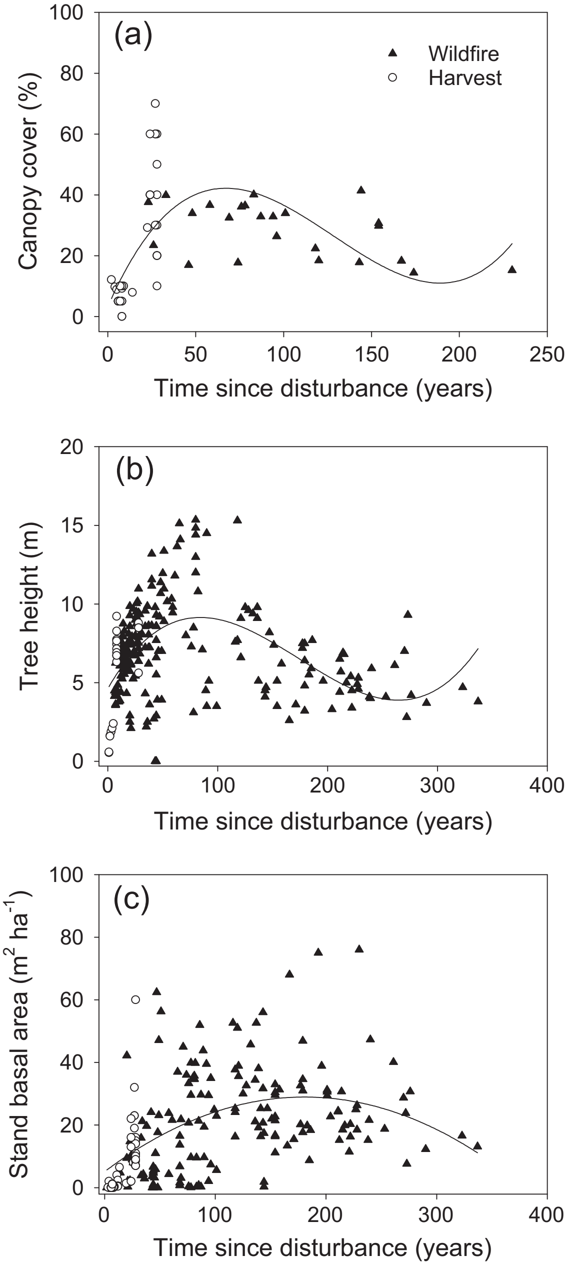

Fig. 4. Relationship between indicator variables of forest structural recovery: (a) canopy cover, (b) tree height, and (c) basal area, and time elapsed since disturbance.

Plains compared to late successional spruce in the Boreal Shield), the difference may also be traced to the effects of edaphic factors, such as the rich mineral deposits of the Boreal Plains in contrast to the mostly clay deposits of the Boreal Shield. Edaphic factors, such as parent material, surficial deposits, and organic matter accumulation influence tree regenerating densities following disturbance as well as the timing of stand developmental stages (Galipeau et al., 1997; Harper et al., 2005; Mansuy et al., 2012).

Although disturbance frequency and intensity were not directly tested in this study, these attributes are important influencing factors of post-disturbance recovery of forest vegetation because disturbances of different intensities contrast markedly in terms of physical impact to soil and existing vegetation, and resultant biological legacies (Foster et al., 1998; Franklin et al., 2007). Of the two most common disturbance types observed across Canada, wildfire and timber harvesting, our results suggest that there is similar or more rapid recovery of canopy cover, tree height, and basal area after wildfire when compared to timber harvesting. This supports evidence presented elsewhere that forests exposed to natural, large, and infrequent disturbances recover faster than those that experience human impacts (Jones and Schmitz, 2009; Cole et al., 2014). We found that most studies rarely made reference to pre-disturbance conditions or included an undisturbed control as a benchmark to assess rates of recovery. These notable limitations in previous studies and data availability constrained our quantitative analysis. Our ability to predict forest recovery times was further constrained by the small number of studies available: many individual studies have not been conducted over the longer time scales necessary to detect recovery, or recovery times have not been documented frequently enough to sufficiently evaluate recovery rates across the forest regions of Canada.

8. Remote sensing of forest recovery: challenges and opportunities

Assessments of post-disturbance forest vegetation recovery, as evidenced from this review, are mostly based on plot-level measurements using chronosequences of varying age and disturbance history in an attempt to infer long-term forest recovery trajectories. While the chronosequence approach (i.e., space-for-time) is useful, observations in many individual studies are conducted at fine spatial scales, often ranging from one to several hectares in spatial extent. However, the spatial and temporal scales of forest disturbance and recovery span large areas, and therefore plot-based chronosequences that span a limited spatial or temporal range of conditions may be inadequate to capture the full range of variability across an entire landscape or ecoregion. Another challenge to ground-based monitoring is the issue of accessibility, as most disturbed forest areas in Canada, and elsewhere, can be remote and difficult to access and therefore do not allow for true spatial interspersion. Moreover, estimation of forest structural recovery by plot-based data collection efforts is both expensive and time consuming. An approach that uses remotely sensed data allows some of these limitations to be overcome; however plot-based data remains a critical source of calibration and validation data to these approaches. The characterization of vegetation return following disturbance in a systematic fashion for both accessible and inaccessible (e.g., northern Canada) areas allows for a comprehensive accounting of forest recovery that supports development of trends and patterns over a range of disturbance types (i.e., wildfire and harvest). Measured trends and patterns of recovery can in turn be related to underlying drivers, such as site conditions and broader ecosystem-level considerations (e.g., stress, Frazier et al., 2015).

Stand replacing disturbances are readily detected with remotely sensed data and are discrete in both time and space (Kennedy et al., 2007), whereas the return of vegetation following disturbance takes place over a period of time and, in the absence of land use change, can be expected to follow ecological successional processes. The monitoring of forest recovery and vegetation reestablishment following disturbances are ideally suited to time series analyses of remotely sensed data (e.g., Sever et al., 2012; Chen et al., 2014); however, a linkage must be made between notions of spectral recovery and ecological or silvicultural understanding of forest recovery. From a remote sensing perspective, the relation between a sequence of spectral values through time and ecological recovery requires both a clear definition of recovery (in an ecological sense), and the identification of appropriate indicators of recovery that may be measured with remotely sensed data. From an ecological perspective, forest recovery is typically considered as the reestablishment of forest biomass or canopy structure

Table 2
Relationship between indicator variables of forest structural recovery and time since disturbance (*TSD*), separately analyzed for wildfire and harvest disturbance. The coefficients of the best model (based on Akaike Information Criterion; *Appendix* Table A2) are used to predict recovery of the indicator variable at 5, 10, and 20 years after disturbance. The predictions were also modeled on a subset of the data ($TSD \leqslant 100$ years). Non-significant predictions (i.e., confidence interval of the prediction includes zero) are indicated by *ns*.

Indicator	Disturbance type	n	Model terms						Predicted recovery		
			Intercept	TSD	TSD^2	TSD^3	p	r^2	5 years	10 years	20 years
Canopy cover (%)	Wildfire	25	42.82	−0.12			0.018	0.22	42.3 (31.5–52.9)	41.6 (31.3–51.8)	40.3 (30.9–49.7)
	Wildfire $TSD \leqslant 100$ y	15	44.18	−0.15			0.391	0.06	43.4 (21.4–65.5)	42.7 (22.3–63.1)	41.2 (24.0–58.5)
	Harvest	39	−4.71	1.69			<0.001	0.67	3.8^{ns} (−2.4 to 9.9)	12.2 (7.3–17.2)	29.2 (24.7–33.7)
Tree height (m)	Wildfire	206	7.01	−7.52	−11.3	13.11	<0.001	0.2	5.4 (4.6–6.2)	5.9 (5.2–6.6)	6.7 (6.3–7.2)
	Wildfire $TSD \leqslant 100$ y	150	6.27	−6.74	0.004	−0.00004	<0.001	0.19	6.0 (4.5–7.5)	5.9 (5.1–6.9)	6.4 (5.8–7.0)
	Harvest	21	5.54	8.24	−9.79	−2.57	<0.001	0.92	3.2 (2.1–4.4)	10.7 (8.9–12.6)	22.8 (13.7–31.9)
Stand basal area ($m^2\ ha^{-1}$)	Wildfire	163	2.9	0.29	−0.0008		<0.001	0.18	4.3^{ns} (−2.1 to 10.8)	5.7^{ns} (−0.3 to 11.7)	8.4 (3.3–13.5)
	Wildfire $TSD \leqslant 100$ y	83	3.73	0.22			0.002	0.11	4.8^{ns} (−3.1 to 12.7)	5.9^{ns} (−1.3 to 13.2)	8.1 (2.0–14.2)
	Harvest	55	−4.66	0.74			<0.001	0.5	-0.9^{*ns} (−4.1 to 2.2)	2.8 (0.3–5.2)	10.2 (7.9–12.4)

Notes: Time since disturbance (*TSD*) for harvest were already ⩽100 years and therefore subsets of harvest data were not analyzed.

[*] Due to the lack of basal area present for young trees, we model a negative, albeit non-significant (−0.9) basal area of trees at 5 years.

Table 3
Epochal summaries of indicator variables of forest structure recovery grouped by years since disturbance, biome, and ecozone.

Indicator	Disturbance	Biome	Ecozone	n	Years since disturbance			
					1–10 Mean (n) Min–Max	10–20 Mean (n) Min–Max	20–30 Mean (n) Min–Max	30–40 Mean (n) Min–Max
Canopy cover (%)	Wildfire	Boreal	Boreal Shield	3			30.5 (2) 23.4–37.6	39.9 (1) 39.9
	Wildfire	Boreal	Atlantic Maritime	1				83.5 (1) 83.5
	Harvest	Boreal	Boreal Shield	6	9.9 (4) 8.9–12.1	7.9 (1) 7.9	29.2 (1) 29.2	
	Harvest	Temperate	Montane cordillera	32	5.6 (16) 0–10.0		40.6 (16) 10.0–70.0	
Tree height (m)	Wildfire	Boreal	Multiple[a]	95	4.6 (12) 4.1–6.5	6.8 (43) 3.9–9.9	8.3 (26) 5.3–10.9	8.9 (14) 6.2–13.2
	Wildfire	Boreal	Boreal Shield	8		2.7 (2) 2.5–2.9	4.2 (2) 2.1–6.2	3.1 (4) 2.2–4.3
	Harvest	Boreal	Boreal Plain	7	1.5 (7) 0.5–2.4			
	Harvest	Boreal	Boreal Shield	14	7.4 (10) 6.3–8.3		7.8 (4) 5.6–8.8	
Basal area ($m^2\ ha^{-1}$)	Wildfire	Boreal	Boreal Shield	18		18.8 (3) 4.8–42.2	6.6 (9) 0.3–14.8	11.3 (6) 4.3–23.7
	Harvest	Boreal	Boreal Shield	9	0.1 (1) 0.1	2.2 (5) 0.4–6.5	8.8 (3) 7.1–10.8	
	Harvest	Boreal	Boreal Plain	13	0.3 (8) 0–2.0	4.0 (1) 4.0	25 (4) 8.0–60.0	
	Harvest	Temperate	Montane Cordillera	32	0.3 (16) 0–1.2		14.8 (16) 2.0–32.0	

Notes: n is the number of observations per data range.

[a] Indicates observations from the various boreal forest ecozones of Canada, including the Boreal Shield, Boreal Plain, and Boreal Cordillera.

following disturbance (Oliver and Larson, 1996) and may be indicated by vegetation structural properties, photosynthetic capacity, height, biomass, and heterogeneity (Frolking et al., 2009). Focus on any one of these indicators would typically require different remotely sensed data and analytical approaches.

Following disturbance, several recovery scenarios are possible: (i) no recovery (e.g., land use conversion), (ii) facilitated recovery toward a predefined stocking or structural target (e.g., plantation forestry), or (iii) natural recovery, characterized by successional processes and the regeneration of vegetation at rates governed by site factors and the severity of the initial disturbance. For all of these scenarios, tracking of spectral values through time can aid in characterizing recovery at a given location (Schroeder et al., 2011). Critical challenges are however associated with appropriately linking changes in remotely sensed spectral information to ecological or silvicultural understandings of recovery. For instance, given sufficient years following disturbance, vegetation indices may inform on the increasing nature of vegetation amount and complexity, but it is widely acknowledged that these indices can saturate at a given stage of vegetation development, and provide little incremental information (Huete, 2012), with lidar data likely required to inform on height, or other vertical structural, characteristics.

From a remote sensing perspective, Landsat is one of the few data sources that provide the spatial resolution and temporal history required to support the monitoring of forest recovery

Table 4
Relationship between indicator variables of forest structural recovery and time since disturbance (*TSD*), grouped by disturbance type, forest biome, and ecozone. The coefficients of the best model (based on Akaike Information Criterion; *Appendix* Table A3) are then used to estimate recovery for each indicator variable at a given benchmark (10%, 5 m, and $10\ m^2\ ha^{-1}$ for canopy cover, tree height, and basal area, respectively).

Indicator	Disturbance type	Forest biome	Ecozone	Model	R^2	Benchmark values of recovery	Estimated time to recovery (years)
Canopy cover (%)	Harvest	Boreal	Boreal Shield	$16.71 - 2.19\,TSD + 0.12\,TSD^2$	0.97	10%	5.7
	Harvest	Temperate	Montane Cordillera	$-37.37 + 7.41\,TSD - 0.17\,TSD^2$	0.66	10%	7.8
Tree height (m)	Wildfire	Boreal	Multiple[a]	$4.46 + 0.13\,TSD$	0.63	5 m	4.1
	Harvest	Boreal	Boreal Plain	$-0.15 + 1.21\,TSD - 0.13\,TSD^2$	0.96	5 m	4.7
Basal area ($m^2\ ha^{-1}$)	Wildfire	Boreal	Boreal Shield	$5.81 + 0.26\,TSD - 0.001\,TSD^2$	0.13	$10\ m^2\ ha^{-1}$	16.9
	Harvest	Boreal	Boreal Plain	$-6.89 + 1.20\,TSD$	0.53	$10\ m^2\ ha^{-1}$	14.1
	Harvest	Boreal	Boreal Shield	$-2.23 + 0.37\,TSD$	0.68	$10\ m^2\ ha^{-1}$	32.9
	Harvest	Temperate	Montane Cordillera	$-4.49 + 0.72\,TSD$	0.64	$10\ m^2\ ha^{-1}$	20.3

[a] Indicates observations from the various boreal forest ecozones of Canada, including the Boreal Shield, Boreal Plain, and Boreal Cordillera.

(Wulder et al., 2012a). A long temporal baseline provides the required time to capture disturbances and assess the subsequent return of vegetation. For more recent disturbances, sufficient time may not have elapsed to allow for statements on recovery to be made. As demonstrated by this review, the amount of time required to relate some level of recovery will be linked to site-specific factors (e.g., productivity, climate) and this expectation of time to recovery should be incorporated into any definition of spectral recovery that is offered. That is, if a given definition of recovery includes a "years-to-condition" provision, it will not be possible to convey information for those disturbances that occur near the most recent end of the time series. Furthermore, the values related from a given spectral index are a function of the image bands used for computation. Indices that emphasize visible wavelengths of the electromagnetic spectrum will saturate sooner and indicate a more rapid uptake of vegetation at a given location (i.e., Buma, 2012), whereas bands located in the longer wavelengths are known to be more sensitive to vegetation structure (such as band 5, SWIR, of the Landsat series; Schroeder et al., 2011; Cohen and Goward, 2004). In general, if the information need is to determine if vegetation is returning following a disturbance, the vegetation index selected is likely less important as the initial pulse of vegetation return (or not) in a short time period would be detected. If the information need is aimed at tracking more long-term and sustained vegetation regeneration and succession, longer wavelengths such as the SWIR, would provide for trends representative of a longer time period following the initial disturbance (Kennedy et al., 2007).

As forest recovery is an ongoing process that is influenced by multiple interacting factors, determination of forest recovery rates must incorporate an understanding of both the nature of disturbance and the structural and ecological characteristics of the study system. Criticisms of remote sensing methods for characterizing forest recovery often relate to the fact that remotely sensed data do not directly measure changes in vegetation biomass or land cover transitions, but rather infer these changes via measured variations in spectral values. Moreover, studies using remotely sensed data to characterize recovery rarely consider the ecology and successional patterns of the study system (as noted by Frolking et al. (2009), Buma (2012), and Chu and Guo (2014)). For effective monitoring of forest cover change and spectral recovery, it is therefore imperative that the goal of the remote sensing approach is clearly articulated, and expectations associated with recovery are well-defined. As indicated above, if the goal is to show that vegetation is returning to a given site following disturbance, spectral recovery logic can be readily applied to relate vegetation presence and increasing complexity over time. If the goal is to capture the moment that tree species begin to dominate a given site (by given height and cover criteria), applications and data sources (such as lidar) that relate three dimensional characteristics are likely required. Airborne Laser Scanning (ALS) can provide a data source in support of such a goal, but will also imply greater data collection costs and smaller areal coverage than studies based upon optical remotely sensed data (such as Landsat) alone (Wulder et al., 2012b). Sampling of lidar to inform on spectral trends is also an option to enable insights on forest recovery over large areas (i.e., Bolton et al., 2015). Ideally, the measures made from remotely sensed data will be supplemented with ground data and an ecological understanding of the forest recovery process to ensure the information needs (and the goals of a particular study) are met with the approach applied. To link what is detectable from remotely sensed data to what is relevant from a forest regeneration or recovery point of view, the recovery definition needs to be formulated around, and supported by, what can be extracted from the remotely sensed data. For instance, applications can be developed that inform on time since disturbance to make inferences about initiation of successional processes (e.g., Kennedy et al., 2010; Schroeder et al., 2011; Hermosilla et al., 2015) or to meet particular forest management (or silvicultural) targets, such as potential height, canopy cover, or desired stocking (Franklin et al., 2002; LePage and Banner, 2014).

In the context of this literature review, we adopted the FAO definition of forest (i.e., an area of land greater than 0.5 ha in size with greater than 10% tree canopy cover, and trees that are capable of reaching a minimum height of 5 m) as our baseline for assessing recovery. From the studies we examined for this review, we learned that the time it takes for a forest to be considered recovered varies according to disturbance type, forest biome, and ecozone. We evaluated recovery according to the rate of change associated with forest structural attributes: canopy cover, tree height, stand basal area. In general, we found that within 5–10 years following stand-replacing disturbance, stands had attained a minimum 10% canopy cover and 5 m height. At this stage, many functional traits of forests are likely also returning (e.g., NPP; Hicke et al., 2003). In contrast, recovery of basal area (benchmarked at $10\ m^2\ ha^{-1}$) after wildfire or harvest took 20–30 years (Table 3), relating information on structural recovery that is indicative of the forest returning to its pre-disturbance state. It is noteworthy that the recovery rates estimated from the plot-based studies in Canada's forested ecosystems were largely consistent with the post-wildfire recovery rates of 5–8 years estimated from remotely sensed data sources (Goetz et al., 2006; Jones et al., 2013; Ireland and Petropoulos, 2015).

Remote sensing approaches provide an opportunity to assess post-disturbance recovery over large spatial extents and a range of disturbance types, when guided by a strong ecological understanding of the factors that may influence the recovery process within the area in question, and when accompanied by a clear definition of recovery and how it is being measured. In particular, the increased application of time series analyses to Landsat data provides unique opportunities to characterize forest recovery retrospectively, providing a long baseline for ongoing and future monitoring efforts. Plot data are a critical component of any remote sensing approach and provide important calibration and validation data for analyses.

9. Conclusion

Advances in remotely sensed data availability and processing methods have created a new capacity to characterize forest recovery post-disturbance using dense time series analyses. While the dynamics of Canada's forests following disturbance has been the subject of active research for many years; there remains a dearth of quantitative information and synthesis concerning rates of recovery across many of Canada's forested ecosystems. The same scenario is true for many forest nations. Moreover, definitions of recovery from a forest management or ecological perspective are somewhat ambiguous, further complicating the characterization and measurement of an already complex phenomena. The present study offers clarity on terminology, illustrates the importance of understanding forest recovery rates, and provides baseline information of the trends across Canada's forests. Our review identifies many research initiatives with regard to forest stand dynamics, such as the need for a baseline definition of forest recovery to facilitate characterization of land cover transition and vegetation regrowth patterns following disturbance. The majority of studies on post-disturbance stand dynamics have relied heavily on field campaigns. However, there is notable lack of information on forest structural attributes that are important to characterizing forest recovery. Measures such as canopy cover are not typically captured or are overlooked in many field-based sampling efforts. With the rapid development of remote sensing capabilities, it is becoming increasingly possible to obtain some of this relevant information with which to augment field-based measurements. The applicability of remote sensing to characterizing forest recovery in recent years has been instrumental to eliminating some of the bias introduced by disturbance type, dominant tree species, and abiotic factors in interpreting and classifying land cover transitions following disturbance.

We recognize the applicability of emerging remote sensing technologies for the study of forest recovery patterns; however, all studies on post-disturbance dynamics of forest ecosystems are in great need of field campaigns. The results of this study, obtained from quantitative analysis of empirical field studies across Canada, reflect the intensity of research efforts and information available on the subject. For the most part, our ability to quantitatively predict forest recovery times was constrained by data availability. Our study nonetheless can serve as a benchmark for addressing variability in recovery rates following harvest and wildfire in the various terrestrial ecozones of Canada. Such information is necessary to inform studies that will undoubtedly take advantage of the potential offered by dense time series analyses using remotely sensed data to characterize forest recovery post-disturbance over large areas. Our analysis approach could likewise be applied in other forest environments using available field data to obtain the necessary baseline information to inform and support subsequent large-area remotely sensed investigations of forest recovery. The context we have provided in this review is useful for bridging the conceptual understanding of forest recovery from an ecological or forest management perspective, with theories of spectral recovery offered by remote sensing approaches.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2015.11.015.

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