



Change in forest condition: Characterizing non-stand replacing disturbances using time series satellite imagery

Nicholas C. Coops^{a,*}, Chen Shang^a, Michael A. Wulder^b, Joanne C. White^b, Txomin Hermosilla^b

^a Integrated Remote Sensing Studio, Department of Forest Resources Management, Faculty of Forestry, University of British Columbia, 2424 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada

^b Canadian Forest Service (Pacific Forestry Centre), Natural Resources Canada, 506 West Burnside Road, Victoria, British Columbia V8Z 1M5, Canada



ARTICLE INFO

Keywords:

Time series
Landsat
Land cover
Land use
Disturbance
Insects, drought

ABSTRACT

Objective information is required to monitor and characterize disturbances and disturbance regimes as related to changing climate and anthropogenic pressures. Forest disturbances occur over a range of spatial and temporal scales, with varying extent, severity, and persistence. To date, most of our understanding of detecting forest disturbances using remotely sensed imagery has been based on detecting abrupt and rapid, stand replacing disturbances, such as those related to wildfire and forest harvesting. Conversely, more continuous, subtle, and gradual non-stand replacing (NSR) disturbances, such as those related to drought stress or insect infestation have been subject to less focus. This can be attributed to the variability of NSR in space and time, as well as detection difficulties due to their often-subtle alterations to forest canopies and structure. Time series remote sensing techniques offer new opportunities for the capture and characterization of NSR disturbances. In this research, we investigate NSR disturbances as detected using a Landsat time series-based disturbance detection algorithm, Composite2Change (C2C) applied to the 650 Mha forested ecosystems of Canada. We first examined three key characteristics of the spectral trajectory of NSR disturbances: pre-disturbance conditions, disturbance severity and disturbance persistence. From these characteristics, we defined seven typical NSR patterns (exemplars) for Canada's forested ecosystems. Using annual information on predicted stand-level cover and biomass, we found that all NSR exemplars resulted in a loss of canopy cover, ranging from an average loss of between 5 and 31%. For instance, the most common exemplar was linked to a 15% reduction in canopy cover and a 13 Mg/ha reduction in biomass. While stands lost biomass, over the duration of the NSR, most stands increased slightly in stand height likely due to growth of the remaining trees or release from competition from the remaining stems. Comparing exemplars across Canada with independent data on NSR disturbance events confirmed that NSR exemplars that had larger severities, and shorter disturbance persistence times, were more commonly associated with insect infestations (e.g. mountain pine beetle (*Dendroctonus ponderosae*) and spruce budworm (*Choristoneura fumiferana*)), whereas exemplars with a lower severity, and longer persistence were more commonly associated with drought events. Developing a nomenclature around remote sensing based characteristics of NSR disturbances provides an approach to both map NSR disturbances and better understand their impact on forest attributes, as well as provide tools to assess if these disturbances are changing over space and time.

1. Introduction

Terrestrial disturbances are the major driver of vegetation dynamics and significantly impact the distribution, abundance, composition and structure of species by changing fluxes of water, energy and nutrients (Cohen et al., 2016). For example, the recent mountain pine beetle (*Dendroctonus ponderosae*) outbreak in British Columbia, Canada, has shown to not only significantly impact timber supply but also to have severe impacts on water quality, aquatic habitat for fish species and

short term negative effects on nutrient cycling (Dhar et al., 2016). Disturbances can occur over a range of spatial and temporal scales, and vary by severity and length of the time of impact on vegetation (Kennedy et al., 2014). As a result, the composition and distribution pattern of vegetation today is a function of both continuous, subtle, and gradual disturbance forces, as well as a discontinuous, often catastrophic, and sudden disturbances acting in concert to impact the vegetated landscape (Oliver & Larson, 1996). These are also commonly described as press versus pulse events respectively in ecological

* Corresponding author.

E-mail address: nicholas.coops@ubc.ca (N.C. Coops).

<https://doi.org/10.1016/j.foreco.2020.118370>

Received 12 April 2020; Received in revised form 28 May 2020; Accepted 26 June 2020

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disturbance theory (Bender et al., 1984). Regarding forested environments, lower severity disturbances occurring over long periods of time will manifest different impacts on the stand than more severe disturbances. Forest structure, such as height, cover and above ground biomass, will differ depending on the type of disturbance, with stand replacing disturbances leading to pioneer species quickly regenerating through a resiliency to disturbance while subtle, long-term disturbances often lead to a more variable stand structure with both residual conditions and new regeneration influencing stand conditions (Peng et al., 2011).

There is increasing evidence that the rate and extent of terrestrial disturbances are increasing globally under a changing climate and modification of landscapes by anthropogenic forces (Van Mantgem et al., 2009). Changing climate specifically has been linked to increasing rates of vegetation disturbances and mortality, promoting major changes in the condition of forest and woodland ecosystems (McDowell et al., 2015) with studies suggesting that warming is associated with increased physiological stress causing elevated mortality of tree and woodland species (Breshears et al., 2005; Carnicer et al., 2011). Patterns of land use change have also been attributed to changes in disturbance regimes with, for example, forest management leading to active fire suppression and longer rotation ages (Oswalt et al., 2014) potentially increasing forest fire extent and severity (Westerling et al., 2006). Similarly, anthropogenic actions through management have also altered the interactions between insects and forests, resulting in more widespread insect outbreaks (Senf et al., 2017).

If a management aim is to mitigate or adapt to the impacts of changing disturbance regimes, it is much easier to do so if the type of disturbance and its likely impacts on the stand condition are known before hand (McDowell et al., 2015); however, to do so requires an understanding of where and when these disturbances are occurring. To date, however, most of our understanding of forest disturbances, particularly non-stand replacing (hereafter NSR) disturbances come from targeted monitoring efforts that produce regional estimates, often over broad spatial scales, that are challenging to compare and synthesize across different disturbance agents, regions, and time periods (Hall et al., 2016). Field surveys for example, through national or jurisdictional (state or provincial) forest inventories often provide limited information on the disturbance patterns as they are undertaken at discrete periods of time where the dynamic nature of the disturbances are not well captured, and may or may not be located where NSR disturbances are present. For example, the effect of drought on the condition of a stand is not recorded as part of a standard forest inventory survey, nor is the duration or the severity of the drought known to the forester at that time. Likewise, wind throw events are not recorded or mapped explicitly as part of an inventory. Aerial overview surveys as undertaken by forest management agencies do provide for more frequent data collection than plots, with an aim to identify what disturbances are ongoing (most often in relation to forest health) and to capture, in a general sense, where these disturbances are located on the landscape. These strategic overview surveys provide a rapid means for visual capture and provision of information to enable high-level decision making and to guide or target field-based assessments. However, known shortcomings related to spatial location, attribution, and severity, limit the utility of these strategic overview surveys in spatial analyses, motivating the application of remote sensing as an alternate data source (Cohen et al., 2016; Kennedy et al., 2014; Senf et al., 2015; Wulder et al., 2006a,b,c).

Our ability to detect and map forest disturbances using satellite based remote sensing approaches has been greatly enhanced by advances in open and freely available (Woodcock et al., 2008; Zhu et al., 2019) and increasingly analysis ready satellite data products (Dwyer et al., 2018). The Landsat satellite program provides spatially exhaustive observations of the globe and when analysed using time series based approaches are able to quantify diverse patterns and dynamics of land cover and land use change over past decades (Cohen and Goward,

2004; Hansen et al., 2013; Hermosilla et al., 2018; Wulder et al., 2019). However, while observations from the Landsat satellite record have been shown to be highly applicable to detect and map forest disturbances (Hansen & Loveland, 2012), their detection reliability tends to depend on the severity of the disturbance events themselves (Coops et al., 2006). High-severity, short-duration disturbances, which are often stand replacing, such as fire and clear-cut harvesting, facilitate more straightforward detection as they result in a near complete removal of vegetation from the landscape and hence have a markedly different spectral signature over time (Gong & Xu, 2003). By comparison, disturbance events which happen (comparatively) slowly over time such as insects and pathogens, ice, hail, drought (Gong & Xu, 2003), and some management activities such as thinning are more difficult to detect, partly due to more subtle and gradual changes in the spectral responses, but also due to the highly variable way in which these disturbance impact the stand, with both the degree of severity and the persistence varying depending on the driver of the change (Coops et al., 2006; Jarron et al., 2017). As a result, spectral trajectory based methods are designed to detect linear or more complex (i.e. sinusoidal) trajectories from the spectral values over time, and assess the degree of variation from that trajectory in order to define a disturbance event (e.g. LandTrendr (Kennedy et al., 2010), BFAST (Verbesselt et al., 2010), and CCDC (Zhu and Woodcock 2014)). More severe disturbances result in distinct variations in the spectral response, and as a result these are often manifest as more defined temporally and spatially discrete disturbance events. Verification of these approaches is often undertaken, at least initially, on these more severe disturbance events as they are both easier to detect and in many cases there are corresponding forest inventory or land management records which can be used for validation. While all of these approaches are also capable of detecting lower severity, NSR disturbances, less emphasis has been placed on what might drive these disturbance events and analysis of if different lower severity disturbance events have similar trends within the spectral trajectories. This can inform on both improving methods to detect NSR disturbances, as well as offer insights into the spatial location and duration of these events over the landscape.

In this study, we focus on the characterisation of NSR disturbances that are typified by some form of canopy stress and/or decline. NSR disturbances involve more subtle spectral changes due to an incomplete loss of foliage or leaf area associated with a change in vegetation condition or structure, rather than a change in land cover. To do so, we conduct a comprehensive analysis of the treed area (> 350 million ha) found within Canada's forest dominated ecosystems. We use a time series-based disturbance detection algorithm, Composite2Change (C2C, Hermosilla et al., 2016) which utilises annual pixel composites generated from optimal pixel observations from all available Landsat imagery (Hermosilla et al., 2015a; White et al., 2014a,b) at 30-m spatial resolution since 1984. The C2C approach builds spectral trajectories for each pixel which describe variations in annual spectral indices and through modelling, identifies a number of change elements relating trends, including pre-disturbance spectral values, magnitude of change (i.e. severity), and persistence. We examine these trends over the 30+ year record of NSR disturbances to determine if changes in the spectral trajectories associated with NSR disturbances can be characterised broadly, across space and time, into a series of exemplary behaviours. Once NSR exemplars are defined we assess the characteristics of the forested vegetation prior to the NSR disturbances using other available comprehensive datasets on forest structure, and the relative occurrence and spatial pattern associated with the NSR exemplars across Canada. We finally determine and share insights by examining the temporal patterns of the NSR exemplars in terms of likely underlying biotic or abiotic drivers of disturbance across Canada's forested ecosystems.

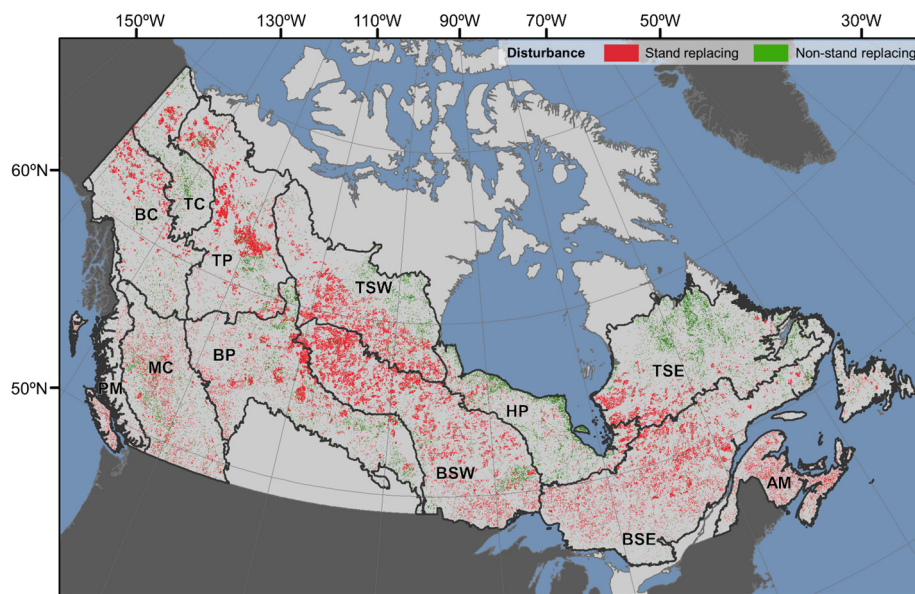


Fig. 1. Distribution of stand replacing and non-stand replacing (NSR) disturbances over treed vegetation from 1985 to 2015 in Canada's forest dominated ecozones as detected by the Composite2Change (C2C) algorithm. Ecozones' acronyms: Atlantic Maritime (AM), Boreal Cordillera (BC), Boreal Plains (BP), Boreal Shield East (BSE), Boreal Shield West (BSW), Hudson Plains (HP), Montane Cordillera (MC), Pacific Maritime (PM), Taiga Cordillera (TC), Taiga Plains (TP), Taiga Shield East (TSE), and Taiga Shield West (TSW).

2. Study area and data

2.1. Canada's forested ecosystems

Canada's forested ecosystems occupy ~650 Mha, or 65% of Canada's total area (Wulder et al., 2008a,b,c), comprising a combination of trees, shrubs, wetlands, and lakes, with treed and other wooded lands reported as occupying 347 Mha (Natural Resources Canada, 2018). Over the 31 years analyzed—from 1985 to 2015, a total of 18.3% of Canada's net forested ecosystem area experienced disturbances (Hermosilla et al., 2019). Previous compilations of provincially acquired disturbance data suggests that insects alone impact an estimated 16.6 Mha on average each year with varying defoliation or mortality effects from trace level of defoliation to severe levels and mortality (<http://nfdp.ccfm.org/en/index.php>). We used Canada's forest dominated ecozones to guide our analysis of the variations in NSR disturbances (Ecological Stratification Working Group, 1996; Stinson et al., 2011). Fig. 1 provides an overview of the NSR and stand replacing disturbances over the forested ecosystems of Canada, over the entire 31-year analysis period.

2.2. Non-stand replacing disturbance information

Pixels identified as experiencing a NSR disturbance were detected using the Composite2Change or C2C approach (Hermosilla et al., 2016). In brief, scoring functions were defined to rank and identify seasonally optimum pixel observations (White et al., 2014a,b) from all available atmospherically-corrected Landsat images (Masek et al., 2006; Schmidt et al., 2013) acquired between 1984 and 2016. These composites were further refined by removing anomalous spectral observations (e.g., noise due to unscreened cloud, shadow, smoke, and haze) using a spike detection algorithm (Kennedy et al., 2010), and by infilling data gaps (due to a lack of suitable observations) with synthetic proxy values informed by the temporal trend and change characteristics present for each pixel (Hermosilla et al., 2015a). Temporal trends and changes were identified using a bottom-up breakpoint selection algorithm (Keogh et al., 2001) over Normalized Burn Ratio (NBR) values (Key & Benson, 2006). Temporal trends with negative slopes represent disturbances in vegetation and are identified as changes between 1985 and 2015 (i.e., no change events are detected the first and last years of the time-series). Detected changes were attributed as either stand replacing (which included fire, harvest, and roads) or NSR disturbance based on their spectral, temporal, and geometrical characteristics using

a Random Forests model in an object-based framework according to the change hierarchy introduced in Hermosilla et al. (2015b). Only stand replacing disturbances were further typed by causal agent (i.e., fire, harvest and road) following a change type labelling hierarchy. Pixels classified as NSR disturbance remained untyped to a causal agent. An independent validation of the outcomes was conducted via photointerpretation for the period 1985–2011 using as main reference sources Landsat composites, high spatial resolution imagery from Google Earth, and ancillary change information sources (e.g., Canadian National Fire Database, and regional spatial coverages depicting insects). The results indicated an overall accuracy of 89% on the change detection and an overall accuracy of 92% on the attribution of changes to a change type. In 89% of the cases the year of change occurrence was correctly identified, and 98% within a ± 1 year range (Hermosilla et al., 2016). Of the samples, 84% allocated in NSR disturbances were satisfactorily detected as change. The attribution of NSR disturbances achieved a user's accuracy of 86% and a producer's accuracy of 96%. We extracted all NSR disturbances from the dataset occurring between 1985 and 2015 and restricted our analysis to pixels within the treed classes derived from the land cover maps (Hermosilla et al., 2018).

2.3. Land cover and forest structure data

Land cover information was extracted from the Virtual Land Cover Engine (VLCE) framework described in Hermosilla et al. (2018). The VLCE framework initially produced annual land cover maps using the Landsat composites described in Section 2.2 combined with topographical data (Tachikawa et al., 2011) using a Random Forests classifier. These initial annual maps were post-processed to reduce spurious class transitions by integrating change information, land cover transition likelihoods, and year-on-year class membership likelihoods. The map legend comprises 12 land-cover classes, including non-vegetated (i.e., water, snow/ice, rock/rubble, exposed/barren land), vegetated non-treed (i.e., bryoids, herbs, wetland, shrubs), and treed-vegetation (i.e., wetland-treed, coniferous, broadleaf, mixedwood).

We obtained wall-to-wall, 30-m resolution, structural information from Landsat-derived forest structural layers implemented as per (Matasci et al., 2018a; Zald et al., 2016) and generated annually representing conditions present from 1985 to 2015 (Matasci et al., 2018b). To do so, estimates of forest structure were derived from seven airborne laser scanning (ALS) collection campaigns, the primary one being a national campaign of 34 transects totaling 25,000 km (Wulder et al., 2012). From these datasets, we derived ALS metrics of height and

canopy cover, as well as area-based modelled inventory estimates of biomass (amongst others). A k-NN imputation approach was developed using a Random Forest-based distance metric with topographic and Landsat spectral predictors to extrapolate these ALS metrics over the forested ecosystems of Canada, at a 30-m pixel resolution from 1984 to 2016. Models were validated using reserved validation plots, with model R^2 ranging from 0.62 to 0.71 for ALS metrics. Model extension through time was evaluated at the forest stand-level using independent ALS data representing a latitudinal gradient of forest conditions and that was not used in model development with R^2 values ranging from 0.36 to 0.77.

3. Methods

3.1. Conceptual approach

The temporal trajectories associated with NSR disturbances were characterised using three key attributes, namely the initial pre-disturbance spectral value, the severity or magnitude of change, and the persistence of the spectral change over time (Hermosilla et al., 2015a). The initial spectral value (in this case NBR) is prior to the commencement of the disturbance and is indicative of the amount of standing vegetation in the pixel in the year prior to the disturbance. The severity or magnitude is the change in the NBR value associated with the disturbance event from the year of commencement to the year in which the disturbance ends (defined when the fitted segment trajectory ends, and a new segment begins). Lastly, the persistence or duration is the time between the initial and the end year of the disturbance. In Fig. 2 we show how a hypothetical NSR disturbance spectral trajectory is expected to vary in response to a range of disturbance agents. Drought may have a greater severity and shorter-term impact on productive forest conditions than, for example, a defoliation event. Defoliation events may be expected to exhibit a more gradual and have a longer persistence impacting the overall condition of the stand over an extended number of years. In contrast, based upon an understanding of the disturbance agent, such as bark beetles, there could be an expectation of a more immediate initial impact on the trajectory, with differing levels of severity associated with different stages of attack ultimately killing individual trees, but not completely killing all trees in a stand. Pathogens such as fungus may impact the stand initially with some degree of severity, and then the impact will reduce as the stand builds defences against the infestation and may, after a period of persistence, ultimately recover.

3.2. Clustering

Due to the relatively low occurrence of NSR disturbances across the large expanse of the forested ecosystems of Canada we first produced a heat map to more clearly locate areas of NSR disturbance hotspots from 1985 to 2015. To do so, we imposed a 50-km tessellation over the 30-m Landsat cells and counted the occurrence of NSR disturbances within each grid cell over the analysis period. We used two-stage multivariate clustering to develop groups of pixels with similar trajectory behaviour. The first step generated pre-clusters, and this was followed by agglomerative hierarchical clustering on the centroids produced by the k-means pre-clustering step. Multivariate agglomerative clustering is one of the most common quantitative processes to derive clusters representing ecological regionalisations (Snelder et al., 2010) and the two-stage approach has been successfully applied for ecosystem-related classification in Canada (Coops et al., 2009; Fitterer et al., 2012; Guo et al., 2017; Thompson et al., 2016) and elsewhere (Hargrove & Hoffman, 2005). To build the clusters, we utilised a stratified subset of 10% of pixels per ecozone across Canada of NSR disturbances occurring over treed areas to ensure a strong representative, longitudinal representation. Using the three key attributes of change (pre-disturbance spectral value, severity, and persistence) we initially developed 100 classes and then selected a reduced number of clusters based on the dendrogram to focus upon a smaller number of numerically representative trajectory exemplars.

3.3. Exploration of response data

In order to examine patterns of NSR disturbances over the forested ecosystems of Canada, we utilized three independently derived datasets of forest condition change over time. Two of these datasets were acquired through provincial Aerial Overview Surveys (AOS; also known as sketch maps) from western and eastern Canada. AOS are designed to provide rapid regional or province-wide assessment of forest health conditions (Wulder et al., 2006a,b,c), and are undertaken visually by trained operators from either aircraft or helicopter platforms and are designed to survey the maximum possible area and facilitate rapid dissemination of that information to forest managers (Wulder et al., 2006a,b,c). In western Canada, the AOS captured the location, extent, and severity of mountain pine beetle (*Dendroctonus ponderosae*) damage. Severity classes included trace, light, moderate, severe, and very severe. While mountain pine beetle infestation typically leads to mortality in individual host trees, and has impacted large swaths of lodgepole pine (*Pinus contorta*) forests in British Columbia, it does not kill

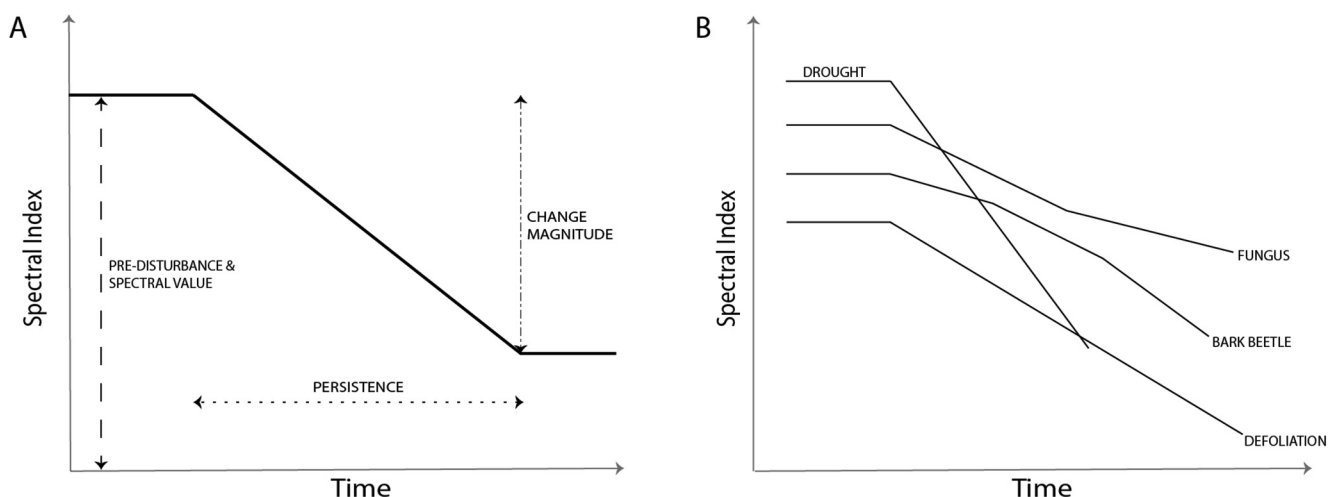


Fig. 2. (a) Schematic diagram of the three key attributes extracted from the spectral trajectory for a pixel that has experienced a NSR disturbance and (b) expected behaviours of various NSR disturbances and their impact on the spectral trajectory over time.

every tree in the stand. Trees of insufficient size, or other species in many cases persist in the stand following a mountain pine beetle attack and once the susceptible pine in the stand has been killed, these other species, or younger pine age classes remain and in some cases increase their growth rates in the stands (Meyer et al., 2017). We used annual AOS data from 1999 to 2008, encompassing the beginning to the end of the major mountain pine beetle outbreak in British Columbia and focused on areas identified as severely or very severely impacted (<https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-health/aerial-overview-surveys/data-filesREF>) to produce a cumulative severity attack map across the region. The eastern Canada AOS dataset informed predominately on the spruce budworm (*Choristoneura fumiferana*) outbreaks. The spruce budworm does not generally kill an individual tree unless severity is extreme, however repeated annual defoliation has been found to increase mortality. Generally, the stand-level impact of defoliation is to reduce tree growth, stand vigour, and diameter increment (Baskerville & MacLean, 1979). AOS data on spruce budworm were classed into five levels of severity, similar to that of the AOS data for mountain pine beetle datasets, and represented the period 1992 to 2016 (<https://www.donneesquebec.ca/recherche/fr/dataset/donnees-sur-les-perturbations-naturelles-insecte-tordeuse-des-bourgeons-de-lepinette>). Lastly, we used broad-scale maps on regional monthly drought anomalies over Canada for the past 15 years to locate areas of prolonged lower than average precipitation. Areas are identified based on monthly climate observations and placed in a five-class scale from highly above average to highly below average (<http://www.agr.gc.ca/atlas/data/donnees/cli/canadianDroughtMonitor/shp/areasOfDrought/>). We combined the monthly anomalies over the time period to assess cumulative drought. While precipitation anomalies are common across most forested ecosystems regions, anomalies in northern Alberta were clearly evident as having seen markedly reduced precipitation from 2003 to 2007 with lower anomalies continuing until 2015, which is known to increased stress in both the tree and shrub vegetation in these environments (Bonsal et al., 2011). Fig. 3 shows the spatial distribution of these three datasets over their specific regions of impact across Canada.

3.4. Assessment of forest structural changes associated with NSR

To assess the impact of the NSR disturbances on the overall condition of the forest stands, we utilised the annual forest structure layers representing the forest regions of Canada (Matasci et al., 2018a). We extracted the stand height, cover, and aboveground biomass the year before the beginning of the NSR disturbance and again at the end of the detected disturbance (year at the end of the disturbance persistence) to provide a mean change in height (m), cover (%) and biomass (Mg/ha) associated with each of the NSR exemplar behaviours.

4. Results

As NSR disturbance rates are relatively low, at around 5% per year of Canada's net forested ecosystem area. The 50-km tessellated heat map shows information on the spatial distribution of the NSR disturbances across the forested ecozones of Canada over the entire 31-year analysis period. As Fig. 4 shows, NSR disturbances are detected broadly across the entire country. More spatially clustered areas of greater NSR occurrence are in the Montane Cordillera, Boreal Plains and Taiga Shield West in the west, and Hudson Plains and Taiga Shield East in the east. Comparatively there are less NSR disturbances along the southern coasts in the Atlantic Maritime and Pacific Maritime and in the south-east, more mixedwood, environments of the Boreal Shield East. Overall, the Mountain Cordillera had proportionally the most NSR disturbance, with over 25% of the area influenced by NSR disturbances being attributed to this particular ecozone over the 31 years. In contrast, the Pacific Maritime and Atlantic maritime ecoregions exhibited the least NSR disturbance over the time period covering less than 3% of

the area.

Clustering of the three key attributes of change (pre-disturbance spectral value, severity, and persistence) resulted in 100 classes which we reduced to seven numerically representative trajectory exemplars based on a logical cut off of 4.3 on the dendrogram. Each of the 100 classes, grouped into seven NSR exemplars is shown in Fig. 5 and indicates that Exemplar 1 consists of a single cluster of pixels, whereas Exemplars 2, and 4–7 have large numbers of sub-clusters with similar behavior.

The overall behavior of each NSR exemplar mean is shown in Figs. 5 and 6. For example, Exemplar 1 is characterized by a relatively moderate length of persistence compared to all of the other exemplars, yet has the highest pre-disturbance spectral value and severity. In contrast, Exemplars 5 and 6 are more indicative of a gradual change, which have a longer persistence of 8–10 years and a lower severity, suggesting a less dramatic disturbance event. Exemplar 3 indicates a very slow gradual disturbance event, persisting over a long period of time, up to 20 years.

The spatial location of the NSR exemplars across the forested ecozones of Canada is shown in Fig. 7. Areas dominated by Exemplar 6 are grouped in the northern forested regions of Canada. Exemplar 7 is consistently distributed over the entire forested regions, except for the Boreal Shield. Exemplar 2 occurs solely in the west. In contrast, Exemplars 1 and 3 have limited geographic coverage and never dominate a 50-km cell. The mean and variation of each of the three key attributes of each exemplar is presented in Fig. 8 and demonstrates how, when combined, each exemplar offers different insights into the behavior of the disturbance event itself. Generally, Exemplar 1 is the most variable, unsurprisingly as it was a single cluster at the 100-cluster stage, and is found to occur in stands with high pre-disturbance spectral values, with high severity, and short persistence when references against the other NSR exemplars. In contrast, Exemplars 3 and 4 show similar pre-disturbance spectral values and severity but with Exemplar 3 having a long persistence and Exemplar 4 have a shorter persistence.

Overall Exemplars 7, 4, 6, 5 and 2 were the most common across Canada respectively while Exemplar 1 was the least common (0.01 Mha, Table 1). Exemplars 7, 4, and 6 represented 1.70, 1.66, and 1.47 Mha respectively, while 2 and 5 had more similar areal extents covering 0.66 and 0.84 Mha respectively. While more abundant than Exemplar 1, Exemplar 3 was relatively low in areal coverage at 0.05 Mha. Proportional to the predicted forest cover types, as Canada is dominated by coniferous forest types, forest type with the most NSR disturbance was coniferous forest stands (Fig. 9a). Proportionally, however, the second most dominant cover type experiencing NSR disturbances is treed-wetlands, which is impacted more by NSR disturbances than its proportion across the landscape would suggest. In contrast both broadleaf and mixed-wood vegetation types have very low amounts of NSR disturbances, especially relative to the amount of area they occupy on the landscape. While approximately 6.4 Mha of forest stands over the analysis period underwent NSR disturbance, the proportion of NSR disturbance within each ecozone of Canada varied markedly (Fig. 9b).

Forest structural information was extracted from Matasci et al., (2018b) for each pixel classified as NSR for the year pre- and post-disturbance event. Table 2 shows the pre- and post- distribution of ALS metrics and estimated cover and aboveground biomass allowing insights into the change in forest structural condition as a function of the disturbance exemplar. Results indicate that while all NSR exemplars resulted in a loss of cover of the stand level, and in six of the seven caused a loss in aboveground biomass, the majority of stands increased in their height due to growth over the period of the NSR disturbance. As would be expected stands with the largest pre-disturbance spectral value experienced the greatest loss in cover and aboveground biomass and in most cases also suffered an overall reduction in stand height. In contrast, NSR disturbances which had a lower pre-disturbance spectral value had a smaller reduction in aboveground biomass and experienced only slight changes in height, most often with a positive increment over

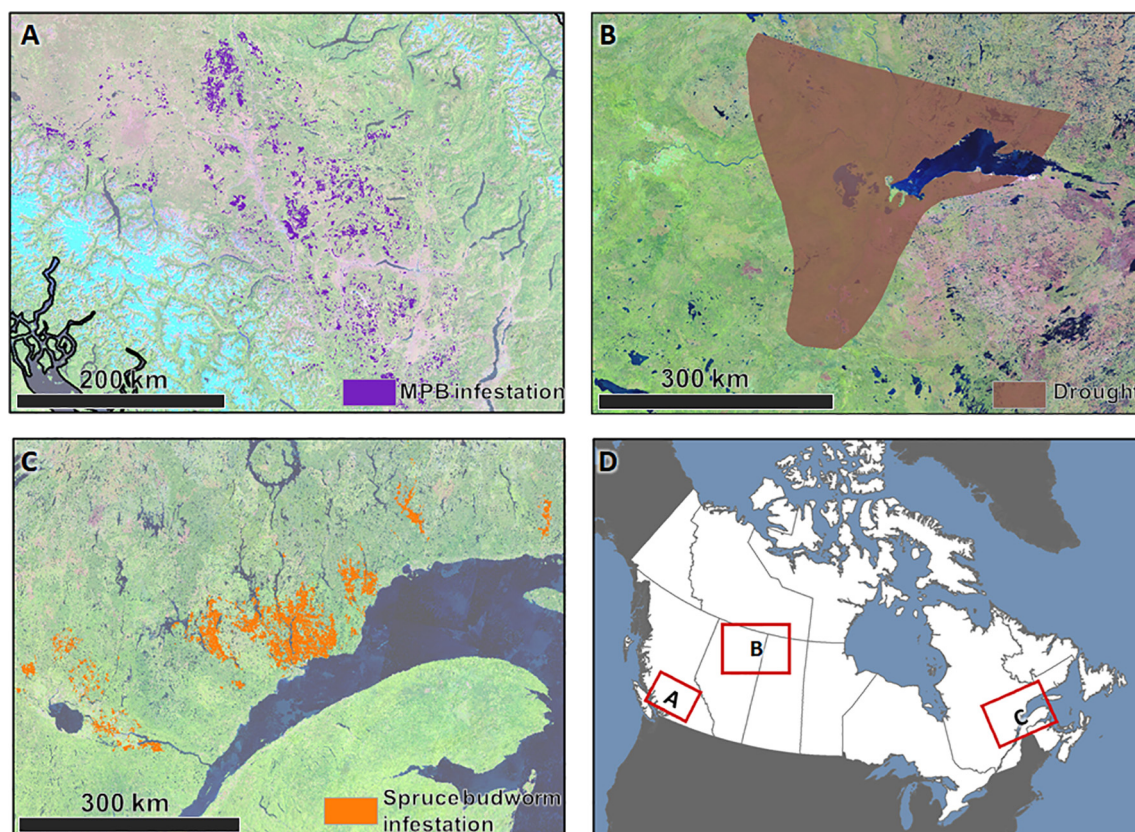


Fig. 3. Location of known areas of forest decline associated with (a) severe Mountain Pine Beetle damage in British Columbia, (b) drought in northern Alberta and (c) Spruce Budworm in eastern Quebec, Canada. Background: Landsat surface-reflectance pixel composite relating 2010 conditions (Red: shortwave infrared band, Green: infrared band, Blue: red band). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the persistence of the NSR disturbance.

Fig. 10 provides some insights into the likely underlying biotic or abiotic drivers of the NSR exemplars the forested ecosystems of Canada. Compared to the proportion of NSR disturbances across Canada we see that Exemplar 7 is more common in areas of known insect and budworm infestation, based on the provincial and federal data sources cited in 2.3. Exemplar 7 is indicative of a higher pre-disturbance value than

many of the other NSR exemplars and has a one of the shortest persistence values of the seven NSR exemplars. The mountain pine beetle infestation in western Canada also shows an increase in NSR Exemplar 6, compared to the overall NSR proportions, which is indicative of a longer persistence NSR disturbance in less productive forests than Exemplar 7. In contrast, the areas impacted by the spruce bud worm also saw a proportional increase in Exemplar 2. Exemplar 2 occurs in highly

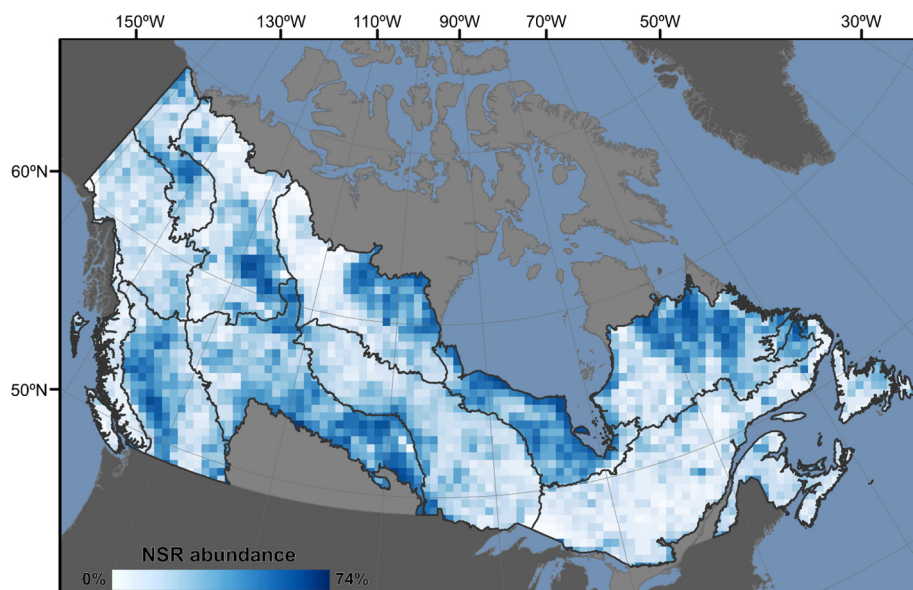


Fig. 4. Heat map with a spatial resolution of 50 km indicating spatial distribution of NSR disturbances across Canada's forested ecosystems from 1985 to 2015.

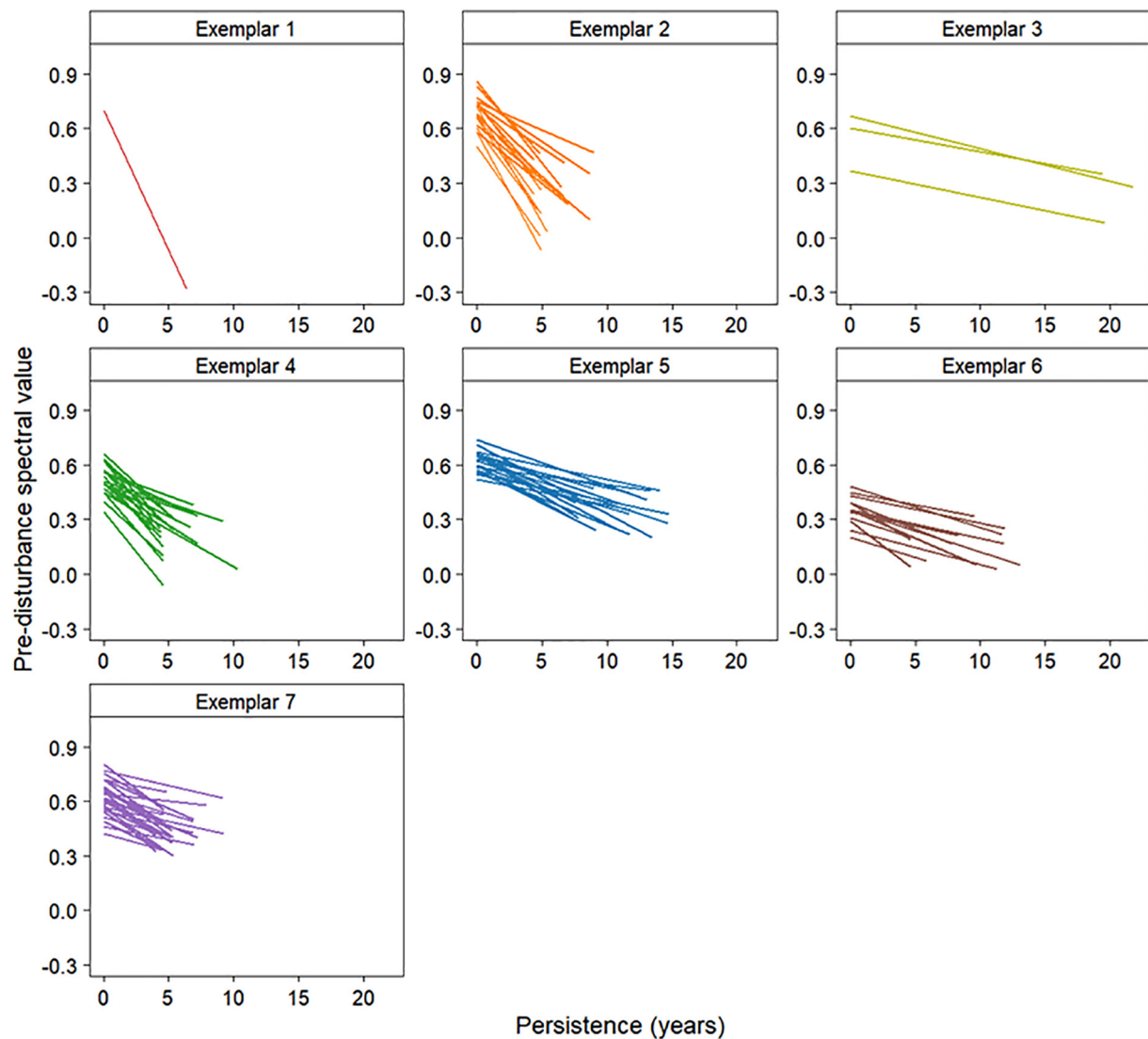


Fig. 5. Clustering of the initial 100 clusters into seven NSR exemplars that characterize the patterns of NSR disturbances over Canada's forested ecosystems.

productive forest and with a higher severity which may be related to initial canopy loss associated with the defoliator, compared to needle stress brought about by mountain pine beetle infestation (from a remote sensing perspective, [Wulder et al., 2006a,b,c](#)). In contrast, the distribution of drought events clearly coincides with the spatial extent of Exemplar 6 which conveys a lower level of severity, over longer persistence, typically evident of boreal drought stress which results in long term reductions in stand condition.

5. Discussion

The attribution of disturbance events to their causal agent is a necessary prerequisite for reporting impacts of forest change ([White et al., 2017](#)), as well as for characterizing forest dynamics, carbon consequences, and sustainable forest management, among others. While stand replacing disturbances in a forestry context are readily detected and attributed, non-stand replacing disturbances are much more challenging to characterize ([Cohen et al., 2016](#)). Recognizing these limits, herein our approach has been exploratory and data driven, whereby we examine the characteristics associated with NSR disturbances in order to determine their unique qualities. In reality, there will be limits to what NSR disturbances can be detected and attributed with Landsat time series data: various NSR disturbance agents have impacts in

different regions of Canada's forested ecosystems (and in some cases multiple factors in the same area such as drought as a precursor of insects). Moreover, different agents in different regions may have similar spectral manifestations. By synthesizing the characteristics of the NSR exemplars, we can start to get a better sense of how, and where, each of these exemplars are occurring across Canada's forests and what their impact is on the overall structure of the forest resource. By relating these exemplars to dominant NSR agents in each of these regions, we gain insights on how these disturbances manifest and inform attribution. We note that these relationships are not causal and at this stage, analyses are exploratory.

The most common exemplar across Canada is Exemplar 7. This exemplar is defined by a relatively short persistence time (< 5 years), low – moderate severity occurring in forest stands with medium pre-disturbance spectral values, implying that this NSR exemplar occurs over shorter periods of time and the change that we see in the condition of the forest is relatively low – moderate impact. This exemplar typically occurs in stands with a moderate pre-disturbance spectral value, which is indicative of moderate cover. When we examine the impact of the exemplar over the landscape we see that it only has a very slight impact on the underlying structure of the forest, as assessed using the available structural layers. This NSR exemplar results in a 15% reduction in canopy cover and a 13 Mg/ha reduction in biomass, and is

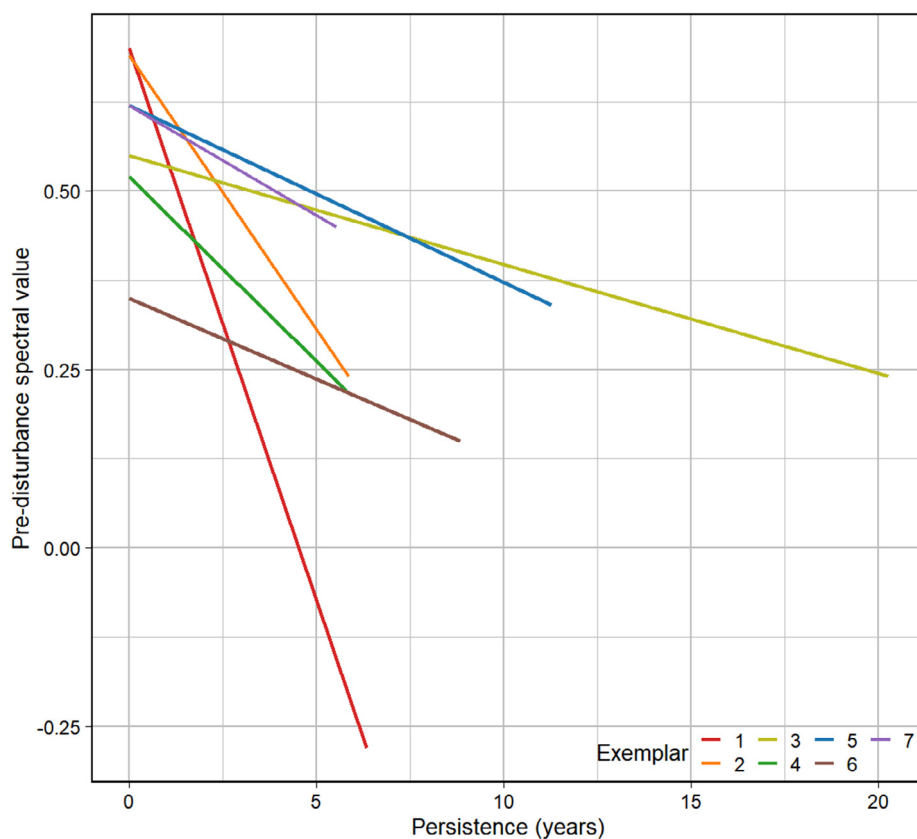


Fig. 6. Overall behavior of the seven NSR exemplars based on the pre-disturbance spectral NBR, severity and persistence.

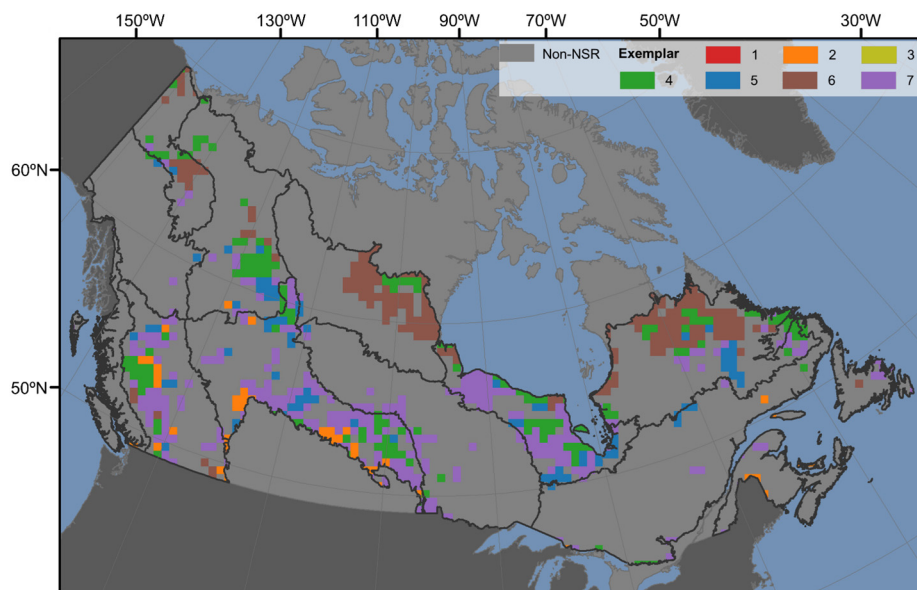


Fig. 7. Spatial distribution of the dominant NSR exemplars across Canada's forested ecosystems. 50-km grid cell size used. Note that due the limited geographic coverage of Exemplars 1 and 3, these never dominate a cell.

associated with a slight increase in height in the stand likely associated with release from competition and/or annual growth. In relation to the spatial pattern of this exemplar, we see it is scattered across the entire Canadian forested ecosystem, occurring in every forested ecozone and across the range of forest types. Comparing AOS spatial information, mountain pine beetle and spruce bud worm extent and severity suggests that this type of NSR disturbance pattern from a remotely sensed spectral signature could be indicative of loss of condition associated

with outbreaks of pests and disease.

Similar trends are found for Exemplar 4, which is also occurring across most of the forested ecozones of Canada. This exemplar is also defined by a short persistence (< 6 years), and low severity but occurs in stands with higher cover based on the higher pre-disturbance spectral values, implying that this NSR happens relatively quickly with low impact confirmed by a 13% reduction in canopy cover and a 14 Mg/ha reduction in biomass. In contrast, Exemplar 6 occurs in specific

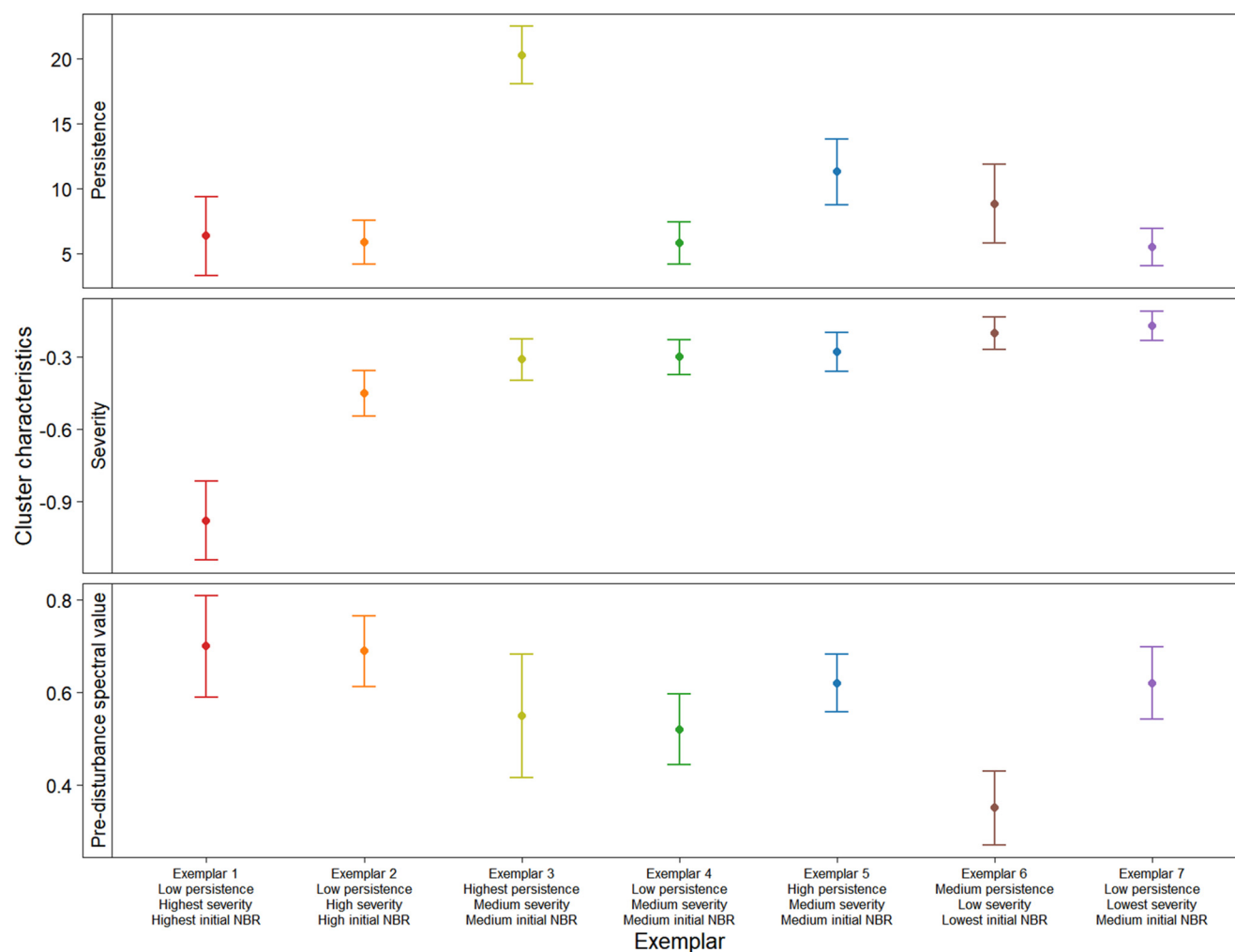


Fig. 8. Overall behavior of each exemplar with respect to the mean and standard deviation of each of the clusters in terms of their pre-disturbance spectral value, severity, and persistence.

Table 1
Areal coverage of NSR exemplars across forested ecozones of Canada.

Exemplar	1	2	3	4	5	6	7	Total
Area (Mha)	0.01	0.66	0.05	1.66	0.84	1.47	1.70	6.4

geographic regions, typically occurring in northern Canada in the Taiga Shield East and West. These areas typically have low cover, and as a result, the pre-disturbance spectral values are low for this type of NSR disturbance. The persistence of Exemplar 6 is moderate, occurring for up to 8 years with moderate severity. As a result, we see small reductions in biomass associated with this exemplar, which is in fact the lowest of all of the exemplars across Canada, with a reduction in cover by 5% and slight increases in biomass and height over the length of the NSR disturbance event. Comparing these patterns to precipitation anomalies suggests that these longer-persistence NSR disturbances may be indicative of a drought response.

A unique response was found on Exemplar 2, with a short persistence (< 6 years) and occurs predominantly in western Canada in the Montane Cordillera and the Boreal Plains, in stands with very high pre-disturbance spectral values, indicating that it impacts stands with high cover. The impact on the structure is also notable with a 30% loss in cover and a 45 Mg/ha reduction in biomass. We also find that the stands will become shorter in response to this disturbance by up to 2 m. As a result, Exemplar 2 is the most impactful on the landscape in terms

of structural impact. We see that some areas of spruce budworm attack in Quebec have proportionally more of this NSR exemplar suggesting focused high levels of attack and severity in some specific forest stands.

While the results presented with respect to changes in height, cover and biomass are consistent with what we would expect with NSR events, these estimates of change however are based on forest structure attributes which themselves are not without error. Extending estimates of forest structure in both time (over a multiple decades) and space (i.e., annually over the complete extent of the Canadian forested ecosystem) is complex and relies on the use of calibrated surface reflectance values from the Landsat series of sensors. While this time-series surface reflectance dataset provides a sound foundation for both detection of NSR and estimation of forest structure (in addition to other geospatial datasets) additional processing is required (such as trajectory fitting). Similarly, the forest structure model development requires the full range of forest structural variability in Canada to be captured which is also unlikely to be the case (Matasci et al., 2018a,b). As a result, there is uncertainty in both the detection of the NSR as well as the characterisation of its impact on forested stands.

The results of the research presented herein mirrors that of other recent studies. For example, the research by Cohen et al. (2016) investigated the emergence of increasing levels of forest decline in the conterminous United States using Landsat imagery. Similar to our findings, the authors report, that NSR disturbances occur due to a variety of different drivers including primary drivers such as hydraulic failure and canopy defoliation, as well as secondary drivers such as a

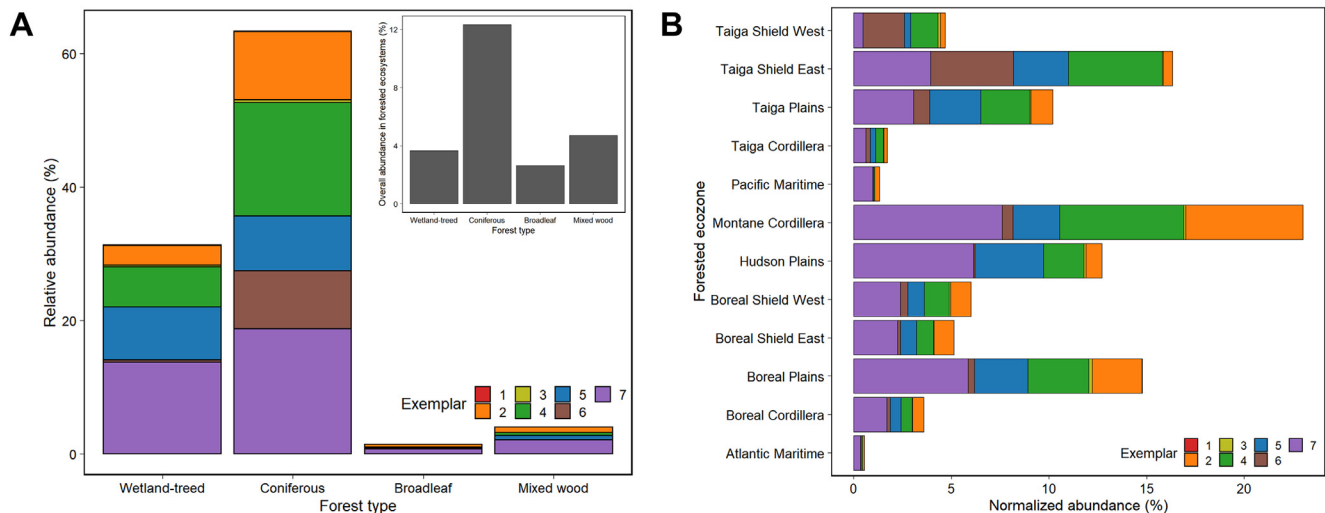


Fig. 9. (a) Occurrence of NSR disturbances by land cover types and (b) forested ecozone.

reduction in production that can predispose a tree to a subsequent insect attack or pathogen. In our analysis of NSR disturbances in Canada's forested ecosystems, we found that a number of exemplars had low or moderate initial NBR, suggesting that these stands, with lower pre-disturbance forest cover as a function of site productivity or water or temperature stress, may be more susceptible to NSR disturbances when compared to stands with larger initial NSR values. The one exception we found to this trend was that of Exemplar 2, which, as noted above was characterized by high pre-disturbance cover coupled with high severity and very short persistence of NSR disturbance. This behavior is likely to be driven more from abiotic conditions, such as drought, than a reduction in condition from biotic factors. Similar to Cohen et al. (2016), we also found that NSR events generally occur over much longer time periods than stand replacing disturbances. For example, Cohen et al. (2016) found the majority of the stands undergoing forest decline in the United States did so for periods greater than five years.

Although we identified pixels from the time series with varying degrees of NSR disturbances corresponding to areas of known forest decline such as insect damage and drought, there are many other areas across the country highlighted as having experienced some degree of NSR for which we have limited records as to what might be the underlying causal agent. One possibility, for example, could be low/moderate severity fires accompanied by delayed mortality. Fire is classified within the C2C nomenclature as a stand replacing disturbance, however in some ecosystems lower intensity fire may also occur. In these cases, substantial canopy structure could remain reducing our ability to consistently detect this disturbance using remote sensing approaches. As a result, this type of disturbance could also

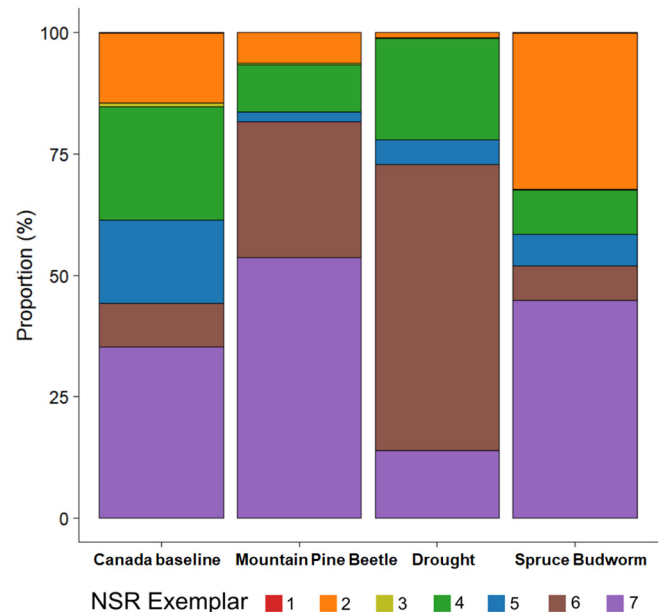


Fig. 10. Proportions of NSR exemplars within each of the known forest damage locations associated with overall proportion of NSR exemplars over the entire Canada's forested ecosystems (baseline) in comparison to mountain pine beetle, drought, and spruce budworm.

Table 2

Average forest structural parameters (as derived from Matasci et al., 2018b) for one year pre- and one year post- NSR disturbances, grouped by NSR exemplar across the forested ecosystems of Canada. Numbers in parenthesis indicate standard deviations.

NSR exemplar	Forest structure											
	Canopy height stddev (m)		Canopy height mean (m)		Canopy height p95 (m)		Canopy height cv (m)		Canopy cover (%)		Total biomass (Mg/ha)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1	2.6 (1.8)	3.0 (1.9)	7.6 (5.2)	9.0 (5.6)	12.0 (7.4)	13.5 (7.7)	0.34 (0.10)	0.33 (0.10)	56.3 (27.2)	25.3 (25.5)	78.0 (85.5)	69.8 (82.7)
2	3.6 (2.4)	3.1 (1.5)	9.8 (6.1)	8.6 (4.1)	15.6 (8.9)	13.5 (5.7)	0.37 (0.14)	0.36 (0.09)	61.0 (26.5)	30.0 (22.1)	109.1 (100.5)	63.4 (61.9)
3	2.5 (1.7)	2.5 (1.4)	7.1 (4.4)	7.4 (3.9)	11.1 (6.2)	11.5 (5.4)	0.34 (0.13)	0.34 (0.08)	42.1 (27.7)	22.6 (20.8)	61.1 (69.1)	50.2 (53.8)
4	2.8 (1.6)	2.6 (1.3)	7.5 (4.2)	7.5 (3.7)	12.2 (6.2)	11.8 (5.0)	0.37 (0.09)	0.35 (0.08)	39.2 (24.4)	25.0 (19.1)	63.1 (63.8)	50.1 (49.6)
5	2.5 (1.7)	2.5 (1.3)	6.7 (4.3)	6.9 (3.3)	10.9 (6.4)	11.1 (4.9)	0.36 (0.10)	0.36 (0.08)	42.2 (27.1)	24.7 (20.1)	60.1 (68.6)	47.1 (45.7)
6	2.1 (1.0)	2.1 (1.0)	6.0 (2.9)	6.3 (3.4)	9.6 (4.2)	9.8 (4.6)	0.35 (0.06)	0.33 (0.07)	26.1 (17.7)	20.9 (19.2)	40.2 (40.8)	41.6 (49.5)
7	2.8 (1.8)	2.8 (1.5)	7.6 (4.7)	7.6 (3.8)	12.1 (7.0)	12.2 (5.5)	0.36 (0.12)	0.37 (0.09)	45.5 (28.3)	30.9 (23.9)	70.3 (75.1)	56.7 (56.5)

likely be classified as NSR and would align with a specific NSR exemplars. Changes in forest condition at a national scale are difficult to assess annually using either plot- or aircraft-based methods due to the vast expanse of forested ecosystems, and the differences in data collection protocols across jurisdictions. As a result, satellite based methods offer one of the most viable sources of data with which to undertake these type of analyses. Moreover, although calibrated, harmonized surface reflectance observations are increasingly available from a number of global satellite programs including Landsat and the European Sentinel program, difficulties using spectral data to accurately detect NSR disturbances exist because the impact of these NSR disturbances on forest conditions are variable across forested landscapes in time and space. Thus, even though subtle changes in spectral condition are detectable, the capacity to reliably classify these in an automated way would require another additional complex step to train an algorithm to reliably classify these disturbances into their underlying drivers.

McDowell et al. (2015) discuss the development of a monitoring approach to detect and classify disturbances and propose several future directions for developing a global satellite monitoring system of climate-induced vegetation disturbances. First, they highlight the importance of linking disturbance-based observations from remote sensing technologies to plot networks. In Canada, we have access to a large number of plots across the country and linking observations of forest decline at the plot scale to satellite based observations of disturbance particularly NSR would be a significant step forward. However, plot measurements of forest attributes rarely includes information on canopy decline and, as these plots are often measured at either 5 or 10 year intervals, short term canopy assessments are difficult. However, the longer persistence times of some of the NSR disturbances highlighted by these exemplars does suggest that re-measurement of canopy conditions at permanent sample plots may provide insights into drivers of NSR disturbances. A second key point highlighted by McDowell et al. (2015) was to encourage the integration of other remote sensing data sets from active remote sensing systems such as radar or lidar, into spectral time series analysis.

In this work we capitalized on the availability of airborne laser scanning data acquired as an opportunistic sample of transect covering Canada's forested ecosystems (Wulder et al., 2012). These transects provide very high-resolution three-dimensional data which allowed prediction of several key forest structural attributes. By using interpolated wall-to-wall layers of these lidar-derived attributes (Matasci et al., 2018b), we were better able to understand the impact of NSR disturbances on both the pre- and post-disturbance stand structure. As a result, we can assess the impact of the exemplar NSR disturbance on forest structure using attributes such as height, cover, and aboveground biomass. Further inclusion of additional potential explanatory factors such as dominant forest species maps and refined land cover representations could also provide more insights into both the likely drivers of the NSR as well as inform NSR exemplar behaviour. This necessitates of course the availability of such data, at fine spatial scale, across larger areas, which as discussed throughout the paper may not exist.

Modification of stand conditions based on the impact of NSR disturbances from individual biotic and abiotic conditions at the tree and plot level is well known (Potter et al., 2003). Most studies recognize that a forest stand undergoing a prolonged stress is first impacted by a reduction in canopy cover. This is consistent with these exemplars with canopy cover consistently reduced by up to 40%. This loss of cover is expected as leaf area, and foliage cover, are the most fragile and easily detected biophysical attribute in forest stands and the most sensitive to change. Likewise, leaf area and foliage cover are the most observable attribute from remote sensing technology and as a result, it is logical that canopy cover is the attribute most sensitive to this change. Over the longer term, NSR disturbances also result in reductions in above-ground biomass with most exemplars identified herein demonstrating a

change in biomass over time, however the proportion of biomass reduction associated with each of these exemplars is less than we see with canopy cover. Also of interest in these results, is an increase in canopy height for approximately half of the exemplars, despite the presence of NSR disturbance. This is likely due to the case that NSR disturbances often only impact a portion of trees within the stand as a result the remaining trees, which are not impacted by the disturbance, are likely to continue to grow, and as a result we see increases in height despite reductions in canopy and overall biomass.

6. Conclusions

Investigating the characteristics of NSR exemplars over the forest ecosystems of Canada can provide key insights into the occurrence, extent, and impact of these disturbances on forested ecosystems. The use of spectral trajectories of forest condition derived from Landsat time series allows these exemplars to be detected and mapped consistently over the breadth of Canada's forest ecosystems. By comparing these spatial and temporal distributions with the extent of known biotic and abiotic disturbance agents such as mountain pine beetle, spruce budworm, and drought, additional insights can be gained into the reduction in forest height, cover, and biomass that these disturbances may be linked to. Developing nomenclature around the remotely sensed characteristics of NSR disturbances, including disturbance severity and persistence as characterized from spectral observations over time, provides new tools to understand impacts of NSR disturbances on forest resources, and changes in those impacts over space and time.

CRedit authorship contribution statement

Nicholas C. Coops: Conceptualization, Methodology, Visualization, Investigation, Visualization, Investigation, Writing - review & editing. **Chen Shang:** Visualization, Investigation, Software, Visualization, Investigation, Writing - review & editing. **Michael A. Wulder:** Conceptualization, Methodology, Visualization, Investigation, Visualization, Investigation, Writing - review & editing. **Joanne C. White:** Conceptualization, Methodology, Visualization, Investigation, Visualization, Investigation, Writing - review & editing. **Txomin Hermosilla:** Conceptualization, Methodology, Visualization, Investigation, Software, Visualization, Investigation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was undertaken as part of the "Earth Observation to Inform Canada's Climate Change Agenda (EO3C)" project jointly funded by the Canadian Space Agency (CSA), Government Related Initiatives Program (GRIP), and the Canadian Forest Service (CFS) of Natural Resources Canada (NRCan). Support also provided by a NSERC Discovery grant to Coops. This research was enabled in part by capacity provided by WestGrid (www.westgrid.ca) and Compute Canada (www.computeCanada.ca). Open access is supported by the Government of Canada. We are grateful to Marie McCallum for assistance with drawing a figure and citation compilation.

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