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REVIEW

A review of natural disturbances to inform implementation of ecological forestry in Nova Scotia, Canada

Anthony R. Taylor, David A. MacLean, Peter D. Neily, Bruce Stewart, Eugene Quigley, Sean P. Basquill, Celia K. Boone, Derek Gilby, and Mark Pulsifer

Abstract: Like many jurisdictions across North America, the province of Nova Scotia (NS) is faced with the challenge of restoring its forests to a more natural, presettlement state through implementation of ecological forestry. At the core of ecological forestry is the idea that natural forest structures and processes may be approximated by designing management practices that emulate natural disturbances. Successful natural disturbance emulation depends on fundamental knowledge of disturbance characteristics, including identification of specific disturbance agents, their spatial extent, severity, and return interval. To date, no comprehensive synthesis of existing data has been undertaken to document the natural disturbance regime of NS forests, limiting the application of natural disturbance emulation. Using over 300 years of documents and available data, we identified the main natural disturbance agents that affect NS forests and characterized their regimes. Overall, fire, wind (predominantly hurricanes), and outbreaks of spruce budworm (*Choristoneura fumiferana* (Clemens)) are the most important disturbance agents, causing substantial areas of low- (<30% mortality), moderate- (30%–60%), and high- (>60%) severity disturbance. While characterization of natural historic fire is challenging, due to past human ignitions and suppression, we estimated that the mean annual disturbance rate of moderate- to high-severity fire ranged between 0.17% and 0.4%·year^{-1} (return interval of 250–600 years), depending on ecosystem type. Hurricanes make landfall in NS, on average, every 7 years, resulting in wide-scale (>500 ha) forest damage. While hurricane track and damage severity vary widely among storms, the return interval of low- to high-severity damage is 700–1250 years (0.14%–0.08%·year^{-1}). Conversely, the return interval of host-specific spruce budworm outbreaks is much shorter (<50 years) but more periodic, causing wide-scale, low- to high-severity damage to spruce–fir forests every 30–40 years. Further disturbance agents such as other insects (e.g., spruce beetle), diseases, ice storms, drought, and mammals can be locally important and (or) detrimental to individual tree species but contribute little to overall disturbance in NS. Climate change is expected to significantly alter the disturbance regime of NS, affecting current disturbances (e.g., increased fire) and driving the introduction of novel agents (e.g., hemlock wooly adelgid), and continued monitoring is needed to understand these changes.

Key words: natural disturbance, ecological forestry, sustainability, fire, wind, spruce budworm, climate change.

Résumé : Comme de nombreuses autorités à travers l'Amérique du Nord, la province de Nouvelle-Écosse (N.-E.) est confrontée au défi de restaurer ses forêts dans un état plus naturel, antérieur à la colonisation, par la mise en œuvre de la foresterie écologique. Au cœur de la foresterie écologique se trouve l'idée que l'on peut se rapprocher des structures et les processus forestiers naturels en concevant des pratiques de gestion qui imitent les perturbations naturelles. L'émulation réussie des perturbations naturelles dépend de la connaissance fondamentale que l'on a des caractéristiques de ces perturbations, y compris l'identification d'agents spécifiques de perturbation, leur étendue spatiale, leur gravité et leur intervalle de retour. À ce jour, aucune synthèse approfondie des données existantes n'a été entreprise pour documenter le régime de perturbations des forêts de N.-E., ce qui limite l'application de l'émulation des perturbations naturelles. En utilisant des documents et des données disponibles couvrant une période de 300 ans, les auteurs ont identifié les principaux agents de perturbation naturelle qui affectent les forêts de N.-E. et caractérisé leurs régimes. Dans l'ensemble, le feu, le vent (principalement les ouragans) et les éclosions de tordeuses des bourgeons de l'épinette (TBS; *Choristoneura fumiferana* (Clemens)) constituent les principaux agents de perturbation, produisant des zones considérables de perturbations de sévérité faible (<30 % de mortalité), modérée (30–60 %) et élevée (>60 %). Bien que la caractérisation des feux historiques naturels soit difficile, en raison des allumages et des suppressions d'origine humaine passés, les auteurs estiment que le taux de perturbation annuel des feux de gravité modérée à élevée se situait entre 0,17 et 0,4 %·an^{-1} (intervalle de retour de 250 à 600 ans), selon le type d'écosystème. Les ouragans touchent terre en N.-É. en moyenne tous les 7 ans, entraînant des dommages forestiers à grande échelle (>500 ha). Bien que la trajectoire d'un ouragan et

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A.R. Taylor. Natural Resources Canada, Canadian Forest Service, Atlantic Forestry Centre, 1350 Regent Street, P.O. Box 4000, Fredericton, NB E3B 5P7, Canada; Faculty of Forestry and Environmental Management, University of New Brunswick, 28 Dineen Drive, Fredericton, NB E3B 5A3, Canada.
D.A. MacLean. Faculty of Forestry and Environmental Management, University of New Brunswick, 28 Dineen Drive, Fredericton, NB E3B 5A3, Canada.
P.D. Neily, B. Stewart, E. Quigley, and M. Pulsifer. Nova Scotia Department of Lands and Forestry, 15 Arlington Place, Suite 7, Truro, NS B2N 0G9, Canada.
S.P. Basquill. Nova Scotia Department of Lands and Forestry, Wildlife Division, 136 Exhibition Street, Kentville, NS B4N 4E5, Canada.
C.K. Boone and D. Gilby. Nova Scotia Department of Lands and Forestry, Forest Protection Division, 23 Creighton Drive, Shubenacadie, NS B0N 2H0, Canada.

Corresponding author: Anthony R. Taylor (email: anthony.taylor@canada.ca).

la sévérité des dommages varient grandement d'une tempête à l'autre, l'intervalle de retour des dommages de sévérité faible à élevée est de 700 à 1250 ans (0,14 à 0,08·an^{-1}). À l'inverse, l'intervalle de retour d'éclosions de TBE spécifiques à l'hôte est beaucoup plus court (<50 ans), mais plus périodique, provoquant des dommages à grande échelle de sévérité faible à élevée aux forêts de conifères tous les 30 à 40 ans. D'autres agents de perturbation tels que d'autres insectes (p. ex. le dendroctone de l'épinette), des maladies, des tempêtes de verglas, la sécheresse ou des mammifères peuvent être importants ou nuisibles à l'échelle locale pour des espèces d'arbres particulières, mais ils contribuent peu à la perturbation globale en N.-E. On s'attend à ce que les changements climatiques modifient de manière significative le régime des perturbations en N.-E., en affectant les perturbations actuelles (p. ex. l'accroissement des incendies) et en facilitant l'introduction de nouveaux agents (p. ex. le puceron lanigère de la pruche), et une surveillance continue est nécessaire pour comprendre ces changements. [Traduit par la Rédaction]

Mots-clés : perturbation naturelle, foresterie écologique, durabilité, feux, vent, tordeuse des bourgeons de l'épinette, changements climatiques.

1. Introduction

Over the past several decades, Canada has begun to shift away from production-based "sustained yield" forestry towards ecosystem-based, "ecological" forestry (Canadian Council of Forest Ministers (CCFM) 2008; Natural Resources Canada (NRCAN) 2018). Ecological forestry is a management paradigm that emphasizes the maintenance of natural ecological conditions to achieve the sustained yield of goods and services for meeting human needs (Christensen et al. 1996; Landres et al. 1999; Davis et al. 2001). The shift towards ecological forestry is critical to maintaining forest biodiversity and mitigating impacts of climate change (Fischer et al. 2006).

At the core of ecological forestry is the idea that natural forest structures, including biodiversity, and functional processes are more likely to persist or be best approximated by designing and applying forest management practices that emulate natural disturbance patterns (Seymour and Hunter 1999; Seymour et al. 2002; North and Keeton 2008). Employing natural disturbance emulation as a basis for ecological forestry was first developed in Europe during the 19th century (Kuuluvainen and Grenfell 2012) but has since gained popularity across Canada (e.g., Lieffers et al. 1996; MacLean et al. 1999; Bergeron et al. 2002). The concept of natural disturbance emulation assumes that structures and functional processes of the "natural" forest reflect historic natural disturbance regimes and other determinants of ecosystem pattern. Accordingly, the success of natural disturbance emulation depends on (*i*) how well defining characteristics of the natural forest are known; (*ii*) how well the natural disturbance regime is known, including disturbance agents, their spatial extent, severity, and return interval; and (*iii*) the degree to which ecological consequences of natural disturbances can be emulated by forest management practices (Seymour and Hunter 1999; North and Keeton 2008; D'Amato et al. 2018).

The province of Nova Scotia, on Canada's east coast, lies within a transition zone between coniferous-dominated boreal forests to the north and temperate deciduous forests to the south and west, resulting in a unique mixture of about 32 tree species (Loucks 1962; Rowe 1972; Saunders 1996). Forests of Nova Scotia have a long history (>300 years) of land clearing, timber harvest, and invasion by non-indigenous species, which has altered the natural species composition and structure of the landscape (Fernow 1912; Johnson 1986; Loo and Ives 2003). Consequently, Nova Scotia's provincial government is under increasing public pressure to return its forests to a more natural, pre-European settlement condition through implementation of ecological forestry (Nova Scotia Department of Natural Resources (NSDNR) 2011*a*; Lahey 2018). In response, forest management policies that support emulation of natural disturbance regimes are now being reviewed, including reductions in clear-cut harvesting and promotion of partial-cutting methods (Nova Scotia Department of Lands and Forestry (NSDLF) 2018). However, while previous efforts to determine natural disturbance regimes in Nova Scotia have been conducted (e.g., Neily et al. 2008), to date, no comprehensive synthesis of existing literature and data has been undertaken to document and interpret Nova Scotia's natural disturbance regimes. This limits the provincial government's ability to implement natural disturbance emulation and ecological forestry.

In this paper, we review and synthesize current knowledge of natural forest disturbance regimes (i.e., agent, extent, severity, and return interval as defined in section 3) in Nova Scotia, Canada, to support implementation of natural disturbance emulation and ecological forestry. Section 2 begins with a brief natural history of Nova Scotia to help set the context of the review. Section 3 outlines the primary natural disturbance agents that affect Nova Scotia's forests and provides a detailed characterization of each natural disturbance agent. Section 4 summarizes the spatial extent, severity, and return interval of the major natural forest disturbances and describes interactions between disturbance agents, while section 5 provides an outlook on the future of natural disturbances in Nova Scotia with particular emphasis on the impact of climate change. We restrict coverage in this review to natural disturbance regimes of Nova Scotia but are currently preparing a follow-up paper on methods to apply natural disturbance regimes to forest management planning, i.e., how to use natural disturbance parameters to derive forest management guidelines that target harvest rotations, age structures, and residual stand structures.

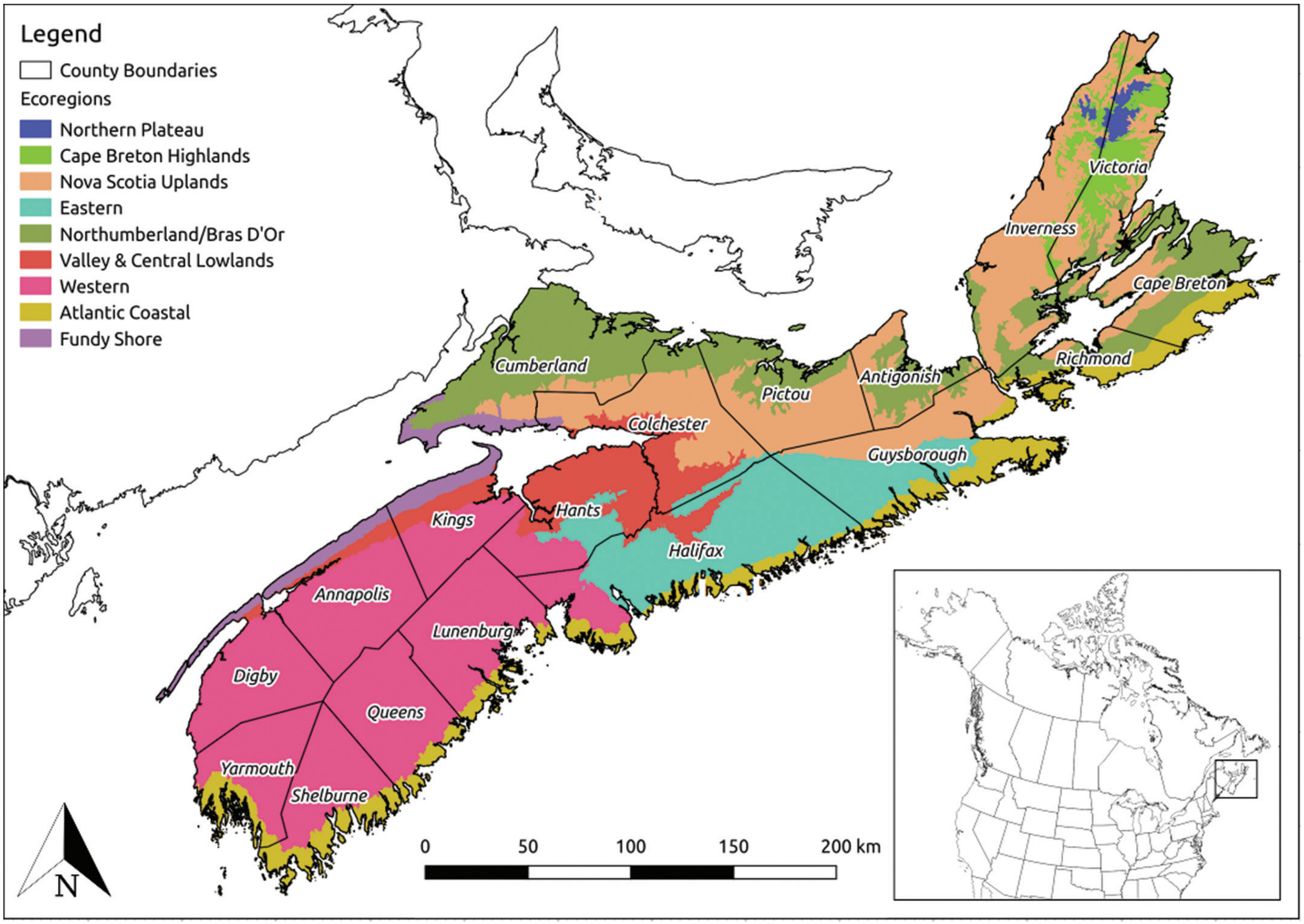
2. A brief natural history of Nova Scotia

2.1. Climate and physiography

Nova Scotia is a peninsula, approximately 55 000 km^2 in area (42 000 km^2 of which is forest; NSDLF 2016), jutting into the Atlantic Ocean and lying approximately halfway between the equator and the North Pole (Fig. 1). Climate is largely determined by prevailing, continental westerly winds but is moderated by the North Atlantic Gulf Stream, resulting in high humidity, frequently fluctuating weather conditions, mild winters, and cool summers (Environment and Climate Change Canada (ECCC) 1990). Mean annual temperature and total annual precipitation are 6.6 °C and 1396 mm, respectively, with an average annual frost-free period of 163 days (ECCC 2019*a*). Mean monthly temperatures range from 22 to 23 °C in July and from –8 to –12 °C in January. Mean total annual precipitation ranges from approximately 1200 mm in the interior to 1400 mm along the Atlantic coast (ECCC 2019*a*).

The physiography of Nova Scotia has largely been shaped by the advance and retreat of repeated glaciations over the past two million years, with the most recent Wisconsin Glaciation ending approximately 10 000 years ago in this region (Davis and Brown 1998; Shaw et al. 2006). Topography varies substantially, with elevation rising from sea level to 535 m at White Hill, Cape Breton, the highest point in the province. High total annual precipitation combined with cool, humid summers encourages soil podzolization, resulting in relatively infertile, acidic surface soils across much of the province, particularly in coastal areas. However, soil conditions vary substantially and many uplands and rich river

Fig. 1. Map showing location of study area, ecoregions (Neily et al. 2017), and counties of Nova Scotia. Map created with QGIS v2.18 software using spatial data provided by the Nova Scotia Department of Lands and Forestry.



flood plains support diverse assemblages of plant and animal species (Loucks 1962; Neily et al. 2013; Basquill and Baldwin 2020).

2.2. Ecological land classification

Nova Scotia is part of the Atlantic Maritime Ecozone, one of 18 broad, ecological land units covering Canada (Canadian Council on Ecological Areas (CCEA) 2014) that are characterized as contiguous areas with similar macroclimate, physiography, geological features, and vegetation. Nova Scotia has been further categorized into nine ecoregions, ranging in size from 416 km² to 16 870 km² (Fig. 1; Neily et al. 2017). Ecoregions are subdivisions of ecozones based on local physiographic features (e.g., highlands versus lowlands) and climate (e.g., coastal versus interior climatic influences), which result in unique vegetation patterns. While the Nova Scotia ecological land classification further divides ecoregions into finer scale ecological land units (e.g., ecodistricts and ecosites; Neily et al. 2017), the ecoregion level provides a suitable spatial scale for synthesizing natural disturbance regimes because the spatial resolution is fine enough to capture important differences in physiography, climate, and vegetation patterns, which are known to influence disturbance regimes (Seymour et al. 2002; Senici et al. 2010; Taylor et al. 2019) yet broad enough to be used in strategic-level forest management planning (Davis et al. 2001; McGrath 2018). For example, the high elevation and cold, wet climate of the Cape Breton Highlands ecoregion (Fig. 1) supports a boreal forest like character, with high abundance of balsam fir (*Abies balsamea* (L.) Mill.), making it more susceptible to spruce budworm (*Choristoneura fumiferana* (Clemens)) outbreaks (MacLean 2016). In contrast, the warmer climate and sandy, granitic soils of portions of the Western ecoregion (Fig. 1) promote stands of *Pinus* spp. that are more susceptible to fire (Wein and Moore 1979; Basquill et al. 2001). For the remainder of the paper, we will use the ecoregion classification level to help frame our discussion of natural disturbance regimes of Nova Scotia.

2.3. Forest vegetation

Common tree species of Nova Scotia are red spruce (*Picea rubens* Sarg.), black spruce (*Picea mariana* (Mill.) B.S.P.), white spruce (*Picea glauca* (Moench) Voss), balsam fir, red pine (*Pinus resinosa* Ait.), eastern white pine (*Pinus strobus* L.), eastern hemlock (*Tsuga canadensis* (L.) Carrière), eastern larch (*Larix laricina* K. Koch), sugar maple (*Acer saccharum* Marsh.), red maple (*Acer rubrum* L.), yellow birch (*Betula alleghaniensis* Britt.), American beech (*Fagus grandifolia* Ehrh.), white ash (*Fraxinus americana* L.), red oak (*Quercus rubra* L.), white birch (*Betula papyrifera* Marshall), and trembling aspen (*Populus tremuloides* Michx.). Other less common species include jack pine (*Pinus banksiana* Lamb.), eastern white cedar (*Thuja occidentalis* L.), largetooth aspen (*Populus grandidentata* Michx.), ironwood (*Ostrya virginiana* (Mill.) K. Koch), balsam poplar (*Populus balsamifera* L.), black cherry (*Prunus serotina* Ehrh.), and black ash (*Fraxinus nigra* Marsh.) (Loucks 1962; Rowe 1972; Saunders 1996; Basquill and Baldwin 2020).

Forest tree species composition is a major determinant of many kinds of disturbances such as host-specific insect outbreaks and differences in fire susceptibility among stand types. Table 1 summarizes leading (most prevalent) species composition by ecore-

Table 1. Current area (ha) of leading (most prevalent) tree species by ecoregion estimated using Nova Scotia's photo-interpreted forest cover layer.

	Area by leading species (ha)								
Ecoregion	BF	WS	RS–EH	BS	PINE	OSW	TH	RM	Total area (ha)[a]
Northern Plateau	7 221	2 783		4 988		10	27	405	15 639
Cape Breton Highlands	67 220	25 302	180	26 937	230	108	14 991	17 311	158 786
Nova Scotia Uplands	115 975	85 683	72 751	84 665	9 188	15 807	262 418	138 987	901 901
Eastern	52 088	7 147	96 994	108 778	6 998	4 892	22 159	82 712	442 867
Northumberland Bras d'Or Lowlands	41 371	61 719	72 377	109 323	10 621	18 030	27 238	168 110	581 832
Valley & Central Lowlands	21 675	21 366	38 032	33 845	4 561	4 087	5 946	67 588	228 466
Western	71 084	35 885	292 003	277 144	117 883	12 941	66 472	331 336	1 313 220
Atlantic Coastal	43 180	32 038	14 275	107 312	1 056	2 799	3 527	46 587	279 362
Fundy Shore	4 530	23 744	16 666	4 101	186	17 141	17 180	22 301	118 256
Total	424 344	295 667	603 278	757 093	150 723	75 815	419 958	875 337	4 040 329

Note: Species abbreviations: BF, balsam fir; WS, white spruce; RS–EH, red spruce – eastern hemlock; BS, black spruce; PINE, white, red, and jack pine; OSW, other softwoods (planted Norway spruce, tamarack); TH, shade-tolerant hardwoods (sugar maple, yellow birch, beech); RM, red maple.

[a]Total exceeds sum of listed species because some areas of "unclassified hardwoods" and "unclassified softwoods" were too young to determine species identity from aerial photo interpretation and are not included here.

gion. Of the total 4.2 million ha of forest, the largest areas by leading tree species are 875 000 ha red maple, 757 000 ha black spruce, 603 000 ha red spruce – eastern hemlock, 424 000 ha balsam fir, 420 000 ha shade-tolerant hardwoods (sugar maple, yellow birch, American beech), and 296 000 ha white spruce (Table 1). Tree species and ecoregion characteristics such as climate and physiography are the primary determinants of natural disturbance regimes (White and Pickett 1985; Smith and Smith 2015).

2.4. Management history and resulting forest changes

A long history of land clearing, timber harvest, human-caused fire, introduction of non-indigenous invasive species, and more recently, fire suppression have altered the historic species composition and age structure of Nova Scotia's forests (Fernow 1912; Johnson 1986; Loo and Ives 2003). Over the past 100 years, abandonment of farmland, increased clear-cut harvesting, and shorter harvest rotations have contributed to increases in the abundance of young, even-aged forests dominated by white birch, red maple, and trembling aspen (Simpson 2008). These same practices, along with fire suppression, have also contributed to increased abundance of balsam fir, which historically was considered a minor species across much of Nova Scotia (Loo and Ives 2003). Erdle and Pollard (2002) addressed the question of whether forest plantations are changing the tree species composition of neighbouring New Brunswick forests and concluded that plantations established from 1967–1982 differed little from the natural forest that they replaced in terms of total softwood tree representation but differed markedly by having much higher proportions of jack pine, lower levels of red spruce, and reduced understory biodiversity (Betts et al. 2005). Early succession species tend to be well adapted to open site conditions created by large-scale disturbances such as wildfire and clear-cutting (Whittaker 1975; Reiners 1992; Taylor et al. 2020). In contrast, most long-lived, shade-tolerant species do not recruit or perform well under open site conditions and may take decades to become re-established unless sufficient advance regeneration survives disturbance (Marks and Gardescu 1998; Leak 2005; Fraver and White 2005).

In addition to past harvesting, the introduction of non-indigenous insects and pathogens have also greatly altered the structure and function of Nova Scotia's forests (Loo and Ives 2003; Loo 2009). Beech bark disease, introduced to Nova Scotia in 1890, has decimated the American beech population, which was once dominant throughout the province (Fernow 1912; Taylor et al. 2013). Similarly, American elm (*Ulmus americana* Augustine), once abundant along many river valleys, is greatly diminished due to the introduction of Dutch elm disease in the early 20th century (Loo 2009). As a result of these changes and the many other impacts of European settlement over the past 400 years, Nova Scotia's forests today are, on average, younger, more fragmented, and of altered tree species composition.

3. Natural disturbance regimes of Nova Scotia

Natural disturbance is a fundamental driver of forest and landscape dynamics (Barnes et al. 1998; Smith and Smith 2015) and has played an important role in shaping the forests of Nova Scotia (Neily et al. 2008, 2017). Natural disturbance may be defined as any relatively discrete event (such as a fire, windstorm, or insect infestation) that disrupts the physical structure and (or) resource availability of an ecosystem (White and Pickett 1985; Smith and Smith 2015). A particular driver of natural disturbance is referred to as an "agent". Here, "natural" means "without human influence" (Hunter 1999), and a natural disturbance "regime" refers to the average behavior and variability of a natural disturbance agent, inherent to a forest landscape, over a defined time period.

Integrating natural disturbance regimes into ecological forestry first requires identifying which specific natural disturbance agents have major effects on forested landscapes. Numerous historic accounts document the occurrence of natural disturbances across Nova Scotia since early European settlement, beginning in the 1600s. In 1672, Nicolas Denys wrote: "From the end of the spring and during the summer and autumn, the thunder falls sometimes in fire and strikes in the woods, where everything is so dry that it continues there some three weeks or a month. Unless rains fall sufficiently to extinguish it, the fire will burn sometimes 10, 12, and 15 leagues [50–75 km] of country. At evening and at night, one sees the smoke 10 and a dozen leagues away" (Denys 1672). Fernow (1912) stated: "approximately one-fourth of the present forest area of the province is semi-barren of commercial trees. This condition has been brought about by repeated fires in situations possessing naturally the coarser soils". Titus Smith, who provided some of the earliest and most extensive reports of the natural history of Nova Scotia during his 1801–1802 expedition, witnessed extensive blowdown: "in some places, particularly north of St. Margaret's Bay, there were miles of country where nearly all the trees had been blown down in the Great Storm of September 25, 1798" (Smith 1802).

Native insect populations and disease infestations in Nova Scotia also create considerable changes to forest ecosystems in short time periods. Several pests, including, for example, spruce budworm, spruce beetle (*Dendroctonus rufipennis* Kirby), and white-marked tussock moth caterpillar (*Orgyia leucostigma* J.E. Smith), can destroy entire stands. Such population outbreaks are responsible for large-scale disturbances, especially in ecosystems that are comprised largely of their preferred food source. Historical insect outbreaks are not well recorded as in many cases, the more sus-

Table 2. Primary variables used to review and characterize natural disturbance regimes in Nova Scotia.

Variable	Definition	Levels	Units
Spatial extent	Total landscape area affected by a single disturbance agent event	Wide scale Medium scale Small scale	>500 ha 500–50 ha <50 ha
Severity[a]	Total amount of tree biomass killed per unit of forest area during a single disturbance agent event	High Moderate Low	>60% 60–30% <30%
Return interval[b]	Average time elapsed between successive disturbance agent events of a particular severity level at the same place on the landscape	Long term Medium term Short term	>150 years 50–150 years <50 years
Mean annual disturbance rate	Amount of eligible forest area disturbed per year by a specific disturbance agent and severity level		

Note: For mean annual disturbance rate, "amount" of area is usually expressed as a percentage and "eligible" signifies that not all forest areas on a landscape are vulnerable to each disturbance, as some disturbance agents are specific to tree species (e.g., spruce budworm).

[a]Severity levels were designed to coincide with definitions of clear-cut and partial-cut harvesting intensities used by the Nova Scotia Department of Lands and Forestry (https://novascotia.ca/natr/strategy/clear-cut-definition.asp).

[b]Return interval may also be interpreted as the time it would take for a disturbance agent to disturb an area equivalent in size to the landscape under consideration at a particular severity level.

ceptible trees, for example, balsam fir and eastern larch, were of little or no use to the early settlers and thus infestations were ignored. Today, the NSDLF Forest Protection Division (https://novascotia.ca/natr/forestprotection/) surveys the most common natural disturbances that affect Nova Scotia's forests. Using this information, combined with past observations from numerous historic accounts (e.g., Denys 1672; Fernow 1912; Johnson 1986), we have developed a list of the dominant (in terms of extent and severity) natural disturbances that affect the forests of Nova Scotia. Forest fires, hurricanes, and spruce budworm outbreaks are the most important disturbances in Nova Scotia. Smaller or local disturbances include windstorms, other insects and diseases, and miscellaneous other disturbances, including ice storms, drought, floods, landslides, soil subsidence (e.g., karst sinkhole formation), and disturbances originating from animals such as North American beaver (*Castor canadensis* Kuhl, 1820), snowshoe hare (*Lepus americanus* Erxleben, 1777), common porcupine (*Erethizon dorsatus* (Linnaeus, 1758)), white-tailed deer (*Odocoileus virginianus* (Zimmermann, 1780)), and moose (*Alces alces* (Linnaeus, 1758)). A summary of noteworthy natural and human-caused disturbances recorded in the literature that have influenced Nova Scotia's forests over the last 400 years is included as Appendix A.

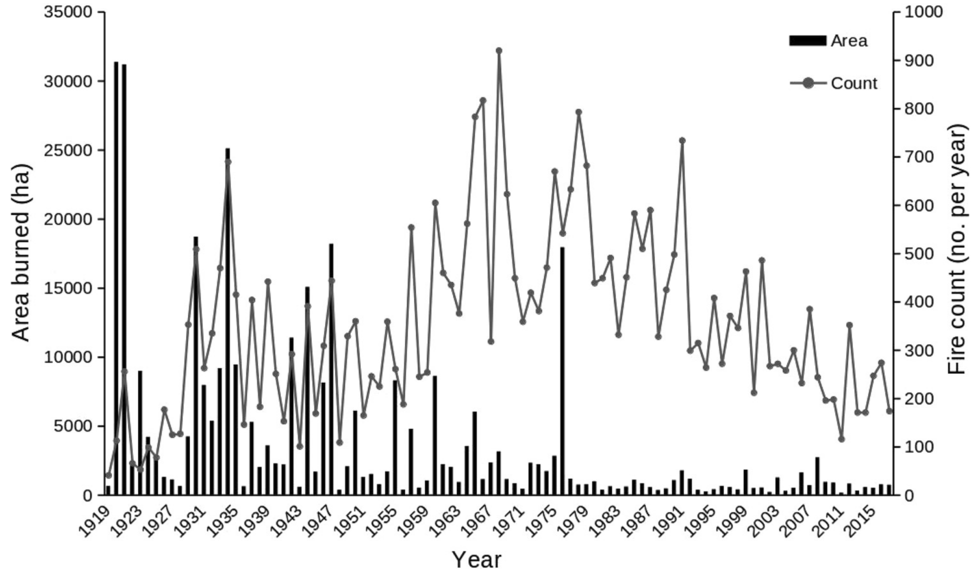
Although many descriptors have been used to characterize natural forest disturbance regimes in eastern North America (e.g., White and Pickett 1985; Seymour et al. 2002; Lorimer and White 2003; DeGrandpre et al. 2018), most are based on three main variables (Table 2): (*i*) spatial extent, which defines the total landscape area over which a single disturbance agent event occurs (i.e., a single episode of that disturbance agent); (*ii*) severity, which refers to the intensity of damage caused by a disturbance agent and can be quantified by the total amount of tree biomass killed per unit of forest area during a single disturbance agent event; and (*iii*) return interval, the average time elapsed between successive disturbance agent events of a particular severity level at the same place on the landscape. Return interval may also be calculated on an annual basis as "mean annual disturbance rate", which is the amount (usually expressed as a percentage) of "eligible" forest area disturbed per year by a specific disturbance agent and severity level. Here, "eligible" signifies that not all forest areas within a landscape are vulnerable to each disturbance. Some disturbance agents are specific to tree species such as spruce budworm and only affect forest areas that include host tree species (e.g., balsam fir and spruce). Each disturbance variable may be further categorized as the mean and range of values characteristic of each natural disturbance agent regime unique to a landscape (e.g., ecoregion). Table 2 describes each natural disturbance regime variable and its levels, which were used to characterize natural disturbances in the following sections.

3.1. Fire

Fire has affected the forests of Nova Scotia since the last glaciation and has been an important disturbance agent since European settlement, with some very large historic fires noted (e.g., Denys 1672; Perkins 1766–1812; Smith 1802; Fernow 1912); however, it is difficult to separate natural and human-caused fire in the postcolonial period, and natural fire occurrence in Nova Scotia is low relative to most other areas of Canada (Boulanger et al. 2014; Erni et al. 2020; Basquill and Baldwin 2020). Based on analyses of pollen and charcoal in cores of sediment from lakes in southwestern Nova Scotia (which may or may not be reflective of the whole province), Green (1981) concluded that large intense fires occurred 11 000 to 6000 years before present (BP). These repeated, widespread fires maintained the forest in constant disequilibrium, with each fire triggering rapid, major forest composition changes, especially proliferation of invading tree species previously excluded by competition. The absence of such widespread fires left most tree populations in near equilibrium for much of the last 6000 years (Green 1982). From examining soils and charcoal at several sites in Kejimkujik National Park in western Nova Scotia, Ponomarenko (2007) determined that four large-scale fires occurred 1500, 800, 500, and 250 years ago and that these fires occurred shortly after hurricanes and affected tens of square kilometres. Nearly all paleoecologists who have examined lake sediments or bog profiles in the Maritime Provinces and New England have found evidence of fire in the form of charcoal (Wein and Moore 1979). Palaeoecological analyses of wetlands in New England also showed that the pre-European period of 3500–1000 BP was marked by two 1000+ year periods of stable forest composition, attributed to ongoing disturbance by fire and windstorms, separated by an abrupt compositional shift, apparently due to cooling and an increase in moisture availability, ca. 1500 BP (Foster et al. 2002). Climate is the main factor influencing distribution of fires, directly affecting physical conditions conducive to fire ignition and spread and indirectly affecting fire through its influence on the distribution of vegetation (Parshall and Foster 2002). The local fire regime is also influenced by landform effects on vegetation, soil properties, firebreaks, and prevailing winds (Edmonds et al. 2011).

Forest fires in Nova Scotia often occur in late spring prior to vegetation green-up or in the summer during periods of low humidity and rainfall. Human activities during these periods increase the probability of forest fires. Most fires kill both overstory

Fig. 2. Area burned and count of fires per year in Nova Scotia from 1919 to 2018.



and understory species, with varying damage to the forest floor dependent on ground moisture conditions and amount of fuel buildup (Edmonds et al. 2011). Fire occurrence in Nova Scotia over the last 80 years has ranged from about 100 to 900 fires per year, with peak years evident in nearly every decade (Fig. 2); however, the mean number of fires per decade has declined, from 553 and 551 fires·year^{-1} in the 1960s and 1970s, respectively, to 448, 397, 284, and 222 fires·year^{-1} in the 1980s, 1990s, 2000s, and 2010s, respectively. Area burned exceeded 25 000 ha·year^{-1} only in early years: 1920, 1921, and 1934 (Fig. 2). The most recent "bad" fire year in Nova Scotia, in terms of area burned, was 1976, with 18 000 ha burned. The number of fires has declined and there has been a consistently low area burned (<2000–3000 ha) since 1980 (Fig. 2).

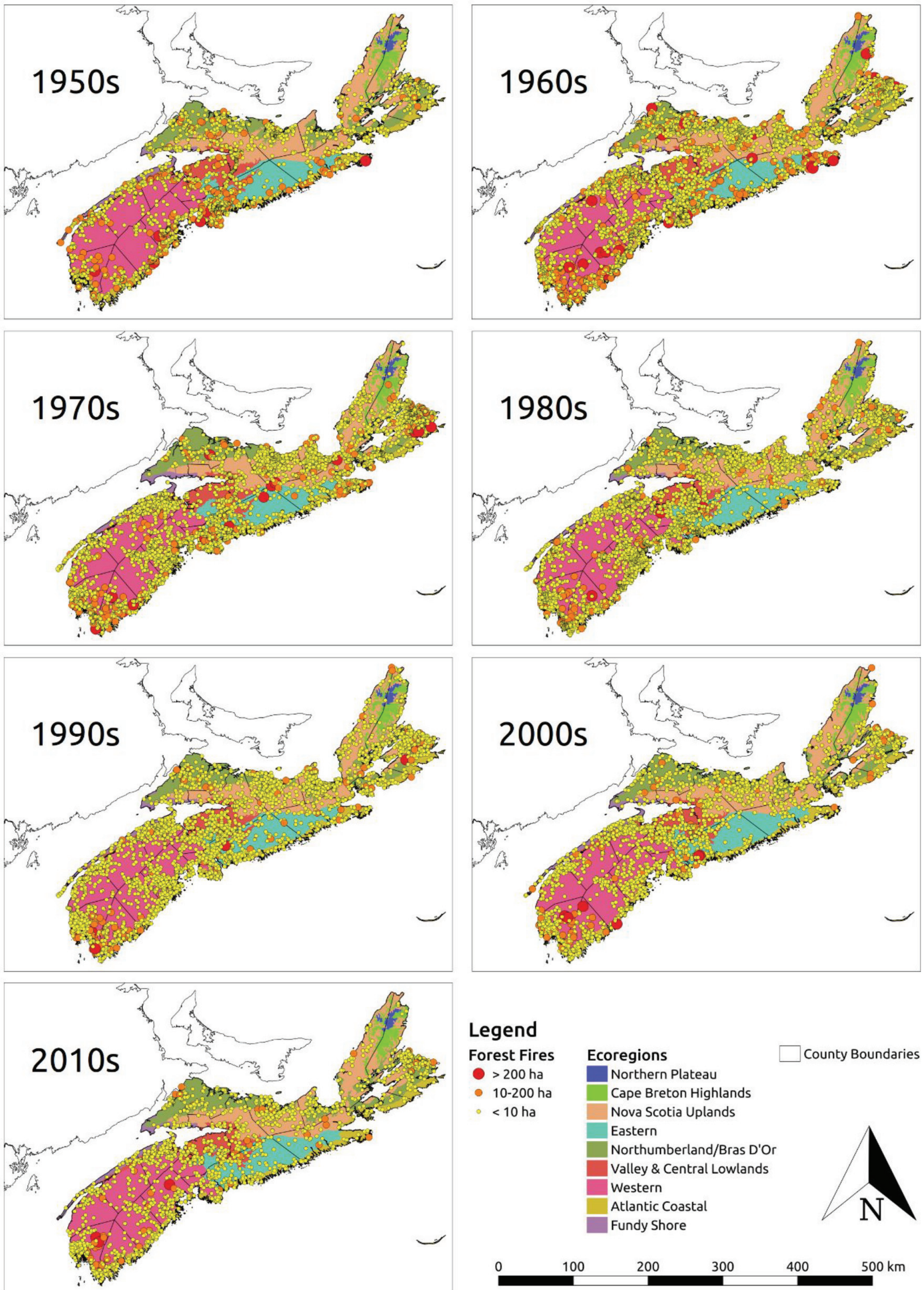
Fire records in Nova Scotia clearly reflect effective fire suppression and a high proportion of human-caused ignitions, with numerous fires, but most remaining small. Locations of fires are shown as points, by size class (0–10 ha, 11–200 ha, and >200 ha) and decade in Fig. 3. The vast majority of fires were <10 ha, and nearly all regions of Nova Scotia have had many fires. Only the Cape Breton Highlands and parts of the Eastern and Western ecoregions have consistently had few fires (Fig. 3). In general, locations of fires typically correspond with settled and roaded areas, while those portions of the Western and Eastern ecoregions with lower relative fire frequencies are less densely settled and less traveled.

The role of fire, both before and after settlement, in forming the forests of Nova Scotia is contentious. Some believe that much of the provincial forest reflects extensive use of fire by settlers to clear unwanted forest for agriculture and perpetuation of crops of wild berries, but historical writings also refer to careless ignitions by colonial settlers that resulted in large fires (e.g., Smith 1802). Others suggest that First Nations peoples used fire to encourage berry production and to maintain browse for moose and caribou (the historical presence of caribou indicates that fires created enough open habitat to support viable population levels) (Joudry 2016). While researching the history of fires in Kejimkujik National Park, Basquill et al. (2001) could find little conclusive written information to confirm use of fire by First Nations peoples outside their encampments. Joudry (2016) interviewed Mi'kmaq Elders or Knowledge Holders about their physical, mental, emotional, and spiritual relationships with fire, and unique fire regimes occurred in three cultural districts in Nova Scotia. Many Elders referred to lightning-caused land fires but also spoke of Mi'kmaq burning small areas of nonforested lands for various purposes as a common or shared cultural practice (Joudry 2016). Joudry (2016) concluded that historically, there was very little large-scale fire on the land, and most fire came by way of lightning rather than Indigenous Peoples in this region. In the northeastern United States (US), Russell (1983) concluded that First Nations' use of fire was only locally near camps or villages, or with accidentally escaped fires, and that frequent use of fires by native Americans to burn the forests was probably, at most, a local occurrence. The presence of native Americans in the region and their use of fire for many purposes did, however, increase the frequency of fires above the low levels caused by lightning and thus had some effect on the vegetation (Russell 1983). In New England, Parshall and Foster (2002) also concluded that native Americans likely influenced local occurrence of fire, but did not determine regional fire regimes.

Gajewski and Neil (2019) recently used pollen analyses from lake sediment cores retrieved at three sites in central Nova Scotia to produce a history of vegetation and fire disturbances for the past ~2500 years. Pollen data were analyzed at high temporal resolution (15–70 years), and comparisons of microcharcoal from pollen slides and macrocharcoal from lake sediments were used to determine regional and local fires, respectively. Although microcharcoal indicated a continual series of background fires somewhere in the region, macrocharcoal indicated relatively infrequent fires in the immediate slopes surrounding the study lakes, with only three to four local fires recorded at each lake over the past 2500 years. Schauffler and Jacobson (2002) analyzed pollen stratigraphies from small forested hollows in Maine and showed that refugia along the coast and in isolated sites inland may have played an important role in rapid regional expansion of spruce around 1000 years ago, during a period of cooler and moister conditions.

Large historical fires were recorded by several authors, including Simeon Perkins (1766–1812), who described a fire south of Lake Rossignol in 1800 that covered an estimated 175 000 ha, and Titus Smith (1802), in Queens and Lunenburg counties, where an estimated 150 000 ha burned in 1720, preceded by a hurricane. Ponomarenko (2007) also found that a large fire occurred in the eastern part of Kejimkujik National Park between 1700 and 1764, supporting Smith's observation. Throughout his traverse of western Nova Scotia, Smith (1802) repeatedly drew attention to fire barrens and extensive areas of burned forest. Johnson (1986) stated that "although most settlers tried to be careful with fire, burning only at what they considered to be safe times, fires often got out of control and burnt extensive areas". Perkins (1766–1812)

Fig. 3. Locations of forest fire occurrence in Nova Scotia from 1950 to 2019, by decade. Maps created with QGIS v2.18 software using spatial data provided by the Nova Scotia Department of Lands and Forestry.



described many fires around Liverpool in June and July 1792, with nothing done to stop them. In 1803, Perkins entered in his diary that "smoak [from the Port Mouton and Beech Hill fires] is come down upon us so thick as to darken the air to such a degree that one can scarcely see acrost the street". Wein and Moore (1979) concluded that fires between 1500 and 1914 mostly occurred from land clearing.

The barrens of southwestern Nova Scotia have often been considered the product of frequent fires, many of them human caused, and subsequent impoverishment of soils. Fernow (1912)

Table 3. Forest fire occurrence in Nova Scotia from 1950 to 2018 by ecoregion.

Ecoregion	Area burned (ha)		Count (no. per year)		Count of lightning-caused fires[a]		
	Sum	Maximum annual	Sum	Mean annual	Sum	No. per 1000 km²	No. years with >200 ha burned
Northern Plateau	0	0	1	0	0	0.0	0
Cape Breton Highlands	2 047	1 716	122	3	10	4.9	1
Nova Scotia Uplands	6 794	1 092	2 507	37	47	4.3	4
Eastern	25 236	13 625	2 683	38	42	6.5	16
Northumberland Bras d'Or Lowlands	19 295	2 883	6 393	94	553	6.5	31
Valley and Central Lowlands	14 352	10 352	3 147	46	18	4.4	3
Western	30 406	4 196	6 984	101	170	10.1	37
Atlantic Coastal	20 467	3 576	3 764	55	10	2.1	23
Fundy Shore	1 160	107	672	10	8	5.6	0
Total	119 757	18 087	26 273	380	360	44.4	115

Note: Only the count of lightning-caused fires is considered a natural disturbance. Area burned, number of fires, and number of years with >200 ha burned data are all for combined human- and lightning-caused fires but are included to show the large differences in historic fire among ecoregions.

[a]Data for lightning-caused fires are for the period 1959–2019, because data were not available for 1950–1958.

described locations of recent burns and old fire barrens, most in the Western and Eastern ecoregions (Fig. 1), and dated the fires and resulting forest stands, some back to the 1830s, indicating that fires had not recurred for 80 years on some barrens. Basquill et al. (2001) concluded that the barrens originated well before European colonization, and although fire was a potent factor in maintaining shrub cover, pollen analyses indicated that an open woodland developed many centuries ago in response to soils and climate, as well as burning (Strang 1972).

Wein and Moore (1979) used provincial fire records from 1915 to 1975 to calculate a return interval for Nova Scotia of 1000–2500 years. In contrast, calculations of burned areas on maps produced at the turn of the century by Fernow (1912) resulted in a pre-suppression return interval of just over 200 years. Based on charcoal particle abundance in cores from lakes in southwestern Nova Scotia, Green (1981) calculated a return interval of about 400 years for the years 6600 to 2200 BP. With the advent of fire suppression and improvement of response times and equipment, fire return intervals have lengthened. From 1915 to 1994, a total of 371 000 ha of forest in Nova Scotia was burned. At this rate, it would take about 900 years to burn the entire mainland of Nova Scotia. Considering only the period from 1958 to 1975, the fire return interval in Nova Scotia was approximately 2000 years (Wein and Moore 1979).

3.1.1. Fires caused by lightning

The natural cause of ignition in Nova Scotia is lightning strikes. Based on records from NSDLF, from 1929 to 2019, 309 forest fires (1% of all ignitions) were attributed to lightning strikes (3.4 forest fires per year). Early fire records were inconsistent, and none were kept during 1931–1936. Areas burned of the seven largest lightning-caused fires (>100 ha) were 163 ha in 1929, 100 ha in 1930, 370 ha in 1942, 283 ha in 1944, 192 ha in 1952, 517 ha in 1961, and 113 ha in 1965. Of the 260 lightning-caused fires since 1970, most were ≤2 ha, while the remaining fires ranged from 2.1–17 ha. Wein and Moore (1979) mapped the locations of lightning-caused fires in Nova Scotia from 1958–1975, and most were located in interior portions of the Western ecoregion. In the adjacent province of New Brunswick, lightning caused 7% of fires from 1929 to 1975 (Wein and Moore 1977). Environment Canada weather data for 1998–1999 indicated that most of Nova Scotia receives 0.25–0.5 lightning-to-ground strikes·km^{-2}·year^{-1}, with two-thirds of all strikes occurring from June to August (Lanken 2000; Burrows and Kochtubajda 2010; ECCC 2020). Since 1990, causes of fires (based on area burned) were 90% human-caused (37% incendiary, 40% recreation or residents, 11% industry or railways), 1% lightning, and 9% of unknown origin. Of the fires identified as caused by lightning, 43%, 15%, 14%, and 11% were in the Western, Northumberland Bras d'Or Lowlands, Eastern, and Nova Scotia Uplands ecoregions, respectively.

3.1.2. Regional fire history within Nova Scotia

Basquill et al. (2001) described the Western ecoregion of Nova Scotia as one of the most fire prone areas in the Acadian forest region (Rowe 1972), where human- and lighting-caused fires have had a dominant influence on current forest ecosystems. Areas repeatedly burned created fire barrens that prevented seed germination of flame-tolerant species. Abundant charcoal was present at 87% of sites sampled in Kejimkujik National Park, and there was evidence of understory fires dating back to 1803 from bark and tree ring chronology studies (Basquill et al. 2001). There was charcoal evidence that overstory (stand-replacing) fires initiated 100% of fires in sampled red pine stands and 60% of both white pine and white birch stands and, to a lesser extent, also helped initiate some fires in black spruce and red maple stands (Basquill et al. 2001). For their period of study, Basquill et al. (2001) calculated an average overstory fire return interval of 78 years, comparable with the high fire frequency of about 60 years in jack pine stands in northeastern New Brunswick (MacLean and Wein 1977) and northwestern Ontario (Senici et al. 2010).

Bridgland et al. (1995, 2011) analyzed fire history of northern Cape Breton using geospatial analyses of vegetation maps, field studies, and other evidence. Results indicated fire origin for approximately 180 km² or 20% of the Cape Breton Highlands National Park, including much of the taiga region of the park (Northern Plateau ecoregion). Fire was concluded to have an equal or greater role than insect outbreaks in shaping the landscape of northern Cape Breton, and the taiga appeared to be ultimately of fire origin (Bridgland et al. 1995). The Atlantic Slope portion on the park (Nova Scotia Uplands ecoregion) also had evidence of numerous fires of different ages, sizes, and severity, but most evidence of fire seemed to date after the early 1800s, following European settlement (Bridgland et al. 2011).

The presence of fire origin, or fire-adapted, tree species such as jack, red, and white pine and white birch throughout Nova Scotia is evidence of the role of fire in regional forest composition (Loucks 1962; Rowe 1972). Although the occurrence of fire has probably increased since European settlement, many fires have regularly occurred in recent decades, especially in the Valley and Central Lowlands and Western ecoregions (Fig. 3). Total (human- and lightning-caused) fire occurrence since 1950 clearly differs by ecoregion (Table 3). Eastern and Western ecoregions had averages of 25 000 ha and 30 000 ha burned in 38 and 101 fires, respectively, between 1950 and 2018. Atlantic Coastal, Northumberland Bras d'Or Lowlands, and Valley and Central Lowlands ecoregions had 14 000 – 20 000 ha burned, while the remaining four ecoregions had 0–6800 ha burned. The Western, Northumberland Bras d'Or Lowlands, Atlantic Coastal, and Eastern ecoregions (in that order) had 16–37 years with >200 ha·year^{-1} burned (Table 3). The number of natural, lightning-caused fires varied substantially by ecoregion over the 60-year period between 1959 and 2019, from 0–10 in the Northern Plateau and Cape Breton Highlands ecoregions to 42–55 in the Eastern, Nova Scotia Uplands, and Northumberland Bras d'Or Lowlands ecoregions to a maximum of 170 in the Western ecoregion (Table 3). When converted to number of lightning-caused fires per 1000 km^2, to account for differences in ecoregion size, number of lightning-caused fires over the 60-year period was lowest, at 0–2, in the Northern Plateau and Atlantic Coastal ecoregions, highest, at 10, in the Western ecoregion, and 4–6 in all other ecoregions (Table 3). Although area burned from lightning-caused fires was low, it is highly probable that at least some of these fires would have burned substantial areas without suppression. Consistency of locations of fire occurrence was evident from the 1950s to the 2010s (Fig. 3).

Ponomarenko (2018) reconstructed past disturbance regimes at sites sampled to represent six ecosites (i.e., areas of uniform parent material, soils, and potential vegetation and hydrology) in five ecoregions of Nova Scotia using analyses of historical tree uprooting structures that remain discernible in the soil column and identification of macrofossils (e.g., charcoal, plant remains, and insect remains). Each of the 15 sites sampled showed evidence of 2–16 past fires and eight sites also had evidence of insect body parts and feces, indicating past insect outbreaks. Of the total 38 detected fires that were radiocarbon-dated, 39% were from 250–2000 years ago, 3% from 2000–4000 years, 18% from 4000–6000 years, and 16% from 6000–8000 years ago (Ponomarenko 2018). Based on the presence of a charred layer at the base of the forest duff and its correlation with the presence of light-demanding and fire-dependent tree species in the canopy, 20 of 23 studied sites (87%) were affected by fires in the last 250 years. Mean fire-free intervals determined from the radiocarbon dates, in the period 1800–250 years BP, by ecosite were 250–300 years for black spruce – red pine – jack pine ("fresh" soil moisture, very poor soil nutrients ecosite; Neily et al. 2017); 350–400 years for black spruce – white pine – red pine (fresh, poor ecosite); 500 years for Acadian tolerant softwood (red spruce – eastern hemlock on fresh, medium ecosite); 500 years for Acadian tolerant hardwood (sugar maple – beech on fresh, rich ecosite); and 600 years for lowland black spruce (wet, very poor ecosite; however, this is based on only one site, and more data are required) (Ponomarenko 2018). The last 250 years had shorter fire intervals, from <100 to 200 years, but because this time period did not have major climatic changes, increased fire frequencies probably reflect human settlement influences (Ponomarenko 2018).

3.1.3. Effects of fire suppression, industry, and railroads

Humans played a major role in fire occurrence in Nova Scotia over the last three centuries, in terms of both fire initiation and suppression. The Nova Scotia Legislative Assembly first passed an Act designed to "reduce firing of the woods" in 1761, but at the time, there was little concern about damage to forests, but rather to settlers' buildings and crops from fire spreading from the forest (Creighton 1988). In 1864, legislation was passed to imprison anyone convicted of unlawfully setting fires. The frequency of human-caused fires continued to increase into the 19th century, and because there was no modern technology available for extinguishing large blazes, fires were abandoned because they rarely threatened settlers and timber resources seemed inexhaustible (Basquill et al. 2001). In 1904, an Act was established that all firefighting costs were to be paid by municipalities, but in 1926, responsibility for suppression of forest fires changed to the province (Johnson 1986; Creighton 1988). Based on our evaluation of existing data and literature, the most significant technological advances that influenced fire occurrence and burned area were (*i*) railways constructed throughout Nova Scotia between 1858 and 1890, which resulted in significant burning of the woods; (*ii*) the advent, in the early 1900s, of small transportable sawmills that allowed lumbermen to access and accidentally ignite fires in more remote forest areas; (*iii*) use of motorized fire pumps beginning in the 1920s, one of which could do the work of 25 people working with hand tools; and (*iv*) establishment of a fire tower detection network in the late 1920s, with 51 towers located throughout the province. Railways were the largest cause of fires for years and resulted in 20 times as much wood destroyed by fire as was hauled out by the railways (Johnson 1986); however, railway companies eventually developed effective fire protective systems such that by 1926, only 27 acres were burned in 31 fires (Anonymous 1926–1929).

From 1919 to 2018, the area of forest lost to fire decreased substantially from over 30 000 ha·year^{-1} to <500 ha·year^{-1}, but the number of fires per year did not change as much, typically ranging from 200 to 500 fires·year^{-1} (Fig. 2). Reduction in annual area burned through the 20th century resulted from improvement in fire detection and suppression, availability of motorized fire pumps, better surveillance using a network of fire towers, airplanes, and helicopters, and quick response by helicopter crews and local fire brigades. In recent decades, suppression has been very effective, largely eliminating fire from ecosystems (Basquill et al. 2001); however, human-caused fires and, to some extent, lightning-caused fires have had a major role in shaping succession patterns across the landscape, particularly in maintaining stands of red, white, and jack pine, red oak, black spruce, treeless low shrub barrens, and open pine woodlands. Continued fire suppression will likely further influence forest community structure and diversity in Nova Scotia (Basquill et al. 2001).

3.2. Wind

Wind is the bulk movement of air along the Earth's surface in response to atmospheric temperature and pressure gradients and is a major disturbance agent of forest dynamics (Everham and Brokaw 1996; Mitchell 2013). As a peninsula jutting out into the North Atlantic Ocean, Nova Scotia is Canada's stormiest province and is especially vulnerable to wind-caused forest damage (ECCC 1990). Wind damage in Nova Scotia's forests ranges widely from light canopy damage to stem breakage and uprooting of whole stands of trees. The overturning of trees caused by wind is known as "windthrow", but it is also referred to as blowdown, windfall, or windblow (Everham and Brokaw 1996). Windthrow severity is generally reported as percentage of downed (>45° lean) trees per unit of forest area, without necessarily distinguishing between stem breakage and uprooting (Everham and Brokaw 1996).

Windthrow severity depends on several factors, including (*i*) topographical variables that modulate the movement of wind across the land surface, (*ii*) soil variables that influence anchorage of tree roots, and (*iii*) forest stand and landscape variables (e.g., tree species composition and height and structure of adjacent forest stands) that affect tree resistance to wind and gravity (Mitchell 2013; Taylor et al. 2019). However, meteorological variables that characterize the nature of the wind event itself are most important in determining windthrow severity, specifically (*i*) intensity of the wind event (i.e., maximum sustained wind speed, i.e., average wind speed measured 10 m above the ground over a 10-min period; World Meteorological Organization (WMO) 2018), (*ii*) duration of the wind event, and (*iii*) precipitation immediately prior to and during the event (Everham and Brokaw 1996; Mitchell 2013; Taylor et al. 2019). Nova Scotia experiences many wind events annually that range widely in character; however, they may be generalized by their intensity and meteorological origin as windstorms or hurricanes (Everham and Brokaw 1996; Mitchell 2013).

3.2.1. Windstorms

Here, "windstorms" are considered a broad category of non-hurricane wind events that originate from a variety of meteorological conditions and tend to range in wind intensity between 50 and 100 km·h^{-1}. While many parts of Nova Scotia regularly experience sustained winds of 10–50 km·h^{-1}, particularly along coastal areas and across the Cape Breton Highlands (ECCC 2019*a*), wind intensities of this magnitude are unlikely to cause substantial windthrow (Stathers et al. 1994; Nicoll et al. 2008; Taylor et al. 2019) and are outside the scope of this review. Rather, we focus here on windstorms that generate maximum sustained winds in excess of 50 km·h^{-1}, which are likely to cause significant windthrow (i.e., >5% downed trees) (Stathers et al. 1994).

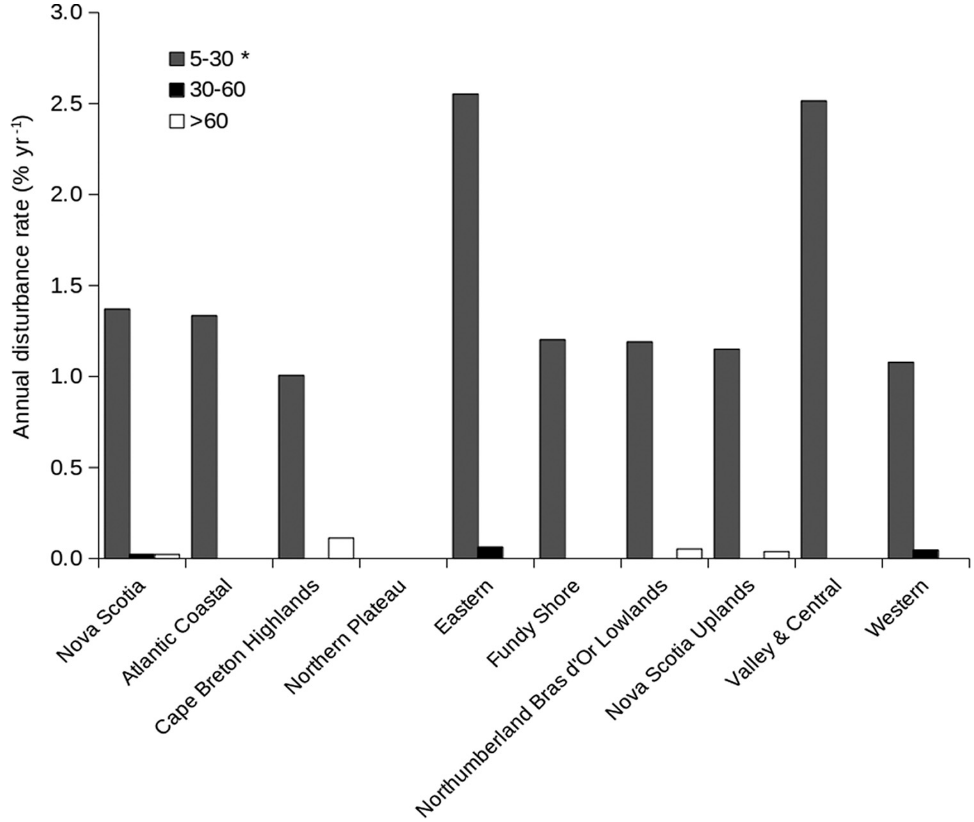
The largest type of windstorm affecting Nova Scotia's forests are extra-tropical cyclones (ETC), also referred to as mid-latitude cyclones or low-pressure systems. These systems form in mid-latitude temperate zones (30°–45° latitude) over the Pacific and Atlantic oceans in response to temperature gradients between tropical and polar air masses (National Oceanic and Atmospheric Administration (NOAA) 2019*a*). They track west to east and are most intense in Atlantic Canada between November and March (Plante et al. 2015). ETC can be large systems (i.e., generally much wider, spatially, than hurricanes) that affect large portions of the province at once. They can produce sustained winds in excess of 100 km·h^{-1}, are often accompanied by rain or snow, and can cause widespread forest damage (Lorimer and White 2003; Valinger and Fridman 2011). ETC are commonly referred to as "nor'easters" (or winter gales) in Atlantic Canada because dominant winds typically blow in a northeasterly direction. Numerous severe ETC have been documented since the 1800s, including the "Great Blizzard" of 1888 (one of the most severe blizzards ever recorded to affect the northeastern US), the "Groundhog Day Gale" of 1976 (which caused forest damage throughout southwestern Nova Scotia, with gusts of 188 km·h^{-1}), and the 1991 "Perfect Storm" (which caused extensive forest damage across much of Nova Scotia, with gusts of 110 km·h^{-1}); however, most ETC are of low severity. Nova Scotia experiences approximately 40 ETC annually, with most (especially those during summer) having maximum sustained winds <40 km·h^{-1} (Plante et al. 2015). Fewer than 2% of annual ETC (approximately one every two years) in Nova Scotia generate sustained winds >90 km·h^{-1} (Plante et al. 2015) required to cause high-severity windthrow (>60%; Table 2) (Stathers et al. 1994; Nicoll et al. 2008; Taylor et al. 2019). One of the most notable nor'easters was "White Juan" in February 2004, just five months after Hurricane Juan severely damaged parts of central Nova Scotia. White Juan dropped a record-breaking 95 cm of snow and produced sustained winds of 80 km·h^{-1}(ECCC 2017). It is unclear how much forest was damaged by White Juan, as estimation of damage from Hurricane Juan was still underway, but widespread patches of windthrow were reported. It is likely that trees weakened by Hurricane Juan were more susceptible to damage from the wind and snow load of White Juan, given the short time interval separating the two disturbances.

Another type of windstorm that commonly affects Nova Scotia's forests are tropical storms, which are tropical cyclones that are not of hurricane intensity (NOAA 2019*a*). Tropical cyclones (i.e., tropical storms and hurricanes) form under different synoptic conditions than ETC in response to temperature differentials between the ocean surface and atmosphere. They are "compact" in size, relative to ETC, and originate over the ocean at tropical latitudes (0°–30° latitude). Tropical cyclones generally track east to west, but often veer north into mid-latitudes, and are most intense in Atlantic Canada during late summer to early autumn (ECCC 2019*b*). Tropical storms have maximum sustained winds that range from 56 to 104 km·h^{-1}, above which they are classed as hurricanes (NOAA 2019*a*). While records of tropical storms affecting Nova Scotia date back to the 1600s (Rappaport and Fernandez-Partagas 1995), reliable monitoring of tropical cyclones along the eastern coast of the US and Atlantic Canada did not begin until the late 19th century (Fernandez-Partagas and Diaz 1996; Chenoweth 2006) and improved when aerial surveys became widespread in the 1940s (ECCC 2019*b*). From 1900 until 2019, a minimum of 27 tropical storms made landfall over Nova Scotia, approximately one every 4 years (ECCC 2019*b*; NOAA 2019*a*). Hurricane Edna, which passed Nova Scotia as a tropical storm in 1954, is recorded as causing the most forest damage, blowing down over 750 million board feet of standing timber in southwestern Nova Scotia. Since 2000, four tropical storms with maximum sustained winds >50 km·h^{-1} have landed, of which tropical storm Dorian in 2019 was the most powerful, with sustained winds of 65 km·h^{-1}, affecting most of south-central Nova Scotia and causing damage province-wide. While fallen trees and minor windthrow were reported, no detailed surveys of windthrow have been undertaken.

Convective storm cells also cause windthrow in Nova Scotia, but unlike ETC and tropical storms, convective storm cells are produced over land from localized surface air temperature–pressure gradients during days of high heating (usually summer months). These can produce strong vertical downdrafts that track with regional air flow (usually west to east in Atlantic Canada) (Mitchell 2013; ECCC 2019*c*). Convective storm cells are small (10s to 100s km^2), relative to ETC and tropical storms (100s to 1000s km^2) but can be very intense over short time periods. They may take the form of small-scale "downbursts" during thunderstorms or large straight-line "derechos" that develop in association with fast-moving bands of severe thunderstorms, which can cause narrow bands (1–10 km wide) of windthrow extending for kilometres (Mitchell 2013; ECCC 2019*c*). Nova Scotia experiences 5–10 severe (wind gusts > 90 km·h^{-1}) thunderstorms per year (ECCC 2019*a*), but damage is uncommon. Reports from nearby New England and boreal forests indicate that windthrow from convective storm cells varies widely from small, dispersed patches (100–1000 m^2) of downed trees to wide-scale, high-severity windthrow over hundreds of square kilometres (e.g., Lorimer and White 2003; Rich et al. 2007; Bouchard et al. 2009). While rare in Nova Scotia, under specific atmospheric conditions, convective super cells may develop and produce tornadoes, but only three F0 (lowest rank on Fujita scale) tornadoes have been confirmed since 1980 (ECCC 2019*c*).

Despite detailed records of windstorm occurrence for Nova Scotia, few data exist on the spatial extent and severity of windthrow caused by these events. Further, windthrow is difficult to characterize due to spreading of patches and delayed tree mortality after a wind event, and many windthrow gaps are small and difficult to assess from aerial surveys and satellite imagery (DeGrandpre et al. 2018). While studies of windstorms from other regions provide benchmarks of potential damage, limited inferences can be drawn because the climate, physiography, and vegetation of Nova Scotia are unique. To address this shortfall, we used Nova Scotia's extensive forest permanent sample plot (PSP) network to estimate windthrow disturbance rates caused by windstorms. The PSP network consists of 3250 circular plots (400 m^2) randomly located across Nova Scotia's forests. Plots are remeasured by NSDLF every 5 years, with some measurements extending back to the 1960s; however, detailed measurement of windthrow did not begin until 2005. To remove windthrow caused by hurricanes, we only used measurements conducted after 2008 (which avoided windthrow from Hurricane Juan) and selected the most recent census for each plot. Only plots that contained at least 10 living trees (stems > 9.0 cm diameter at breast height) were included to avoid sampling very young, regenerating forest stands. This provided 5-year measurement histories of windthrow for 2785 randomly distributed plots across the province, measured between 2008 and 2017. Windthrow estimates for each plot were obtained by tallying the number of downed trees (attributed to wind by the surveyors) since the last census and calculating the proportion of biomass impacted. This proportion was divided by the number of years since the last census to derive the mean annual windstorm distur-

Fig. 4. Proportion of 2785 permanent sample plots distributed across Nova Scotia and measured between 2008 and 2017, by severity level, both overall and by ecoregion. *A lower limit of 5% was used to define low-severity windthrow to remove the effect of deadfall most likely attributed to natural background tree mortality.



bance rate for each plot. Plot estimates were averaged for the entire province and for each ecoregion.

Provincially, results showed that 93% of plots did not experience any significant (i.e., >5% downed tree biomass) windthrow during the 2008–2017 period (Fig. 4). High-severity (>60% downed tree biomass; Table 2) and moderate-severity (30%–60%) windthrow both had mean annual disturbance rates of 0.02%·year^{-1} (or 5000-year return intervals), while low-severity windthrow (5%–30%) was most common at 1.4%·year^{-1} (71-year return interval). A lower limit of 5% was used to define low-severity windthrow to remove the effect of deadfall in plots most likely attributed to natural background mortality versus trees fallen by strong wind.

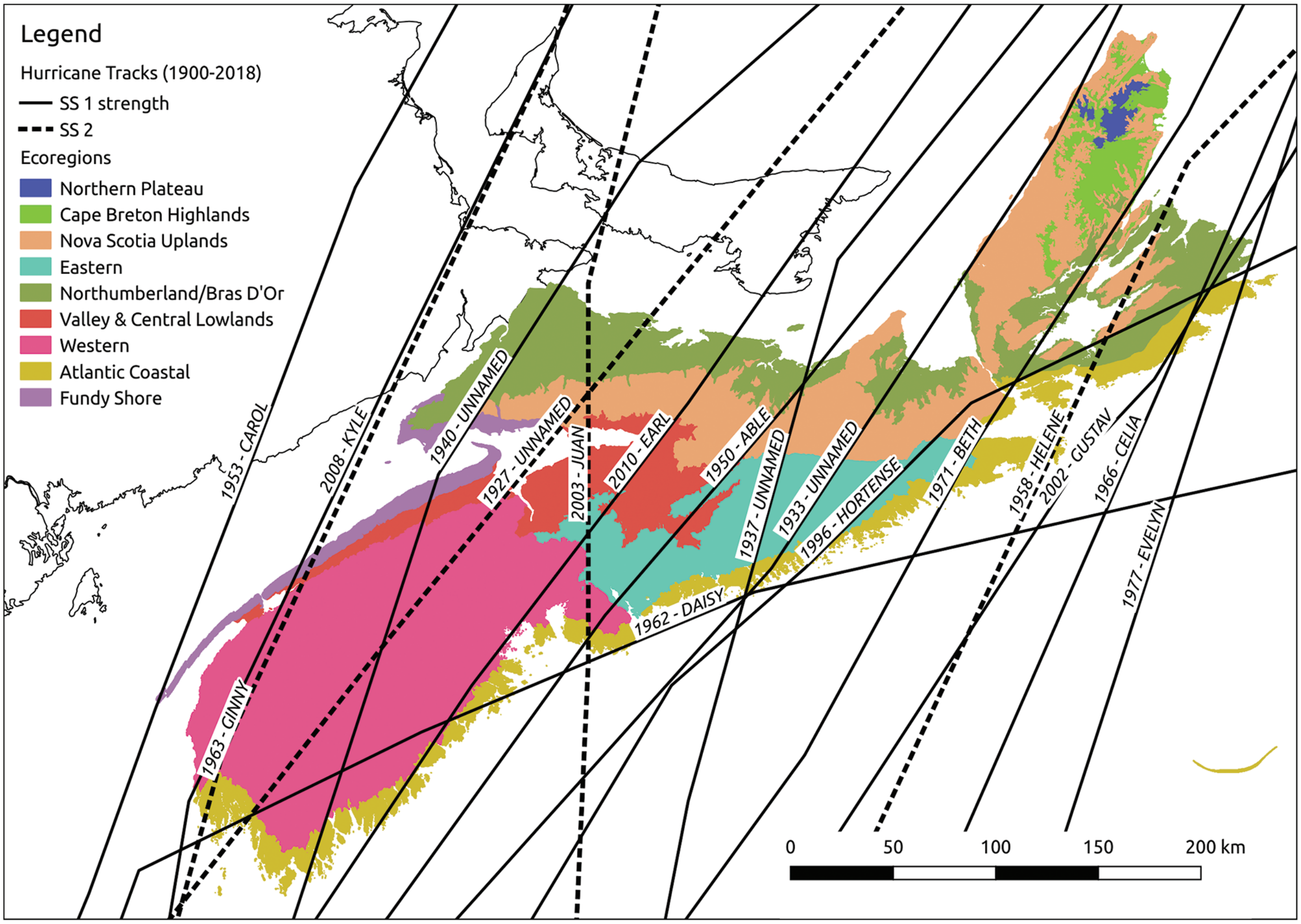
Windstorm disturbance rates only varied marginally by ecoregion, with the Valley and Central Lowlands and Eastern ecoregions having the highest rates of low-severity windthrow, both at ≈2.5%·year^{-1} compared with <1.3%·year^{-1} for all other ecoregions. Moderate- and high-severity windthrow was, generally, very low at <0.1%·year^{-1} for all ecoregions, with most being <0.05%·year^{-1} (Fig. 4). The overall low rate of windthrow detected for the Northern Plateau may be because forests found there are dense, short, and scrubby in stature (e.g., krummholtz or tuckamore) relative to other ecoregions and tend to be confined to sheltered, middle-slope positions (Neily et al. 2017), which reduces windthrow risk (Taylor et al. 2019), despite the fact the Northern Plateau experiences the highest mean annual wind speeds in the province (Keys et al. 2017). On the contrary, the Valley and Central Lowlands and Eastern ecoregions contain some of the most productive and tallest spruce–softwood forests in Nova Scotia, which renders them more susceptible to minor windthrow from windstorms (Neily et al. 2017; Taylor et al. 2019).

3.2.2. Hurricanes

Hurricanes are tropical cyclones that have reached maximum sustained wind speeds of 104 km·h^{-1} (or 1-min maximum sustained winds of 118 km·h^{-1}) and are classified according to the Saffir–Simpson (SS) wind intensity index (NOAA 2019*a*). Nova Scotia has experienced more hurricanes than any other Canadian province (ECCC 2019*b*). From 1900 to 2019, approximately 13 SS1 (104–134 km·h^{-1}) and four SS2 (135–154 km·h^{-1}) hurricanes made landfall over Nova Scotia, on average, one every 7 years (ECCC 2019*b*; NOAA 2019*a*; Fig. 5). There is no record of any hurricane greater than SS2 strength making landfall over Nova Scotia. With the notable exception of Hurricane Juan in 2003, the majority of landfalling hurricanes transit longitudinally through the province's landmass and tend to affect most of the province during an event (ECCC 2019*b*; NOAA 2019*a*; Fig. 5).

As was the case for windstorms, despite frequent reports of hurricane-caused forest damage in Nova Scotia, reliable data on spatial extent and severity of damage are rare. Most relevant studies originate from New England forests where hurricanes cause 1000s of ha of forest damage along their tracks, ranging in severity from creation of forest gaps (10–1000 m^2) to wide-scale (100s ha) windthrow (Foster and Boose 1992; Boose et al. 2001; Lorimer and White 2003). One of the earliest reports of hurricane-caused forest damage in Nova Scotia is by Smith (1802), who witnessed extensive windthrow caused by the Great Storm of 25 September 1798, particularly west of Halifax. He estimated that over a million acres of forest was damaged, stretching from Porter's Lake on the east to Shelburne County on the west and north as far as Windsor (Smith 1802). Similarly, in 1953, Hurricane Carol damaged over 100 000 ha of forest, with many large spruce stands (100s ha) blown flat across western Nova Scotia (Johnson 1955; Dwyer 1958).

Fig. 5. Tracks of hurricanes that made landfall over Nova Scotia, by year and name, from 1900 to 2018. Map created with QGIS v2.18 software using spatial data provided by the Nova Scotia Department of Lands and Forestry and the National Oceanic and Atmospheric Administration.



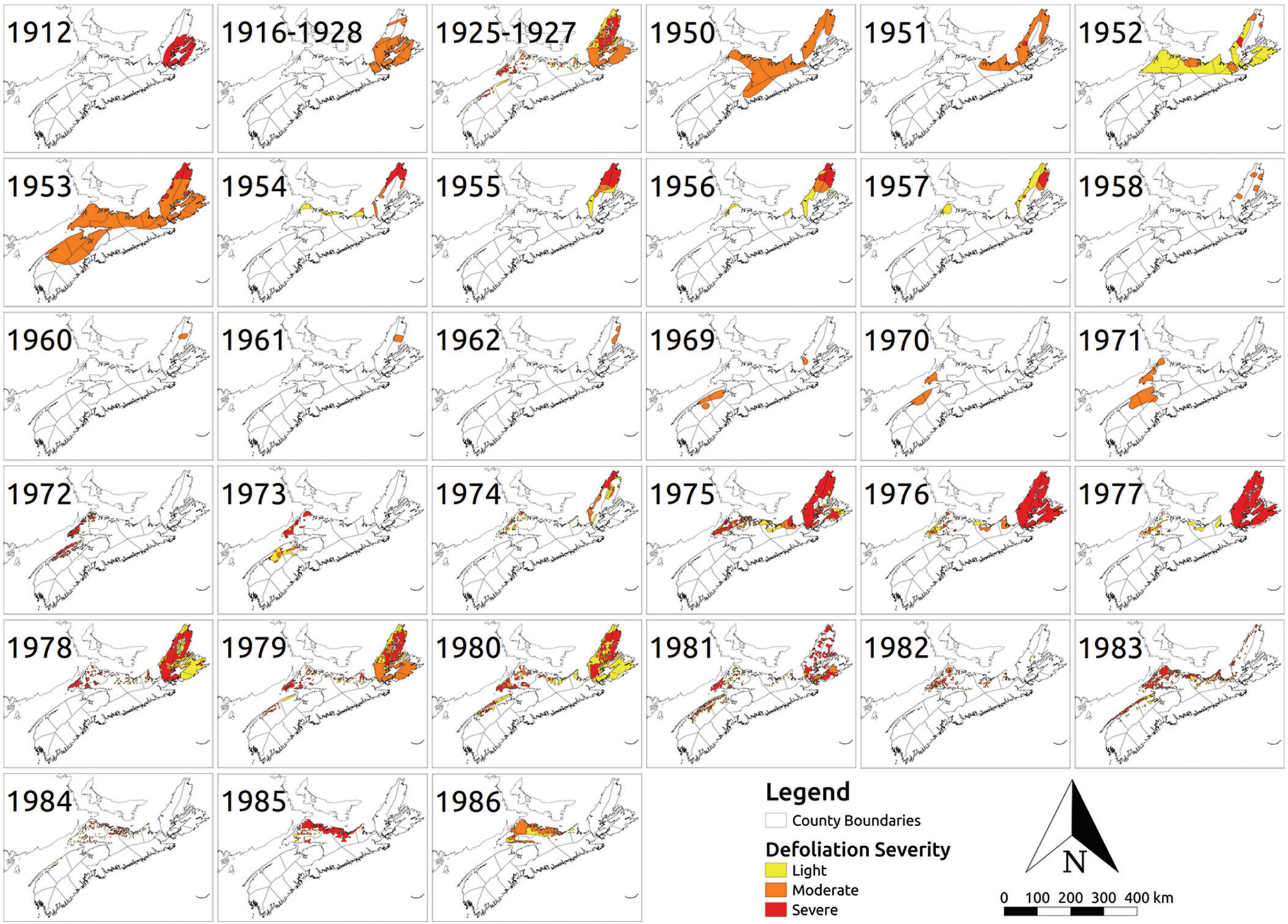
The most documented hurricane damage is from Hurricane Juan in 2003 (e.g., Bruce 2004, 2007; Taylor et al. 2017*b*, 2019), which made landfall near Halifax as an SS2 hurricane, traversed northeasterly over central Nova Scotia, and weakened to a tropical storm as it passed over the Northumberland Strait (Fogarty 2004; Fig. 5). Forest damage caused by Juan spanned over two million hectares, but most of the damage occurred east of the eye of the storm, within a 600 000 ha area. More specifically, using aerial photography and Landsat 5 satellite imagery covering most of the damage extent, NSDLF identified 91 484 ha of windthrow, of which approximately 25% (22 871 ha) was high-severity windthrow (>60% downed tree biomass; Table 2), 46% (41 083 ha) was moderate-severity windthrow (30%–60% downed trees), and 29% (26 530 ha) was low-severity windthrow (<30% downed trees).

Assuming that the area of windthrow detected from Juan is somewhat representative of other land-falling hurricanes and considering that hurricanes make landfall in Nova Scotia (a forest area of 4.2 million ha) every 7 years, on average, then an approximate mean annual disturbance rate for hurricanes can be derived. It follows then that high-severity windthrow caused by hurricanes has a mean annual disturbance rate of 0.08%·year^{-1} (or 1250-year return interval), moderate-severity windthrow has a rate of 0.14%·year^{-1} (714-year return interval), and low-severity windthrow has a rate of 0.09%·year^{-1} (1111-year return interval) for Nova Scotia's forests. However, the disturbance rate for low-severity windthrow is likely underestimated due to difficulty in detecting minor windthrow from remote sensing (Taylor et al. 2019), and low-severity windthrow occurring outside the remote sensing survey area was widely reported after Juan. On the contrary, because Juan was more powerful than most hurricanes affecting Nova Scotia, these rates likely reflect maximum expected disturbance levels rather than average levels, but they are well aligned with hurricane disturbance rates reported for nearby New England forests (Lorimer and White 2003).

3.3. Spruce budworm

Outbreaks of spruce budworm are the most extensive and damaging natural disturbance of balsam fir and spruce tree species in eastern Canada, peaking at over 50 million hectares of defoliation from 1967 to 1993 (Kettela 1983). Spruce budworm outbreaks (i.e., repeated annual defoliation typically lasting up to 10 years) in Nova Scotia have resulted in growth reductions of up to 90% (Ostaff and MacLean 1995), tree mortality in mature balsam fir forests averaging 85% (MacLean 1980; Ostaff and MacLean 1989), and changes in regeneration patterns (Virgin and MacLean 2017). However, because spruce budworm defoliation levels vary by host species (balsam fir > white spruce > red spruce > black spruce; Hennigar et al. 2008), with no defoliation of hardwoods, impacts differ across Nova Scotia. Spruce budworm outbreaks also affect forest landscape structure (i.e., stand species composition and spatial configuration), forest succession (Baskerville 1975), timber production and economics (Chang et al. 2012), and risk of fire (James et al. 2017). Several papers have reviewed the effects of spruce budworm outbreaks on tree mortality (MacLean 1980),

Fig. 6. Spruce budworm defoliation mapped in Nova Scotia in the years from 1912 to 1986. No defoliation was recorded in 1929–1949, 1959, 1963–1968, and 1987–2019. Maps created with QGIS v2.18 software using spatial data provided by the Nova Scotia Department of Lands and Forestry.



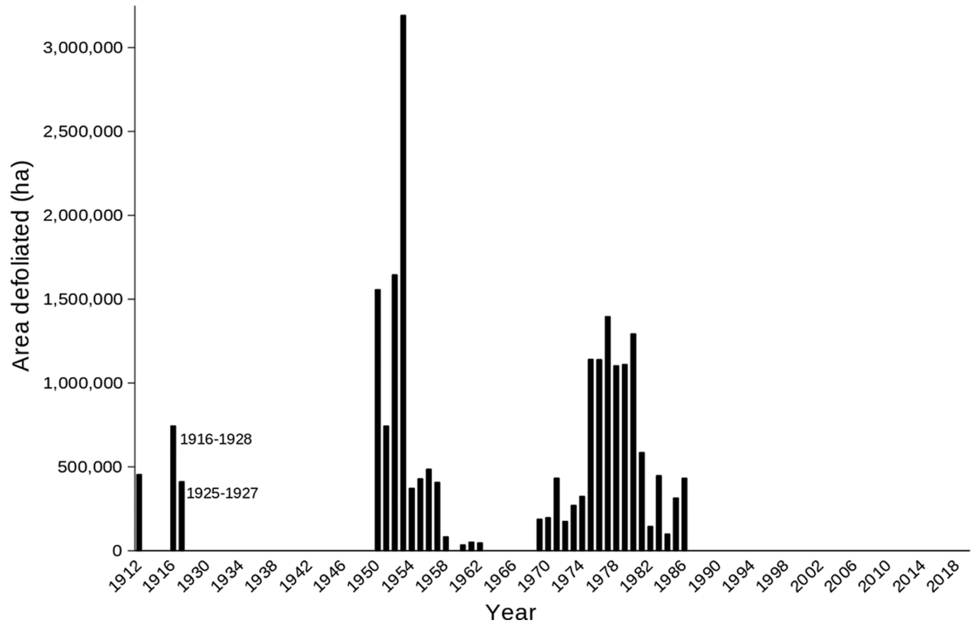
stand development and ecosystem responses (Kneeshaw et al. 2015; MacLean 2016), and ecological mechanisms of spruce budworm population changes during outbreaks (Régnière and Nealis 2007; Johns et al. 2016; Royama et al. 2017).

Recurring cyclic spruce budworm infestations have significantly influenced the successional stage and composition of spruce–fir forests in Nova Scotia. Balsam fir and white spruce trees and stands older than about 40 years are most susceptible to defoliation (Hennigar et al. 2008); red spruce and black spruce and stands <40 years old are less susceptible but not immune to defoliation. In Nova Scotia, the most vulnerable balsam fir ecosystems are primarily in the Nova Scotia Uplands and Cape Breton Highlands ecoregions (Fig. 1), where they cover 235 000 ha (Table 1). However, an additional 424 000 ha across all nine ecoregions have balsam fir as the leading canopy species (Table 1), along with 296 000 ha with white spruce (much in regenerating old fields), 603 000 ha with red spruce – eastern hemlock, and 757 000 ha with black spruce as the leading canopy species (Table 1).

At least seven widespread spruce budworm outbreaks have occurred over the last 250–300 years in eastern Canada (Blais 1968, 1983). Recent analyses of spruce budworm wing scales in sediment cores, extracted from nearly every centimetre of a 500 cm long sediment core, representing 10 000 years of deposition, confirmed that peaks of identified fossil scales corresponded to periods of spruce budworm outbreaks (Montoro Girona et al. 2018). In Nova Scotia, spruce budworm outbreaks have been documented for over 200 years as the primary disturbance in the spruce–fir forests on the Cape Breton Highlands. Evidence of outbreaks was recorded in 1846, 1891–1896, 1911–1915, and 1922–1927 (Hawboldt 1955; NSDLF 1977). Between 1927 and 1950, spruce budworm remained active only in localized areas of northern Cape Breton Island, but between 1951 and 1955, a major infestation occurred in the eastern mainland counties (Cumberland, Colchester, Pictou, Antigonish, and Guysborough; Fig. 1) and throughout Cape Breton Island. By 1956, spruce budworm populations had declined, with the only recorded infestation in 1960–1963 on Cape Breton. Another major outbreak occurred from 1974 to 1981 (Fig. 6), peaking at 1.4 million ha in 1979 (Fig. 7) and resulting in heavy tree mortality.

Maps of defoliation for all years in spruce budworm outbreak periods from 1912 to 2018 (Fig. 6) show that the most severely affected areas were Cape Breton Island and the Northumberland Bras D'Or and Nova Scotia Uplands ecoregions. Spruce budworm defoliation occurred in northwestern Nova Scotia (Kings and Annapolis counties) in a few years, and there is a clear north–south demarcation line, below which little or no spruce budworm defoliation has occurred (Fig. 6). Although balsam fir is the dominant species in the Cape Breton Highlands and Nova Scotia Uplands ecoregions that sustain spruce budworm outbreaks (Table 1), balsam fir is also present in the Western, Atlantic Coastal, and other ecoregions that have little to no spruce budworm activity (Table 1). Hardy et al. (1986) compiled mapped spruce budworm defoliation

Fig. 7. Area of annual mapped spruce budworm defoliation in Nova Scotia from 1912 to 2019. The second and third bars actually represent grouped years of 1916–1928 and 1925–1927, respectively. Annual maps are presented in Fig. 6.



across eastern North America from 1938 to 1980, which also clearly showed that there is a zone in southern Nova Scotia, southern Maine, and the northern Lake States below which spruce budworm outbreaks do not occur. It seems likely that this is controlled by climate and, in particular, effects of temperature on overwintering survival of spruce budworm larvae (Régnière et al. 2012). Han and Bauce (1997) experimentally exposed spruce budworm larvae in an early stage of development to different temperatures, and longer duration of exposure to higher temperatures increased diapause intensity and reduced larval survival.

Compilation of mapped surveys of spruce budworm defoliation across eastern Canada since 1938 by Hardy et al. (1986) showed that spruce budworm outbreaks in Nova Scotia have always followed earlier infestations to the north in Quebec and New Brunswick. The 1950s outbreak in Nova Scotia (Fig. 6, 1950–1958) actually began in 1938 in Ontario, spread through Ontario and Quebec from 1939 to 1944, spread north to south through New Brunswick from 1945 to 1949, and reached Nova Scotia in 1950 (Hardy et al. 1986). Defoliation was mapped in Nova Scotia each year from 1951 to 1958 but was restricted to Cape Breton and the eastern mainland of Nova Scotia in all years except 1953. Defoliation declined in Quebec and New Brunswick in the late 1950s and early 1960s, and by 1962–1967, the only outbreak remaining was in central New Brunswick and northern Maine (Hardy et al. 1986). Expansion of the 1970s outbreak began in southern New Brunswick in 1968 and defoliation was mapped in Kings and Annapolis counties, Nova Scotia, in 1969–1973, eastern mainland Nova Scotia from 1975 to 1986, and Cape Breton from 1974 to 1981 (Fig. 6). A spruce budworm moth migration, presumably across the Bay of Fundy from central New Brunswick, resulted in the infestation in Annapolis and Kings counties (NSDLF 1977).

The 1970s–1980s spruce budworm outbreak resulted in heavy balsam fir mortality on Cape Breton Island and throughout the eastern mainland (NSDLF 1982*a*, 1982*b*; NSDNR 1994). On Cape Breton Island, the spruce budworm population crashed in 1982, but defoliation and mortality continued on the eastern mainland until 1987 (Guscott 2001; NSDLF 1977). Mortality on Cape Breton covered 629 900 ha, reduced the growing stock of spruce and balsam fir by 70% or 21.5 million m^3 (NSDLF 1982*a*), and increased the hardwood cover type from 16% to 36% (NSDNR 1994). Balsam fir mortality in Cape Breton caused by spruce budworm averaged 87% (MacLean and Ostaff 1989), and maximum growth reduction on surviving trees was 74%–92% (Ostaff and MacLean 1995). Losses to spruce budworm in Cumberland County were 3.2 million m^3, 20% of the merchantable volume (NSDLF 1982*b*).

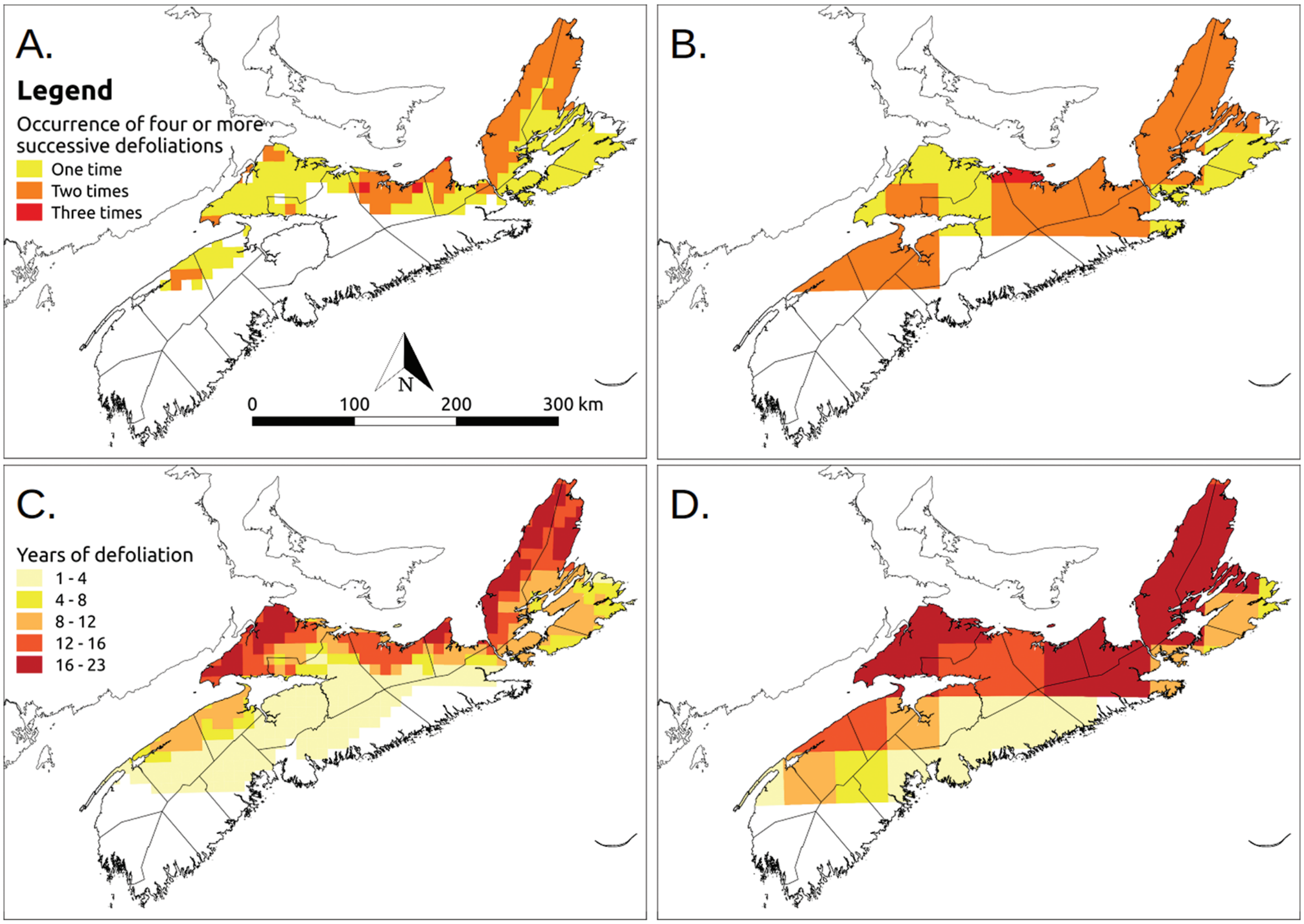
Figure 8 summarizes spruce budworm defoliation survey data from 1912 to 2019, at 10 km × 10 km and 50 km × 50 km scales, in terms of occurrences of four or more successive years of defoliation (which are likely to result in balsam fir mortality; MacLean 1980) and total number of years of defoliation. Most areas that sustained spruce budworm outbreaks in Nova Scotia had either one or two periods of four or more years of defoliation, and only three grid cells had three such periods (Fig. 8A). However, across outbreaks, many grid cells had a total of 15–20 or more years of defoliation (Fig. 8C). The absence of outbreaks in southern and western Nova Scotia is clear.

3.4. Other insects and diseases

Larch sawfly (*Pristiphora erichsonii* (Hartig)) has defoliated extensive areas of larch forests in Nova Scotia, often causing mortality (Fig. 9B). Larch sawfly preferentially attacks relatively pure stands of larch but can also target isolated trees. Defoliation in a single year is usually of little consequence, but repeated damage over several years will kill a tree. There is uncertainty as to whether this insect is native to North America; however, its first recorded outbreak in Canada occurred at Bury, Quebec, in 1878, and by the late 1880s, much of the mature larch throughout North America was dead. The Chief Forester for Nova Scotia reported (Anonymous 1926–1929) that larch sawfly and larch casebearer (*Coleophora laricella* (Hubner)), which had completely killed off the larches in the 1880s, resurged in 1927. Several larch sawfly outbreaks have occurred since then, with large losses occurring in 1936, and severe damage from 1974 to 1977 in much of Nova Scotia (Fig. 9B).

White-marked tussock moth (*Orgyia leucostigma* (J. E. Smith, 1797)) was first reported in 1937 and defoliation was mapped in the 1940s, 1950s, and 1980s (Fig. 9F; Thurston 2002). White-marked tussock moth defoliated 590 900 ha of balsam fir forests between 1996 and 2000 in Halifax, Hants, Cumberland, Colchester, Pictou, and Antigonish counties, resulting in extensive mortality to balsam fir trees in the central and eastern mainland counties by 1999 (Thurston 2002). Broad-leaved trees are the preferred food of this

Fig. 8. Summary of spruce budworm outbreak occurrence in Nova Scotia from 1912 to 2019, summarized at two scales: 10 km × 10 km (A, C) and 50 km × 50 km (B, D). Maps A and B show occurrences of four or more successive years of defoliation, and maps C and D. show number of years of defoliation. Maps created with QGIS v2.18 software using spatial data provided by the Nova Scotia Department of Lands and Forestry.



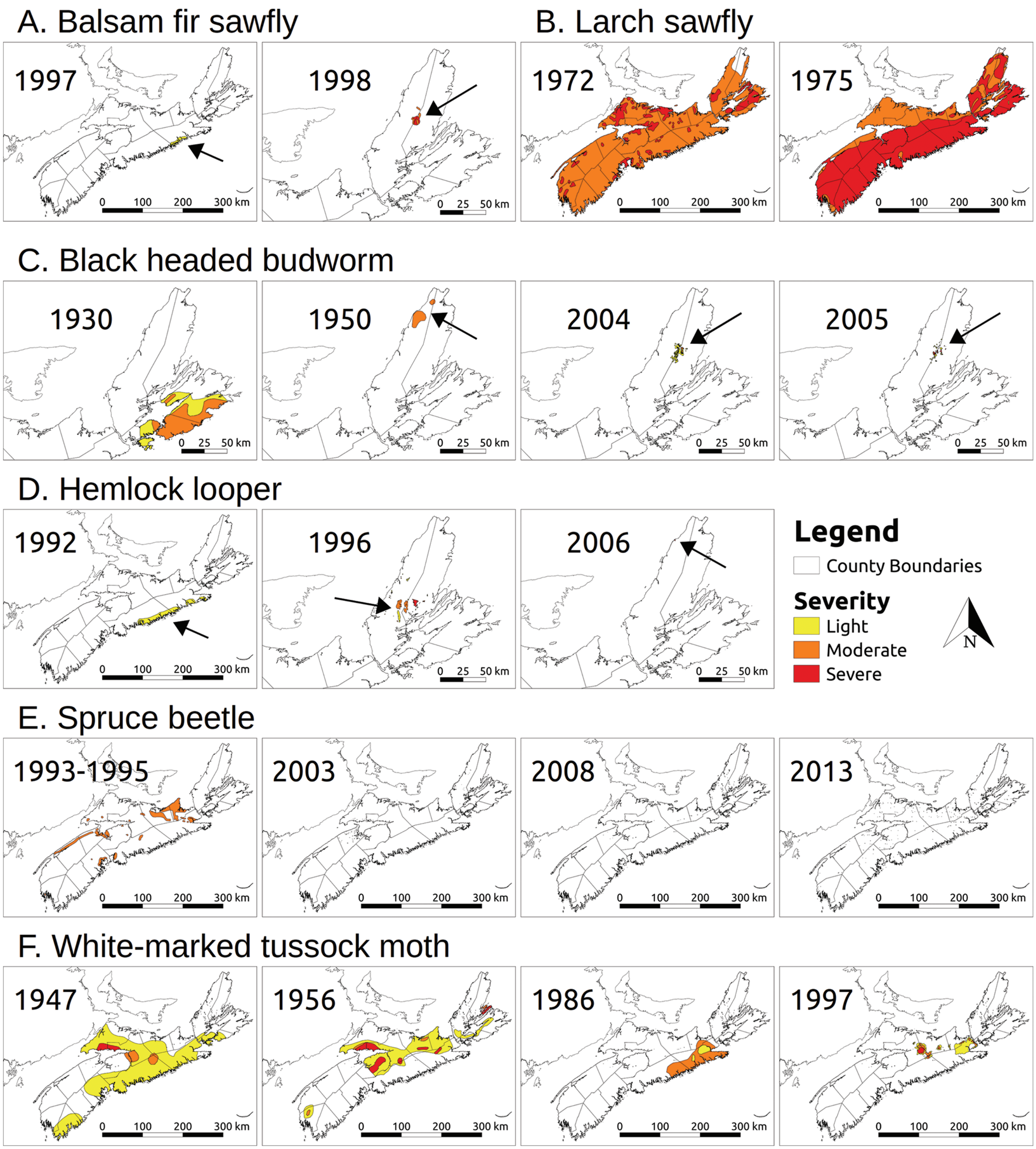
species, but when populations are high, balsam fir, white spruce, and larch are also susceptible.

Spruce beetle (*Dendroctonus rufipennis* (Kirby, 1837)) is a primary disturbance agent in uneven-aged spruce forests, creating many of the gaps associated with this disturbance type (Ostaff and Newell 1981). First identified in Canada in 1923, this insect attacks the tree bole, living under the bark and feeding on the phloem. At low population densities, spruce beetle prefers weakened or downed host material; however, during outbreaks, all spruces, regardless of age, size, or health, are susceptible. In the 1940s, mortality due to spruce beetle was observed on the islands near Argyle, Yarmouth County, with estimated losses of 10%–15% of wood volume. Following the 1970s–1980s spruce budworm outbreak, weakened red spruce in many parts of the province succumbed to spruce beetle. White spruce on Cape Breton Island during the 1970s–1980s spruce budworm outbreak began to die after 6 years of defoliation and reached 27% mortality, but an additional 39% of the weakened spruce was killed by the spruce beetle (Ostaff and MacLean 1989). In the 1990s, spruce beetle induced mortality was widespread in mature old field white spruce, especially in eastern Nova Scotia and along the North Mountain of the Annapolis Valley (Fig. 9E). NSDLF surveys have documented spruce beetle induced mortality in old-growth red spruce – hemlock stands, typically killing the 100–150 year age cohort and resulting in canopy gap formation. In the 19th and 20th centuries, extensive spruce beetle induced mortality of spruce occurred from New York to New Brunswick (Hopkins 1901; Seymour 1992).

Other native insects capable of inflicting serious damage include hemlock looper (*Lambdina fiscellaria* (Guenée in Boisduval and Guenée, 1858)) (Fig. 9D), balsam fir sawfly (*Neodiprion abietis* (Harris) (Fig. 9A), eastern blackheaded budworm (*Acleris variana* (Fernald, 1886)) (Fig. 9C), and the pale winged grey (*Iridopsis ephyraria* (Walker, 1860)). Outbreaks of these insects have generally been localized (Fig. 9) and few data are available to understand their disturbance regimes. Damage by the non-native hemlock wooly adelgid (*Adelges tsugae* (Annand)) has reached almost 18 000 ha, ranging from moderate defoliation to mortality in the Western ecoregion, based on NSDLF aerial surveys in 2018.

Forest pathogens in Nova Scotia seldom cause mortality in mature forests but can significantly affect tree growth and development. The numerous blights, rusts, and other fungal diseases present in the forests only cause mortality when repeated infections occur over several years. Forest pathogens often follow other agents such as insects, environmental and site stresses, or animal predation that have weakened trees and created conditions that eventually lead to mortality. As such, forest diseases are a significant driver of forest gap dynamics in that individual tree mortality creates opportunities for a younger tree cohort to enter the canopy. The only disease significant enough to be included in the NSDNR annual reports on forest pests in Nova Scotia in the last

Fig. 9. Maps of insect damage or defoliation in Nova Scotia. The maps shown are the only surveyed occurrences for balsam fir sawfly, blackheaded budworm, and hemlock looper outbreaks. Spruce beetle damage was observed in 10 years, white-marked tussock moth was observed in 15 years, and larch sawfly was observed in 5 years, but only selected years are shown. Maps created with QGIS v2.18 software using spatial data provided by the Nova Scotia Department of Lands and Forestry.



decade was *Sirococcus* shoot blight (*Sirococcus conigenis* D.C.) in 2008 only (NSDNR 2008). *Sirococcus* shoot blight is a fungal disease widely distributed throughout the Maritime Provinces affecting red pine and black and white spruce, which only kills the current year's shoots, but repeated infections can kill the tree (Wall and Magasi 1976). Damage from *Sirococcus* shoot blight in red pine plantations occurred throughout central Nova Scotia, increasing from low to moderate in 2006 to moderate to severe in 2007, and is believed to have been caused by wet springs in 2004, 2006, and 2007 (NSDNR 2008). Earlier annual forest pest surveys conducted

Table 4. Serious introduced insects and diseases that affect Nova Scotia forests.

Introduced insect or disease	Year	Location	Preferred host
Beech bark disease	1897	Halifax*	American beech
Balsam woolly adelgid	1910s	Western Nova Scotia*	Balsam fir
European spruce sawfly	ca. 1936	Unspecified	Spruce spp.
Mountain-ash sawfly	ca. late 1930s	Unspecified	Mountain ash
White pine blister rust	1929	Chester	Eastern white pine
European winter moth	ca. 1930	Southern Nova Scotia*	Oak spp.
Dutch elm disease	1969	Liverpool	American elm
Gypsy moth	1980	Yarmouth	Hardwood spp.
Brown spruce longhorned beetle	1999	Halifax*	Red spruce
Beech leaf-mining weevil	2012	Halifax, Sydney, Chester*	American beech
Hemlock woolly adelgid	2017	Weymouth	Eastern hemlock
Emerald ash borer	2018	Bedford	Ash spp.

Note: Location refers to where the pest was first reported in Nova Scotia. An asterisk (*) after a location indicates Nova Scotia as the first report of the pest or disease in North America.

by the Canadian Forest Service in Nova Scotia (e.g., Magasi 1983) reported various diseases such as European larch canker (caused by the fungus *Lachnellula willkommii* (Hartig) Dennis); Scleroderris canker (caused by *Gremmeniella abietina* (Lagerb.) Morelet), which infects plantations of jack pine and red pine; and shoot blight of conifers (caused by *Sirococcus strobilinus* Preuss), which infects and kills newly developed shoots, fruits on the twigs, needles, and cone scales. Shoestring root rot (caused by *Armillaria ostoyae* (Romagnesi) Herink 1973) is present in all soils in the province. NSDLF surveys have determined that it has caused significant mortality in balsam fir and white spruce trees in Shelburne, has killed the red maple component in mature red spruce stands, and possibly plays a significant role in the dynamics of coastal balsam fir stands. There are clearly many diseases of forest trees that cause local or species-specific damage, but they do not typically cause widespread forest disturbance.

The introduction of non-indigenous forest insects and diseases to Nova Scotia has had significant impacts on individual tree species such as beech and elm. Most of these pests arrived during the last century to eastern North America in shipments from Europe. Most notably, beech bark disease and Dutch elm disease (Loo 2009) have had the most significant impacts (Taylor et al. 2013). Beech was once the dominant tree species of many hardwood forests across Nova Scotia (Fernow 1912) but has now been relegated to the understory, no longer providing the quantity of nuts that it once did for wildlife forage. A more recent insect introduction of the beech leaf-mining weevil (*Orchestes fagi* L.) in Halifax, identified in 2012, has compounded negative impacts on beech, causing mortality after several successive years of defoliation, including healthy trees. Elm has been widely eliminated from native riparian areas along rivers. Although not of significant timber value, elm did fulfill a vital role in the ecology of these habitats by providing shade, acting as a pump, cycling soil nutrients, and providing habitat for cavity nesting species of birds and small mammals (Bey 1990). Some of the most serious introduced insects and diseases include white pine blister rust (*Cronartium ribicola* J.C. Fisch), beech bark disease, beech leaf-mining weevil, balsam woolly adelgid (*Adelges piceae* Ratzeburg), hemlock woolly adelgid, European winter moth (*Operophtera brumata* L.), European spruce sawfly (*Gilpinia hercyniae* Hartig), gypsy moth (*Lymantria dispar dispar* L.), Dutch elm disease, mountain-ash sawfly (*Pristiphora geniculata* Hartig), brown spruce longhorn beetle (*Tetropium fuscum* Fabricius), and emerald ash borer (*Agrilus planipennis* Fairmaire) (Table 4). Many of these are host species specific, so the extent of their impact is determined by host species occurrence, and several are severe enough to decimate that species.

3.5. Other disturbances

Numerous other forms of natural disturbances are documented for Nova Scotia's forests and are generally considered to be of minor or local importance or little is known about their impacts. These include climate-related disturbances such as ice storms, drought, floods, and temperature extremes; geological disturbances, including landslides and karst sinkhole formation; and disturbances originating from animals such as beaver, hare, porcupine, deer, and moose.

Nova Scotia receives 10–20 freezing rain episodes each year, with some producing enough surface ice to damage trees (ECCC 2019*c*). The most severe ice storm ever recorded for eastern North America was the "Ice Storm of the Century" in January 1998. This storm damaged over 10 million ha of forests across northeastern US, southern Ontario and Quebec, and the Maritime Provinces (Irland 1998; Miller-Weeks et al. 1999), including over 100 000 ha of damage in Nova Scotia (Neily et al. 2008). Surveys of affected areas in New England found >50% of sampled trees experienced no damage, whereas 12% had sustained enough damage that survival was unlikely (Irland 1998; Miller-Weeks et al. 1999). In February 2003, another ice storm caused approximately 110 000 ha of damage to hardwood forests and young plantations across Nova Scotia (Guscott 2003). However, aside from these two documented cases, there has been little effort to quantify forest damage from ice storms.

Similarly, notable examples of damage caused by drought, flooding, and extreme temperatures have been recorded, but long-term estimates of frequency, extent, and severity of damage are not available. The most severe drought to affect Nova Scotia in 100 years occurred during the summer of 2016 (ECCC 2019*a*; Agriculture and Agri-Food Canada (AAC) 2019), with some Christmas tree growers reporting up to 20% mortality of balsam fir seedlings that year (Parsons 2016). Spring thaw and storm-related flooding occur regularly throughout Nova Scotia, with over 150 notable flood events during the 20th century, some damaging trees, particularly along river and stream banks (http://nsfloodhistory.management.dal.ca/). Late spring frosts can cause bud and shoot damage to trees and kill small seedlings (Lester et al. 1977; Man et al. 2009). While uncommon, a severe frost on 4 June 2018, caused by record low temperatures (−2 to −5 °C; ECCC 2019*a*), led to widespread browning of new balsam fir shoots and defoliation of oak and ash trees across large portions of Nova Scotia (Tutton and Thomson 2018).

Colluvial disturbances such as landslides involve mass movement of materials down steep-sided slopes such as rock falls along cliffs (Finck 1993; Monroe and Wicander 2014). Landslides are most common in the Cape Breton Highlands ecoregion where well-drained, steep slopes are frequently covered with talus (Finck 1993). Other notable areas of talus slopes occur along North Mountain (Annapolis Valley) and throughout the Cobequid Mountains (Neily et al. 2008). Karst sinkholes (natural depressions or holes in the Earth's surface) are generally caused by chemical dissolution of water-soluble carbonate rocks or gypsum and are most common in parts of central and eastern Nova Scotia. Sinkholes can

Table 5. Summary of spatial extent, severity, and return interval of natural disturbance regimes in Nova Scotia.

			Disturbance[a]				
Variable	Levels	Classes	Fire	Windstorm	Hurricane	Spruce budworm	Others[i]
Spatial extent (ha)	Wide scale	>500	F[c]	W	H	S	O1
	Medium scale	500–50		W			
	Small scale	<50					O2
Severity (% of stand killed)	High	>60	F1[d]	W1[f]	H1[g]	S1[i]	
	Moderate	60–30	F2[d]	W2[f]	H2[g]	S2[i]	
	Low	<30		W3[f]	H3[g]	S3[i]	O1, O2
Return interval (years)[b]	Long term	>150	F[e]	W1, W2	H1, H2, H3		O1[j]
	Medium term	50–150		W3			
	Short term	<50				S[i]	O2[j]
Mean annual disturbance rate (%·year^{-1})[b]			0.17–0.4[e]	0.02–1.4[f]	0.08–0.14[g]	0.5–2.1[h,i]	N/A

Note: For definition of classes, see Table 2. Return intervals and mean annual disturbance rates apply to eligible forest areas only (see Table 2 definitions).

[a]Numbers following letters (e.g., F versus F1 or F2 for fire) indicate different regime types for a particular disturbance agent. For instance, all fire is considered wide scale and long term (i.e., "F") but tends to occur at two different severity levels (high = F1 and moderate = F2).

[b]Fire (F) rates vary according to species, ecoregion, and ecosite and apply to forest areas classified as a particular ecosite type. For windstorms (W) and hurricanes (H), rates apply to the whole provincial forest area. For spruce budworm (S), rates vary by host-tree species and abundance and apply only to proportions of forest stands containing such species. The "others" (O) category includes a variety of different disturbance agents, including other insects and diseases, ice storms, drought, mammals, etc. Although these other disturbances can be locally important, and in some cases devastating to individual tree species, much less is known of their regimes and (or) if they contribute little to overall natural disturbance in Nova Scotia. While general return intervals for other disturbances (O) are provided here (see footnote *i* below for further explanation), meaningful mean annual disturbance rates could not be estimated (N/A).

[c]Based on relative fire occurrence: area burned and number of years with >200 ha burned under fire suppression from 1950 to 2018 for both human-caused and lightning ignitions (Table 3). Fire spatial extent varies by ecoregion and is largest in the Western, Northumberland Bras D'Or, and Eastern ecoregions; smaller in the Atlantic Coastal and Valley and Central Lowlands ecoregions; and smallest in the Northern Plateau, Cape Breton Highlands, Nova Scotia Uplands, and Fundy Shore ecoregions.

[d]Fire severity is usually either F1 (high, >60% of stand killed) or F2 (moderate, only 30%–60% of stand killed).

[e]Fire return intervals vary from 250–600 years depending on species and ecosite: black spruce – pine, 250–300 years; black spruce – white pine, 350–400 years; Acadian tolerant softwood, 500 years; Acadian tolerant hardwood, 500 years; and lowland black spruce, 600 years. These equate to mean annual disturbance rates of 0.33%–0.40%·year^{-1} for black spruce – pine; 0.25%–0.29%·year^{-1} for black spruce – white pine; 0.20%·year^{-1} for Acadian tolerant softwood and tolerant hardwood; and 0.17%·year^{-1} for lowland black spruce.

[f]Windstorm (W) return interval, calculated based on data from 2785 permanent sample plots for the years 2008–2017 for W1 and W2 (high- and moderate-severity windthrow, respectively) averaged 5000 years (0.02%·year^{-1}) for all of Nova Scotia. For W3 (low severity windthrow, 5%–30% mortality), it was only 71 years (1.4%·year^{-1}).

[g]Based on data from Hurricane Juan surveys, H1 (high-severity windthrow) had a return interval of 1250 years (0.08%·year^{-1}), H2 (moderate severity) had a return interval of 714 years (0.14%·year^{-1}), and H3 (low severity) had a return interval of 1111 years (0.09%·year^{-1}) for all of Nova Scotia. Note that low-severity windthrow from hurricanes is likely underestimated by our data.

[h]Spruce budworm (S) outbreak severity (% tree mortality) varies with host species: S1, balsam fir, >60%; S2, white spruce and red spruce, 60%–30%; and S3, black spruce, <30%. Assuming a 40-year return interval and prorating area disturbed by host mortality rate (balsam fir, 85%; white, red, and black spruce, 60%, 40%, and 20%, respectively), mean annual disturbance rates would be as follows: S1, 2.1%·year^{-1} for balsam fir; S2, 1.5%·year^{-1} for white spruce; S3, 1.0%·year^{-1} for red spruce; and S3, 0.5%·year^{-1} for black spruce. Balsam fir abundance is highest in the Cape Breton Highlands, Nova Scotia Uplands, Northern Plateau, and Northumberland Bras D'Or ecoregions and lower in the Valley and Central Lowlands ecoregions.

[i]Spruce budworm outbreak occurrence and severity vary depending on location in Nova Scotia (see Fig. 8): every 30–40 years and moderate to severe in Cumberland, Colchester, Pictou, Antigonish, Inverness, and Victoria counties; every 30–40 years and low to moderate severity in Annapolis, Kings, Hants, Guysborough, Richmond, and Cape Breton counties; and very low or no outbreaks in Digby, Yarmouth, Shelburne, Lunenburg, and Halifax counties.

[j]Other disturbances were divided broadly into O1 (ice storms, temperature extremes, and drought) as wide scale and long term and O2 (all other disturbances) that are generally small scale and short term. Both types are mostly low severity, often causing less than 5% mortality during a single disturbance agent event.

disturb forests rapidly if the overlying forest area "caves in" due to the removal or weakening of underlying bedrock, or they may form more gradually over long periods of time. Approximately 1057 sinkholes have been recorded, varying widely in size from 1 m to 600 m in both diameter and depth (Nova Scotia Department of Energy and Mines (NSDEM) 2019). Unfortunately, data on how much forest is disturbed by landslides or sinkholes are unavailable but it is likely much less than 0.01%·year^{-1}.

Disturbance caused by animals is usually confined to individual trees. The beaver (*C. canadensis*), an "ecosystem engineer" (Jones et al. 1994), is likely the most recognizable example of animal disturbance to forests in Nova Scotia (Novak 1987; Banks 1999). While no formal surveys of beaver damage are available, cutting of trees and flooding of land by beavers is commonly observed across the province. Other animals frequently causing damage to individual or small patches of trees include porcupines, snowshoe hare, and moose. Porcupine damage to commercial crop trees has been a concern to forest managers in Nova Scotia for many years (e.g., Reeks 1942). Porcupine feed on bark and sapwood peeled from conifers of all age classes and have been documented to kill >1% of crop trees annually in stands where high populations (50–70·km^{-2}) exist (Reeks 1942; Curtis 1944; Eglitis and Hennon 1997). While damage is not always life threatening, it may create a situation in which a secondary agent could kill the tree. Snowshoe hare are found throughout Nova Scotia but tend to inhabit conifer thickets and alder swamps. Local populations undergo periodic fluctuations and small seedlings can be devastated when large numbers of hares are present (Orr and Dodds 1982; Stewart 1996). Hyperabundant populations of large herbivores such as moose have been known to change forest community species composition (Connor et al. 2000; Rae et al. 2014). A study on northern Cape Breton Island showed that 65% of balsam fir and white birch saplings were severely browsed by moose, resulting in stunted, abnormal growth forms (Smith et al. 2010). Such severe moose browsing in areas regenerating after a spruce budworm outbreak can significantly inhibit forest regeneration and, indeed, has resulted in the formation of extensive grasslands in areas that were previously forested in Cape Breton (Basquill and Thompson 1997; Bridgland et al. 2007; Smith et al. 2010).

4. Summary of natural disturbance extent, severity, and return interval

A summary of the spatial extent, severity, and return interval of natural forest disturbances in Nova Scotia is presented in Table 5, as well as important supporting information to clarify the derivation of and assumptions involved in the summary data on each major natural disturbance presented in the table. Overall, we found that fire, hurricanes, and spruce budworm are, by far, the most important natural disturbance agents in Nova Scotia's forests. These are the primary natural agents that can cause substantial areas of stand-replacing disturbance and, depending on conditions, also contribute to many partial stand replacing disturbances. Damage caused by windstorms mainly causes gap formation or partial stand replacement but occurs more frequently (medium-term return interval, 50–100 years). Other forest disturbances such as insects other than spruce budworm, diseases, ice storms, mammal browsing, etc., can be locally important and in some cases devastating to individual tree species, but at the provincial or ecoregion scale, they occur mainly as very low severity disturbances (<5% mortality during a single event), tend to be tree species specific (e.g., spruce beetle), and overall contribute relatively little to natural disturbances in Nova Scotia.

Our review suggests that the return interval of natural fire is long term (>150 years), the spatial extent is wide scale (>500 ha), the severity is moderate (30%–60% of stand killed) or high (>60% of stand killed), and the mean annual disturbance rate ranged from 0.17% to 0.4%·year^{-1} (Table 5). More details about this derivation are described in footnotes *a* to *e* of Table 5. Interpretation of the natural fire regime, however, is difficult because effective fire suppression over the past 75 years has substantially changed its character, and most fires in Nova Scotia are now of human-caused origin. The modified, human-caused fire regime that began upon early settlement and continues to this day (albeit with suppression) should not be the regime that we emulate in designing prescriptions for ecological forestry. Therefore, we based our derivation of natural fire return intervals in Table 5 on results of radiocarbon dating for different stand types and ecosites that ranged between 250 and 600 years for the period 1800–250 years BP (Ponomarenko 2018), which coincides with other paleoecological studies for that time period in the region. However, the importance of natural fire in Nova Scotia undoubtedly varies by ecoregion (Table 3), and as future data on historic natural fire extent and frequency by ecoregion become available, it may change estimated disturbance rates across the province. The fire return interval was even shorter for much of the last 250 years, at <100–200 years (Ponomarenko 2018). These estimates align well with calculations of burned areas on maps produced at the turn of the 20th century, which showed post-settlement, pre-suppression fire return intervals of just over 200 years (Wein and Moore 1979). However, fire return intervals calculated for Nova Scotia from 1915–1975 (i.e., the suppression era) were 1000 or 2500 years, using the mean annual burn or median annual burn, respectively (Wein and Moore 1979). The much longer return interval based on median annual burns reflects the predominance of very small, suppressed fires. Thirty percent of fires occurred in the month of May, before green-up (Wein and Moore 1979), and area burned is always a function of suitable fire weather and fuel conditions. Without suppression, it is likely that natural, lightning-caused fires would be a more important disturbance in parts of Nova Scotia's forests, especially in the Western, Northumberland Bras D'Or, and Eastern ecoregions. Both Green (1981) and Ponomarenko (2007) provided evidence of large intense historical fires, 11 000 – 6000 years BP and 500–1500 years BP, respectively. Some lightning-caused fires that occurred without suppression, under high fire severity conditions (high wind, drought, and high temperature), would probably be wide scale (>500 ha) and high severity (>60% of biomass killed). One way to evaluate the potential importance of unsuppressed lightning-caused fires would be to model their fire spread under hypothetical high fire severity conditions without suppression and to quantify the occurrence probability of both lightning fire starts and high-severity spread conditions.

Hurricanes make landfall somewhere in Nova Scotia every 7 years, on average, and result in wide-scale, low- to high-severity forest damage (Table 5). More details of data for windstorms and hurricanes are described in footnotes *f* and *g* of Table 5. Using Hurricane Juan as an example, of all forest area damaged, 25% was high severity, 46% was moderate severity, and 29% was low severity, but the low-severity rate is likely underestimated. Although hurricane tracks vary across the province (Fig. 5) and can be narrow or broad, the overall province-wide return interval is very likely >150 years. Few data are available on the spatial extent and severity of damage from hurricanes, and this is an area warranting future research. Analyses of damage following Hurricane Juan showed that wind speed and forest structure, specifically stand height and species composition, were most influential in determining windthrow (Taylor et al. 2019). Maximum sustained winds of at least 95 km·h^{-1} or gusts of 130 km·h^{-1} caused >50% probability of windthrow, but taller stands were most vulnerable, especially those dominated by spruce and balsam fir, whereas higher hardwood and pine abundance reduced windthrow (Taylor et al. 2019). As a result, prediction of hurricane damage and effects on resulting natural disturbance regimes should be amenable to modelling.

Spruce budworm outbreaks are the other major recurrent natural disturbance in Nova Scotia. Outbreaks in Nova Scotia always follow outbreaks to the north in Quebec and New Brunswick and have a short return interval (<50 years; typically 30–40 years) (Table 5) in that part of Nova Scotia where they occur, which excludes southern and western parts of the province (Fig. 8). Spruce budworm disturbance differs from fires or hurricanes in that it is host species dependent (only affecting balsam fir and spruce species), with mortality levels differing by species; see Table 5 and more detailed description in footnotes *h* and *i* of Table 5. In Nova Scotia, outbreak occurrence is also location dependent and, to a degree, ecoregion dependent. Balsam fir abundance and damage resulting from spruce budworm outbreak are high in the Cape Breton Highlands, Nova Scotia Uplands, Northern Plateau, and Northumberland Bras D'Or ecoregions and low to moderate in the Valley and Central Lowlands ecoregion. The Atlantic Coastal ecoregion has high balsam fir abundance (Table 1), but much of it occurs in an area where no spruce budworm outbreaks have been recorded in much of southern and western Nova Scotia (Fig. 8), which probably reflects the southern range limit of spruce budworm. However, within balsam fir forests, high-severity and wide-scale damage occurs. In the 1970s–1980s spruce budworm outbreak, an average of 87% of mature balsam fir was killed on the Cape Breton Highlands (MacLean and Ostaff 1989).

It is important to emphasize that the above-mentioned return intervals reflect "landscape averages" and do not necessarily occur equally across the province or within ecoregions. Ecosystem variation reflecting enduring physical features will strongly influence factors that govern disturbance occurrence frequencies and severity and resulting vegetation patterns. Also, the direction and rate of forest succession following disturbance (particularly fire) will result in variable fire risk over time beginning with a period of low risk and leading towards higher risk as fuel loads build (fire), tree heights increase (windthrow), and tree vigour declines (insects, fungus). Vegetation influences disturbance risk, and vegetation, in turn, is influenced by enduring physical features, time and forest developmental processes, landscape patterns that determine spread, and disturbances (both natural and human-caused).

There are also relationships and co-dependencies between these three dominant disturbances. Spruce budworm outbreaks significantly increase forest fire potential in spruce budworm killed balsam fir stands, with resultant fuel complex rearrangement and increased surface fuel loads peaking 5–8 years after mortality (Stocks 1987). Spruce budworm outbreaks also increase windthrow both during and following periods of defoliation (Taylor and MacLean 2009). Hurricanes and other windstorm events result in downed fuels and increase fire potential. Ponomarenko (2018) noted several cases in which major historical fires followed large windthrow events from hurricanes. Spruce beetle outbreaks can follow spruce budworm defoliation and strong wind events, resulting in higher mortality of spruce than expected (Ostaff and MacLean 1989; Wichmann and Ravn 2001; Munson 2010). Also worth considering is how past human-caused disturbance (especially land clearing and forest harvesting) have altered forest landscape age structure and species composition, which in turn influences natural disturbance patterns and ecological responses. Forest harvesting has been the dominant disturbance agent in the northeastern US forests over the past several centuries (Brown et al. 2018), and similar trends are readily apparent in Nova Scotia (Cheng and Lee 2009; Colville and Prakash 2010). Such interactions among natural and human-caused disturbances deserve more attention in future research.

In this review, we have attempted to describe past disturbance regimes for as many natural forest disturbance agents as possible. At the very least, this should provide a rough approximation of what the historic natural disturbance regime was like and may be used by forest managers in Nova Scotia to help estimate expected age structure distribution across the landscape (e.g., Van Wagner 1978; Lorimer and White 2003) and inform desired residual stand structures. More specifically, if managers have an idea of what the historic natural disturbance regime was like and assume that these disturbances will continue into the future, then they can better estimate how much forest area can be harvested each year, and by what method, to be sustainable (e.g., D'Amato et al. 2018). Although application of natural disturbance regime information to forest management planning (e.g., how to derive harvest rotations and target age structures by ecoregion, and what residual stand structures reflect natural disturbance regimes) is beyond the scope of this review, a follow-up paper on methods of application is currently being prepared that focuses on translating disturbance parameters presented in Table 5 into practical forest management guidelines. Still, while enhanced knowledge of past disturbances will undoubtedly help improve forest management in Nova Scotia, the future of natural disturbances is uncertain and should be considered, as discussed in the last section.

5. Future of natural disturbances in Nova Scotia

Disturbance regimes are not static, but change over time in response to natural and human-caused drivers such as global atmospheric change, disturbance suppression, landscape modification, increasing global trade, and invasive species (White and Pickett 1985; Barnes et al. 1998; Dale et al. 2001). While the preceding sections synthesized our knowledge of contemporary disturbance agents and their behavior in Nova Scotia's forests, it is likely that disturbance regimes will continue to change in the future, which may influence how we use natural disturbance emulation to meet ecological forestry targets.

Besides the direct influence of human preventative measures on disturbance behavior such as forest fire suppression or spraying of insecticides, which reduce occurrences of those disturbances, climate change is expected to have the greatest impact on disturbance regimes (Overpeck et al. 1990; Dale et al. 2001; Weed et al. 2013). Changes in climate for the 21st century are projected to be greater than those experienced over the last 100 years (World Meteorological Organization (WMO) 2019). In Nova Scotia, even with the buffering effect of the Atlantic Ocean, it is predicted that mean annual temperature will increase by 2.0–6.0 °C before the year 2100, with only minor (<10%) increases in annual precipitation expected (Bush and Lemmen 2019). Such rapid changes in climate will undoubtedly alter disturbance regimes in Nova Scotia, as each disturbance agent is influenced, to some degree, by climate.

Forest fire is dependent on ignition source (lightning or humans), climate, and fuels (forest structure and composition) (Flannigan and Wotton 2001; Parisien and Moritz 2009). Both ignition and spread of fire depend on local weather, including the amount and frequency of precipitation, temperature, relative humidity, and wind velocity. Studies have already shown rapid responses of fire regimes to changes in climate across North America, with western regions experiencing the greatest shifts (Flannigan et al. 2001; Kelly et al. 2013). Nonetheless, despite its maritime climate and projected increases in precipitation, Nova Scotia is also expected to experience a minor increase in fire activity. Specifically, under the International Panel on Climate Change RCP 8.5 radiative forcing scenario, annual area burned is projected to increase from approximately 0.03%·year^{-1} currently to 0.12%·year^{-1} by 2070 (Boulanger et al. 2014). However, most fire models do not consider forest composition in their projections, ignoring negative feedbacks from post-fire hardwood regeneration or climate-driven shifts in species composition, thus potentially overestimating fire activity (Girardin et al. 2013; Terrier et al. 2013). These fire disturbance rates compare with 0.17%–0.40%·year^{-1} calculated based on historical fire regimes and varying by ecosite (Table 5). Large fires are always driven by extreme events, the coincidence of drought periods, high winds, and lightning storms. They can be exacerbated by earlier insect or hurricane events that create large amounts of downed fuels. Current models cannot replicate these conditions, but they are increasingly being observed in western Canada and the US.

Climate change may also affect future wind disturbance, but the magnitude and direction of change is highly uncertain (Dale et al. 2001). It is difficult to predict effects of climate change on windstorms because many small-scale wind events (e.g., convective thunderstorms) cannot be adequately represented in global circulation models due to resolution constraints (Peterson 2000). However, rising temperatures are expected to increase the intensity of atmospheric convective processes that produce severe thunderstorms (Brimelow et al. 2017), with increases in tornado frequency with rising temperatures observed in western Canada (Etkin et al. 2001). Rising sea-surface temperatures and greater evaporative demand at higher latitudes are expected to influence the track, size, and frequency of tropical cyclones (Knutson et al. 2010). Tropical cyclone projections for the North Atlantic Ocean are also highly uncertain, but although the number of landfalling tropical cyclones over Nova Scotia is unlikely to significantly change over the 21st century, global warming may increase their intensity, with more hurricane-strength storms making landfall (NOAA 2019*b*).

The effect of climate change on forest insect disturbances will likely vary considerably by species and through indirect effects of warming on host trees and interacting disturbances (Weed et al. 2013; Pureswaran et al. 2015). For example, rising temperatures are expected to decrease the severity and duration of eastern spruce budworm infestations over the coming decades in Nova Scotia, relative to 20th century levels (Régnière et al. 2012; Gray 2013) as the climate becomes too warm for spruce budworm to successfully complete its annual life cycle and less suited to its primary host, balsam fir (Pureswaran et al. 2015; Taylor et al. 2017*a*). The relationship between spruce budworm overwintering survival and temperature (Han and Bauce 1997) was used by Régnière et al. (2012) to model the effects of climate change on spruce budworm range, which projected that global warming would shift spruce budworm distributions northward and to higher elevations. Overwintering survival of western spruce budworm (*Choristoneura occidentalis* (Freeman)) is also negatively affected by warming and determines its southern and lower elevation limits (Régnière and Nealis 2019). If temperatures warm at the southern limit, earlier maturation, oviposition, and hatch occur earlier in summer, which extends the warm period during which dormant larvae must use their fixed reserves to maintain themselves. Some larvae may die quickly, but mortality will continue through autumn, winter, and spring, especially if late winter and early spring are warm. This may result in a somewhat nebulous southern range limit, because as long as there are host trees, there will be areas and years when life will be less stressful as phenology is largely weather driven. Over the long term, however, spruce budworm outbreaks will be less likely to initiate and more difficult to sustain. On the contrary, other native insect pests such as eastern spruce beetle may benefit from warming as rising temperatures permit spruce beetles to complete their life cycle faster and reduce over wintering mortality (Berg et al. 2006; Bentz et al. 2010). Further, climate-related stress to spruce trees from drought and wind damage may reduce tree defense response, benefiting the beetles (Wichmann and Ravn 2001; Anderegg et al. 2015).

Climate change may also facilitate invasion of non-indigenous pests and disease. Hemlock woolly adelgid, reported in eastern North America in 1951, has spread throughout the eastern US and was detected in southern Nova Scotia in 2017. Its current northern limit is controlled by low winter temperatures, but projected warming will permit expansion across Nova Scotia over the coming decades (Paradis et al. 2008). Similarly, gypsy moth has been present in Nova Scotia for several decades, but cool summer temperatures slow larval development and delay oviposition. Rising temperatures are anticipated to increase gypsy moth abundance throughout Nova Scotia (Gray 2004). Of recent note has been the eastward advance of the balsam woolly adelgid. This pest and most other introduced species are vulnerable to cold winters, especially temperatures persisting in the −30 °C range or with little snow cover depth. In the past, intensity of balsam woolly adelgid was restricted in central and eastern Nova Scotia due to cold winter temperatures; however, recent winters have been milder with deep snow cover, resulting in noticeable damage to balsam fir trees on the eastern mainland. If winters become less severe in Nova Scotia, several forest pests may increase in importance: gypsy moth, balsam woolly adelgid, European shoot moth, and winter moth. Further south, the southern pine beetle (*Dendroctonus frontalis* Zimmerman), the most economically destructive forest insect in the southeastern US, has recently expanded its northern limit to Connecticut. Northern expansion is primarily constrained by cold winters (−20 °C air temperatures), but the climate of Nova Scotia is expected to become suitable as early as 2020 (Lesk et al. 2017). New pests continue to be detected, including emerald ash borer (*Agrilus planipennis* Fairmaire) outside Halifax, Nova Scotia, in 2018, which has resulted in great concern about the future of ash populations in the province. New pests introduced from overseas are probably more worrying than insects or diseases that expand their range northward, if associated natural enemy species also expand northward.

The impact of introduced and native pests on the forest ecology of Nova Scotia is largely determined by adaptability, natural control mechanisms, and genetics of tree species. Therefore, the extent and influence of climate change on tree performance will likely be a significant factor determining severity of disturbance and forest renewal in the future. However, it is challenging to predict how climate change and other human drivers (e.g., trade, disturbance suppression, and management activities) will affect future natural disturbance regimes, not least of which because of inherent uncertainty in climate change projections, human behavior, and our limited understanding of current natural disturbance agents.

Nonetheless, given the strong influence that climate change will likely have on future natural disturbances in Nova Scotia and the forest types that occur there (Taylor et al. 2017*a*), the question arises: is the goal of restoring our forests to a more natural, pre-European settlement condition through emulation of historic natural disturbance regimes still a reasonable approach? Indeed, a recent study of similar, nearby forests in southeastern Quebec (i.e., Boulanger et al. 2019) suggests that climate change will increasingly inhibit the ability of forest managers to restore and (or) maintain pre-settlement forests there and forest managers must be prepared to adapt and should strive to ensure that adequate levels and appropriate types of natural biodiversity are preserved on the landscape to ensure the natural functioning of future forest ecosystems.

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Appendix A. Significant post-settlement forest disturbances in Nova Scotia

The following is a partial summary of the natural and human-caused disturbances in Nova Scotia recorded in the archives and literature that have influenced the composition of Nova Scotia's forests over the last 400 years. Even if caused by humans, these disturbances provide insight into the potential of natural disturbances such as fire if left uncontrolled. It is expected that some events of significant size and duration may have gone unreported as settlers were not concerned with losses in the forests.

Hurricanes and windstorms

1635 In his study of 280-year-old stands of hemlock and red spruce in the southwest, Dwyer (1958) concluded they may have originated from the "The Great Colonial Storm" on August 15 and another in 1676.

1759 A violent storm on November 3rd hit Halifax (Elliott 1979).

1775 The "Hurricane of Independence" swept from North Carolina to Nova Scotia between September 2 and 9, leaving 4170 dead in New England and Canada (A. Ruffman, personal communication, 2002).

1798 Smith (1802) referred to a "Great Storm" where forest destruction covered an area of over 1 000 000 acres (405 000 ha) stretching from Porters Lake, Halifax County, to Shelburne and north to Windsor. This September storm was also mentioned in the writings of Simeon Perkins (1766–1812) and Thomas Haliburton (1828).

1811 A hurricane was recorded in the writings of Judge John George Marshall who walked "home" from the town of Guysborough to Tracadie after the fall storm and described the road as near impassable, often completely hidden by fallen trees (Black 1978).

1813 Violent gale hit the province on November 13th (Elliott 1979).

1817 Hurricane strikes Cape Breton Island (J. St. Clair, personal communication, 1999).

1821 "The Long Island Hurricane" of September 1–4 was reported by Dwyer (1958) as responsible for the abundance of forest stands in the province aged at 130 years, especially in Cape Breton Island. Petitions requested aid for a road between Whycocomagh and Port Hood blocked with trees (J. St. Clair, personal communication, 1999).

1822 A severe March thunderstorm was reported in the Nova Scotia Book of Days (Elliott 1979).

1851 Yankee Gale (A. Ruffman, personal communication, 2002).

1862 A hurricane blew in the Antigonish area, uprooting trees and causing damage to property (The Casket, Antigonish, October 1862).

1869 "The Saxby Gale" of October 5th, named after a British navy lieutenant who predicted the occurrence one year earlier, devastated and uprooted whole tracts of forest land. The worst damage in Canada was in southern New Brunswick and northern Nova Scotia (Johnson 1986).

1872 "The Jackson Gale" (A. Hanham, personal communication, 1996).

1873 "The August Gale", also known as "The Nova Scotia Storm". In the diary of William Kidston, blowdown was reported on Crowdis Mountain and in Richmond Co., where a fire shortly followed (A. Hanham, personal communication, 1996). Johnson (1986) records that "All over the country for miles inland the trees were wilted and turned brown" due to the salt spray carried by the strong gales.

1889 A cyclone touched down in Bellisle, Annapolis Co., destroying buildings and trees (Morning Chronicle, Halifax, June 8, 1889).

1891 Calnek (1897) wrote of severe thunderstorms causing much damage to buildings and trees in Annapolis County.

1895 Calnek (1897) described a cyclone west of Bridgetown that uprooted large trees on August 3rd. The track of the storm was 100 yards (100 m) wide and six miles (10 km) long.

1953 Hurricane Carol on September 7th downed the equivalent of about 500 000 ft^3 (14 000 m^3) of trees, most of which in areas where some trees were already partially cut (Dwyer 1958; Johnson 1986).

1954 On September 11th, tropical storm Edna blew down 700 million board feet with most of the damage being in mature and overmature stands but younger forests 50 to 70 years old were also damaged (Johnson 1955; Dwyer 1958).

1956 An early winter storm hit Halifax area destroyed over 1000 trees in Point Pleasant Park (Halifax Mail Star, Dec. 31, 1956).

1962 Hurricane Daisy hit the province on October 7th (Chronicle Herald, Halifax, Oct. 8, 1962).

1963 Hurricane Ginny made landfall over Nova Scotia as a strong Category 2 hurricane, the strongest on record to make landfall in Canada (ECCC 2017).

1964 Violent storm with gusts of up to 160 $km \cdot h^{-1}$ hit the Maritimes on December 1st and 2nd (ECCC 2017).

1975 Hurricane Blanche struck Nova Scotia as a tropical storm on July 27th between Yarmouth and Shelburne and north along a 150-mile (241 km) front. It headed east of Greenwood and Amherst. The Annapolis Valley escaped most of the storm. (Chronicle Herald, Halifax, July 29, 1975).

1976 Groundhog Day Storm on February 3rd devastated southwestern Nova Scotia. Winds of 188 $km \cdot h^{-1}$ were measured. Salt spray coated everything for miles inland (ECCC 2017).

2003 Central Nova Scotia was devastated by Hurricane Juan, September 29th (Fogarty 2004).

2008 Hurricane Kyle caused some uprooting of trees and branch breakage (NOAA 2019*a*).

2009 Hurricane Bill brushed the south coast of Nova Scotia as a tropical storm on August 23, with many people losing power, roads washing out, and coastal flooding (NOAA 2019*a*).

2010 Hurricane Earl made landfall at Liverpool on September 4, causing trees to uproot and downed power lines (NOAA 2019*a*).

2014 Wind damage due to post-tropical storm Arthur was recorded over approximately 46 541 ha (NSDNR 2015).

2019 Hurricane Dorion made landfall as an extratropical cyclone near Sambro Creek, west of Halifax, on September 7th, with maximum wind gusts of 155 $km \cdot h^{-1}$ according to the National Hurricane Centre (Global News, Sept. 7th, 2019, Halifax 2019; https://globalnews.ca/news/5870123/hurricane-dorian-nova-scotia/.

Wildfires

1650 The most detailed account of the forests of Acadia in the 17th century was written by the French settler–entrepreneur Nicholas Denys (Denys 1672), who reported lightning-caused fires, the largest burning upwards of 10 to 15 leagues (30 to 45 square miles of country (78 to 117 km^{-2})).

1700 Charred dwarf black spruce were radiocarbon dated to 220–50 years B.P., indicating that these barrens had originated from earlier fires (Bridgland et al. 1995).

1710 Forest fires devastated regions near Windsor. In 1747, Charles Morris told Governor Shirley that the people of Grand Pre and the River Canards had to procure their wood from the east side of the Pisiquid River, namely in that part now covered by the township of Kempt. In 1762, Morris reported on the state of the townships of Falmouth and Horton. He said "In Horton the natural growth is spruce, fir, white birch, poplar and white pine. The growth of timber is small the woods having been leveled by fire about 50 years since." (From the Halifax Herald, October 19, 1897.)

1720 Natives told William Burke, the first settler in northern Queens County, of a hurricane followed the next year by a fire that ravaged an area 30 miles (48 km) long by 20 miles (32 km) wide (from just east of Lake Rossignol to east of Middle River, Lunenburg County). The area had later grown up chiefly in beech according to notes from Titus Smith (Johnson 1986).

1750 Evidence of fire found in MacFarlane Woods, Mull River (J. St. Clair, personal communication, 1999).

1773 Island Barren – White Hill (Cape Breton Highlands National Park) fire origin indicated. Total area burned was estimated at 63 000 ha (Bridgland et al. 1995, 2011).

1784 Fire at Port Mouton spread through the makeshift village and ran for miles through the forest under a strong southwest wind (Johnson 1986).

1800 During his 1801–02 survey, Titus Smith found over a million acres (405 000 ha) of "burn," probably burnt from 1791–1800, and more than 1 300 000 acres (526 000 ha) of "barren," mostly older burn (Johnson 1986).

1800 Many fires in all quarters around Liverpool. Except for bogs and swamps, most of the land south of Lake Rossignol and Jordan Lake from the Liverpool (Mersey) River to the Roseway River was burned (Perkins 1766–1812).

1800 In August, a bad fire swept over much of Wilmot Township, Annapolis Co., causing considerable damage to buildings and crops, as well as to the forests (Johnson 1986).

1815 George Wood requested land because a large fire area severely damaged his property in Southwest Mabou (J. St. Clair, personal communication, 1999).

1820 Sixty families in the southwest part of the province were burned out by a large fire (Wein and Moore 1979).

1825 Numerous fires in the eastern part of mainland Nova Scotia (Wein and Moore 1979).

1829 The bridge over Black Brook on the road between Sydney and Louisbourg was destroyed in August by fire that raged through the woods of that part of Cape Breton (Public Archives of N.S., R.G.7, Vol 5, No. 137)).

1834 Broad Cove Mountain (Cape Breton Highlands National Park). Fire origin indicated (Bridgland et al. 1995).

1849 After an exceptionally dry spring, forest fires in June were recorded at Windsor, St. Margaret's Bay, and along the eastern shore. The Nova Scotian (Halifax, June18, 1849, p. 194) reported "The air was completely impregnated with smoke. The waters assumed a blood red hue, and even at midday, the sun was of a bronzed and coppery colour, and shone dimly through the hazy, murky, and lurid atmosphere, while the ashes fell through the city, like snowflakes at the commencement of a winter storm. Great loss had been sustained. The injury done to the forest trees is irreparable." Other fires were also reported at Three Mile House, Kempt, Cornwallis, and Parrsboro.

1860 Sylvanus Morton of Milton wrote "a remarkable dry time for more than four weeks with not a shower to lay the dust; great raging of fires and a great damage to timberlands." That same spring 20 000 acres (8100 ha) were burned south of the Sissiboo River in Digby Co. until rain put out the fires on May 19th (Johnson 1986).

1863 Cavanaugh Lake (Cape Breton Highlands National Park). Fire origin indicated (Bridgland et al. 1995).

1865 The Dan Moody fire burned 20 000 acres (8100 ha) from

Milton to Upper Great Brook and Ten-Mile Lake between the river and what is now known as Highway No. 8 (Johnson 1986).

1878 Mary Ann Falls (Cape Breton Highlands National Park). Fire origin indicated (Bridgland et al 1995).

1886 Clyburn–Franey–Green Cove (Cape Breton Highlands National Park). A farmer's brush burning spread out of control and burned an estimated 3343 ha (Bridgland et al. 2011).

1901 A lightning strike at Chignecto destroyed over 1000 acres (405 ha) (Amherst Daily News, July 31, 1901).

1903 In June, the Amherst Daily News reported extensive fires in Cumberland County (Spicer 1970): "the fires [Sand River area] in the last three days have covered a distance of 28 miles [45 km], part of the distance being through the best timbered lands in this county and where the sound of the woodsman's axe has not yet been heard. The whole River Hebert Valley endowed with its great forests of valuable pine and spruce are practically given over to the flames".

1909 10 000 acres (4047 ha) of clear-cut harvested land was burned in the heart of the St. Margaret's Bay lands (Johnson 1986).

1910 Fires ignited by the Springfield Railway destroyed more than 100 000 acres (40 469 ha) of forest land in the counties of Annapolis, Kings, and Lunenburg (Johnson 1986).

1912 C.D. Howe reported that there was 500 000 acres (202 343 ha) of recent burns in N.S. (Fernow 1912).

1921 With over 40 fires burning in Cumberland County, the Amherst Daily News headlines "Saturday and Sunday Days of Terror" and "Most Appalling Disaster Ever Menacing This County" were used to describe the "holocaust" of flames. From July 4 to mid-August, at least 250 000 acres (101 171 ha) of forest had been turned into "districts of hideous havoc". Fortunately, no lives were lost, although a number of homes and barns were burned (Spicer 1970).

1931 Lightning caused a fire to burn at least 200 acres (81 ha) at Dennis Boot Lake, Annapolis County (Basquill et al. 2001).

1934 Atkinson Brook and Kelly River, Cumberland County (Spicer 1970).

1935 Unknown cause burned 6070 ha in the Rawdon Hills of Hants County (from the fire records of the N.S. Department of Lands and Forestry, Forest Protection Division, Shubenacadie, N.S.).

1946 Ten thousand acres (4047 ha) burned along the Burma Road, Apple River, Cumberland County (Spicer 1970).

1962 12 000 acres (4856 ha) of forest land burned in one day between Milton and Liverpool during one of the driest summers in more than a century — Otto Schierbeck, Provincial Forester (Johnson 1986).

1976 The largest fire in recent times burned 13 000 ha of primarily softwood forest at Trafalgar (from the fire records of the N.S. Department of Lands and Forestry, Forest Protection Division, Shubenacadie, N.S.).

1992 Untended campfire destroyed 595 ha of forest and wetlands at Goffs, Halifax County (from the fire records of the N.S. Department of Lands and Forestry, Forest Protection Division, Shubenacadie).

1999 Wildfire destroyed 810 ha of coastal forest near Woods Harbour (from the fire records of the N.S. Department of Lands and Forestry, Forest Protection Division, Shubenacadie, N.S.).

2008 A campfire led to a burn of 1925 ha of forest previously damaged by Hurricane Juan at Porters Lake, Halifax County (from the fire records of the N.S. Department of Lands and Forestry, Forest Protection Division, Shubenacadie, N.S.).

2009 An untended campfire at Spryfield, a suburb of Halifax, burned 681 ha, including residential properties (from the fire records of the N.S. Department of Lands and Forestry, Forest Protection Division, Shubenacadie, N.S.).

2016 A small fire ignited by lightning near Ten Mile Brook was quickly extinguished. Fires due to arson further north at Seven Mile Lake burnt 364 ha. The Department of Lands and Forestry used the Canadian Forest Fire Behaviour Prediction System and fire modelling software to aid in decision making and suppression efforts (from the fire records of the N.S. Department of Lands and Forestry, Forest Protection Division, Shubenacadie, N.S.).

Insects and diseases

1846 Spruce budworm infestation in Cape Breton Island (Hawboldt 1955).

1880 A severe outbreak of the larch sawfly killed nearly all mature larch throughout America (Johnson 1986).

1891 Spruce budworm infestation in Cape Breton Island (Hawboldt 1955).

1911 Spruce budworm infestation in Cape Breton Island and Canso (Hawboldt 1955).

1922 Spruce budworm infestation in Cape Breton Island and Canso (Hawboldt 1955).

1940 Birch dieback occurred among white and yellow birch throughout the province (Hawboldt 1945).

1945 Eastern spruce beetle damage noted on Tusket Islands (Anonymous 1945–1991).

1948 Whitemarked tussock moth caused heavy damage to 15 000 ha in Colchester County (Anonymous 1945–1991).

1948 Forest tent caterpillar outbreak in Annapolis Valley and Cumberland County 1948 and 1949 (Anonymous 1945–1991).

1949 Black-headed budworm attacked balsam fir on French and MacKenzie Mountains, Cape Breton (Anonymous 1945–1991).

1950 Spruce budworm infestation in Nova Scotia (Brown 1966).

1954 White-marked tussock and rusty tussock moths attacked hardwood stands in northern Cape Breton (Anonymous 1945–1991).

1966 Balsam fir sawfly in Halifax and Colchester counties in 1966–1969 (Anonymous 1945–1991).

1969 Spruce budworm infestation in Nova Scotia (Kettela 1983). Upwards of 630 000 ha on Cape Breton Island and 430 000 ha on the mainland were affected during the outbreak, which occurred between 1967 and 1987.

1972 A province wide infestation of larch sawfly in 1972–1979 (Anonymous 1945–1991).

1973 Scleroderris canker was discovered for the first time in Nova Scotia on red pine at Garden of Eden Barrens (Anonymous 1945–1991).

1974 Severe widespread defoliation from white-marked tussock moth in 1974–1977 (Anonymous 1945–1991).

1975 Defoliation of 8400 acres (3399 ha) in Yarmouth and Digby counties by eastern hemlock looper (Anonymous 1945–1991).

1978 Spruce beetle caused stand-level mortality in white spruce forests throughout eastern and central Nova Scotia (Anonymous 1945–1991).

1978 Eastern larch beetle attacked and killed larch that survived the earlier larch sawfly outbreak. By 1981, it was estimated that 64% of merchantable larch was dead (Anonymous 1945–1991).

1985 Fall cankerworm and winter moth defoliated 16 000 ha of maple and oak in the central and western counties (Anonymous 1945–1991).

1985 Hemlock looper defoliated upwards 450 ha in Cumberland and Shelburne counties (Anonymous 1945–1991).

1991 Hemlock looper defoliated upwards of 3600 ha of balsam fir in Guysborough and Halifax counties (Anonymous 1992–1998).

1992 Old-field white spruce stands were infested by spruce beetle stem attacks in most mainland counties. Upwards of 4400 ha were affected annually from 1992 to 1999. Red spruce was also affected. Annual infestations of 125–430 ha were recorded between 2000 and 2003 (from the records of N.S. Department of Natural Resources, Forest Protection Division).

1993 *Siroccoccus* shoot blight infested over 165 ha of red pine plantations in Pictou, Guysborough, and Cumberland counties between 1993 and 1994 (Anonymous 1992–1998).

1994 Eastern dwarf mistletoe caused damage and mortality in 1376 ha of coastal white and black spruce (from the records of N.S. Department of Natural Resources, Forest Protection Division).

1996 White-marked tussock moth defoliation of 590 910 ha of balsam fir forests occurred between 1996 and 2000 in Halifax, Hants, Cumberland, Colchester, Pictou, Antigonish, and Cumberland counties (Anonymous 1992–1998).

1996 Hemlock looper defoliated 14 070 ha in Inverness, Victoria, and Antigonish counties (Anonymous 1992–1998).

1996 Forest tent caterpillar defoliated 1300 ha in Annapolis County (Anonymous 1992–1998).

1997 Balsam fir sawfly defoliated 234 ha near New Harbour, Guysborough County, with moderate defoliation widespread along the eastern shore (Anonymous 1992–1998).

1997 An estimated 8000 to 10 000 ha of mature white spruce were affected by spruce beetle (Anonymous 1992–1998).

1997 Increasing populations of eastern black-headed budworm and white-marked tussock moth were detected in the Cape Breton Highlands (Anonymous 1992–1998).

2002 Pale winged grey defoliated 507 ha of hemlock in Annapolis and Queens counties. In 2003, 869 ha were affected (from the records of N.S. Department of Natural Resources, Forest Protection Division).

2002 Gypsy moth defoliated 80 ha of hardwood in Kings County (from the records of N.S. Department of Natural Resources, Forest Protection Division).

2008 Aerial surveys detected 3535 ha affected by the jack pine budworm, up substantially from 1554 ha in 2007 (NSDNR 2008).

2008 About 590 ha of red spruce mortality from spruce beetle was detected in Cape Chignecto Provincial Park (NSDNR 2008).

2011 Widespread spruce beetle induced mortality of mature and overmature white spruce occurred throughout the province (NSDNR 2011*b*).

2013 Pockets of damage were mapped province-wide due to spruce beetle induced mortality (approximately 4650 ha), white-marked tussock moth defoliation approximately 100 ha), beech leaf-mining weevil defoliation (approximately 51 ha) (NSDNR 2013).

2014 Provincial Aerial Overview Surveys: spruce beetle induced mortality (~5334 ha), and *Sirococcus* shoot blight damage (approximately 2098 ha) (NSDNR 2014).

2015 Provincial Aerial Overview Surveys: in August 2015, Departmental field staff reported unidentified defoliation in Valley and Central Lowlands ecoregion. The sites were ground truthed and a detailed aerial survey was conducted. This mapping delineated 198 ha of beech leaf-mining weevil defoliation and 260 ha of defoliation and browning due to oak leaftier and leafroller caterpillar feeding (NSDNR 2015).

Other

1835 Petitions for Government assistance due to extreme cold and frost between 1835and 1838 (Nova Scotia Archives).

1838 Hail storm, July 16th, in Windsor (Elliott 1979).

1840 Church documents mentioned two large landslides in Hillsboro, Inverness County, possibly associated with “sink holes” (J. St. Clair, personal communication, 1999).

1997 A July hail storm caused damage to 2300 ha in the Cape Breton Highlands north of St. Ann’s Harbour (Anonymous 1992–1998).

1998 The “Ice Storm of the Century” caused extensive damage to trees and forests from Ontario to Nova Scotia (January 4–9).

2003 Ice storm in February caused extensive breakage in hardwood forests and young softwood plantations in Cumberland and Colchester counties. Approximately 110 064 ha were affected (Guscott 2003).

2004 A nor’easter nicknamed White Juan brought heavy snow, high wind, and low visibility to Nova Scotia and Prince Edward Island. Winds gusted to 124 $km \cdot h^{-1}$ and Halifax received 88.5 cm of snow in one day. (“Top ten weather stories for 2004”, Environment and Climate Change Canada, August 8, 2017; http://www.ec.gc.ca/meteo-weather/default.asp?lang=En&n=9CA2BD37-1#top2).

2014 Pockets of damage were mapped province wide due to flooding (~3906 ha) (NSNDR 2014).

2018 A late spring frost, June 4, 2018, damaged new growth and killed some young trees. Damage was especially noticeable on balsam fir, red oak, and white ash. (E. Quigley and P. Neily, personal observations, June 2018.)