Multidimensional assessments of long-term anthropogenic
impacts on domed peatlands: Learning from two centuries
at Alfred Bog, Ontario Canada.

by

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A thesis submitted to the Faculty of Graduate and Postdoctoral
Affairs in partial fulfillment of the requirements for the degree of

Master of Science

in

Geography

Carleton University
Ottawa, Ontario

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Abstract

This study examines changes in a domed peatland's areal versus volumetric reduction, impacts of anthropogenic drivers and supply of three ecosystem services (ESs) (carbon storage, food production, peat production) over 11 dates covering 200+ years (1800-2014). Historical air photos, maps and texts were used to map changes. Trends in area versus volume, for both the peatland's reduction and impacts of individual drivers, diverged. The divergence varied in magnitude both between examined drivers and dates, as their distribution across the depth profile changed. Despite greater areal losses in the 1800s, deeper disturbances in the 1900s yielded greater volumetric changes. This paralleled the shift from agricultural conversion to commercial peat extraction, underscoring their distinct and temporally dynamic effects on ES supply. Shorter intervals helped identify changing relationships between ESs and drivers, and broader human-environmental interactions. Thus, detecting spatial and temporal variations in ES responses to disturbances within domed peatlands necessitated multidimensional analyses.

Acknowledgements

My deepest gratitude to PCI Geomatics for use and support of its Historical Airphoto Processing (HAPs) software, with particular thanks to Kevin Jones, Jean Sébastien-Bouffard and Rob Keeping. The HAPs software substantially reduced the time and labour associated with georeferencing and mosaicking hundreds of collected air photos. Further thanks to Naomi Langlois-Anderson and South Nation Conservation for providing key contacts and historical air photos in the pursuit of this project. I also sincerely appreciate the time taken by Dr. Ted Mosquin, Frank Pope and Louis Prévost to meet and discuss past alterations and conservation efforts at Alfred Bog. A special thanks to my supervisors, Drs. Murray Richardson and Michael Brklacich, whose guidance, insights and contributions were invaluable in completing this thesis. Finally, thanks to my colleagues in the Department of Geography and Environmental Studies and my family for providing endless moral support; helpful suggestions and revisions; and the perseverance to complete this thesis.

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List of Abbreviations

Acronym	Full
CSUs	Competing Site Uses
DEM	Digital Elevation Model
DS	Domed Sites
ECO	Environmental Commissioner of Ontario
EC	Entire Complex
ESs	Ecosystem Services
GCP	Ground Control Point
GHGs	Greenhouse Gasses
GDP	Gross Domestic Product
HAPs	Historical Airphoto Processing software
MA	Millennium Ecosystem Assessment
NAPL	National Air Photo Library
OFNC	Ottawa Field Naturalists' Club
OMB	Ontario Municipal Board
OMNR	Ontario's Ministry of Natural Resources
OMAFRA	Ontario's Ministry of Agriculture, Food and Rural Affairs
PLS	Provincial Land Surveyor
§	Section or Subsection
TPs	Tie Points

1 Chapter: Introduction – Benefits of Intact and Disturbed Peatlands

1.1 Life-supporting services and other key benefits of undisturbed peatlands

Peatlands are wetland ecosystems that are characterized by a near-surface water table and the accumulation of partly decomposed organic matter (*i.e.* peat) over millennia (Belyea, 2009). They account for 50% to 70% of global wetland coverage (Joosten and Clarke, 2002). Peatlands develop when organic matter is produced and accumulates below the water table at a rate that exceeds net decomposition (*i.e.* aerobic and anaerobic decay) (Holden, 2005). Many properties regulate the depth of the water table, which is the main control on long-term development (Belyea, 2009; Price and Waddington, 2000). These properties also lead to peatlands' non-linear responses to external changes (Belyea, 2009).

Intact peatlands provide many benefits to human well-being. Major benefits include moderating the global climate and local hydrology (Zelder and Kercher, 2005). Peatlands are unmatched by other terrestrial ecosystems in the density of their carbon stores, storing a third of the world's soil carbon while covering 3% of the Earth's land surface (Joosten and Clarke, 2002). They also store 10% of surficial, liquid freshwater resources and can be associated with flood attenuation and water filtration. Some other services are wild food production (*e.g.* berries), habitat support, recreation and knowledge functions (Joosten and Clarke, 2002; Glenk *et al*, 2014; Webster *et al*, 2015).

1.2 People's interactions with peatlands: Exploitation and irreversible trade-offs

Humans have exploited peatlands for millennia in favour of an array of altered site uses (*i.e. in-situ*) and applications of extracted peat (*i.e. ex-situ* uses) (Chapman *et al*, 2003; Joosten and Clarke, 2002). Food, timber and raw peat production are major drivers of peatland disturbances (Joosten and Clarke, 2002). Long-term benefits of undisturbed

peatlands to humans continue to be underrepresented and foregone for more immediate returns in material goods and economic gains from their exploitation (Evans *et al*, 2014).

The timescales of peat accumulation versus those of disturbances are irreconcilable: peat is removed at rates far exceeding those of accumulation (Cleary *et al*, 2005). Further, disturbances begin with drainage to draw the water table down (Grand-Clement *et al*, 2015). As a result, even disturbances that leave a peatland partly intact can alter its state (*i.e.* accumulating, inactive or degrading) through enhanced aerobic decay. This affects the net balance of carbon sequestration versus emissions and may create positive feedbacks that accelerate degradation (Belyea, 2009; Swindles *et al*, 2016). Thus, disturbances often lead to step changes in the hydrological and ecological conditions that regulate peatlands (Belyea, 2009), resulting in the release of the carbon store (Grand-Clement *et al*, 2015).

Humans have altered approximately 20% of peatlands globally (Joosten and Clarke, 2002). Peatlands are found in many climatic regions, yet the majority formed in boreal and subarctic regions (Joosten and Clarke, 2002). As such, most peatlands are intact, having faced less development pressures. Past disturbances were concentrated in more densely populated areas (Chapman *et al*, 2003), particularly in temperate and, more recently, tropical regions (Joosten and Clarke, 2002). For example, in Ireland raised bogs and blanket bogs have been reduced to 7% and 18% of their original extents (Joosten and Clarke, 2002). Similarly, 70% of peatlands in southern Canada are disturbed (Keys, 1992). Thus, many of the older, rarer and more accessible peatlands, with the capacity to supply services to nearby populations, have been irreparably exploited (Chapman *et al*, 2003; Evans *et al*, 2014).

The expansion of disturbances into remote regions has increased pressures on the remaining undisturbed peatlands (Webster *et al*, 2015). Unlike past disturbances, many of these pressures are not focussed on peatland exploitation. Instead, the peatlands are collateral losses in infrastructural developments or resource extraction. Many examples exist in Canada, with the construction of hydroelectric dams and reservoirs cited as a major driver of national peatland degradation¹ (Joosten and Clarke, 2002). Similarly, the release of greenhouse gasses (GHGs) with bitumen extraction in Alberta, already an emissions-intensive form of oil production, are even greater when the land-use emissions from displaced and destroyed peatlands are included (Brandt, 2012). Thus, no benefits are gained directly from their destruction, while still losing the services they provided.

1.3 Ecosystem services: Emphasizing underrepresented benefits of ecosystems

Ecosystem services (ESs) are the direct and indirect benefits to human well-being derived from a variety of ecological functions. ESs are categorized as provisioning (*i.e.* material goods), regulating (*i.e.* moderating ecosystem functions) or cultural (*i.e.* non-material benefits). Human-induced alterations of ecosystems tend to enhance the supply of a few provisioning services at the loss of other ESs, particularly cultural and regulating ESs (Rodriguez *et al*, 2006; Raudsepp-Hearne *et al*, 2010a). The anthropocentric portrayal of ecosystems attempts to better account for their benefits, which have been reduced by human activities and underrated in past land-use decisions.

An ES approach can represent the benefits derived from peatlands and the changes in their supply with disturbances. This is particularly relevant to the carbon stores in

¹ The associated release of GHGs from inundated peatlands (7500 km²) with constructed dams and reservoirs represents 5% of Canada's annual anthropogenic emissions (Joosten and Clarke, 2002; Poulin *et al*, 2004).

peatlands. Losses in directly provided ESs are more readily perceived by beneficiaries and measured. The release of a single peatland's carbon store on global climate regulation is minimal (Glenk *et al*, 2014), yet the cumulative effects of exploitation are substantial. An extreme example is the Indonesian peat fires in 1997 that released between 0.81 and 2.57 gigatonnes of carbon, which represents 13% to 40% of global carbon emissions from fossil fuel use for that year (Page, 2002). These peat fires recur annually and are one of many disturbances that occur globally, exacerbating anthropogenic releases of GHGs and threatening the future stability of major life-supporting functions.

The carbon stored in peatlands is a product of their net carbon sink (*i.e.* negative carbon balance) with peat accumulation over millennia (Holden, 2005) and is a significant component of their climate regulating ESs. However, many peatland ESs studies focus on restoration and examine the carbon balance. This is critical in assessing a peatland's state and future role as a carbon sink or source, but alone underrepresents its climatic effects. Both the existing carbon store and carbon balance must be included to fully assess the role of peatlands on climate regulation (Joosten and Clarke, 2002; Zelder and Kercher, 2005).

Despite containing roughly 30% of global peatland coverage (Joosten and Clarke, 2002) and numerous studies on Canadian peatlands, few have applied an ES approach in their examination. Peatlands vary in structure and are diverse in their landscape and climatic settings. Many peatland subclasses have non-uniform peat depth profiles. As a result, the volumetric distribution of peat can vary both within and between peatlands. For example, the greater dry weight and volume of peat in Ontario, despite the greater area of peatlands in the Northwest Territories and Nunavut, demonstrates that the areal versus volumetric distribution of peatlands are not interchangeable (see Table 1-1). The non-

uniform distribution of peat depths and volume must be considered in spatially explicit analyses of the carbon store and its response to anthropogenic disturbances (Joosten and Clarke, 2002). Thus, the geographic setting and structure of peatlands may impact their supply of ESs (Glenk *et al*, 2014), reinforcing the value of empirical and ecosystem-specific studies (Evans *et al*, 2014).

Table 1-1– Peatland area, volume and dry weight at two sites in Canada (Source: Tarnocai, 1984).

Province/Territory	Area (km²)	Volume (m³)	Dry Weight (t)
Ontario	2.25×10^5	6.76×10^{11}	7.71×10^{10}
Northwest Territories and Nunavut	2.51×10^5	5.77×10^{11}	6.58×10^{10}

The distribution of peatlands and peat depths also varies substantially at regional and local levels. For example, Ontario’s Ottawa-Brockville region overlaps with the St. Lawrence Lowlands and the Ottawa Valley: areas that were favourable for post-glacial peatland development (Bird and Hale, 1984b). As such, the region has the second greatest total peatland area and the greatest coverage per unit area of surveyed sites in southeastern Ontario (Riley, 1994, p.37). The region is characterized by expansive, but shallow peatlands, with a total average depth of 1.5 metres (m) and site averages seldom above 2 m (Bird and Hale, 1984b). Yet, the Ottawa area also contains two of the largest domed peatlands in southern Ontario (Cuddy, 1983; Riley, 1994), Alfred and Mer Bleue Bogs, with greater depths and total volumes (Bird and Hale, 1984a).

While many peatland ESs may be inferred through area-based proxies (*e.g.* habitat support, recreation and food production), a major part of the carbon store is based on the chemical composition and dry mass of peat. The latter is linked to the peat’s depth, dry-bulk density and volume (Gorham, 1991; Joosten and Clarke, 2002). Thus, in a domed peatland the distribution of the carbon store is spatially varied and its response to

disturbances are sensitive to changes in volume (*i.e.* depth and area). As such, disturbances of equal area may produce differing impacts on the carbon store, as shown in Figure 1-1. Further, the response of area versus volume-based ESs may differ. The divergence is important to consider the response of peatland ESs to disturbances, and how they may vary both spatially and temporally with the progression of disturbances. To date, variations in the response of the carbon store has not been thoroughly assessed in peatland ESs studies.

Figure 1-1 – Divergent volumetric impacts of equal-area disturbances in a domed peatland (adapted from “Bogs and Drainage”, 2015).

One area of ES research examines relationships between multiple ESs. Relations can be synergistic, mutually enhancing or degrading the supply of two or more ESs, or trade-offs, where the intensification of one ES leads to a decline in others (Bennett, Peterson and Gordon, 2009; Mouchet *et al*, 2014). Identifying common relationships between multiple ESs and factors that affect their recurrence may enhance the synergistic return of ESs and avoid undesirable trade-offs in land-use decisions (Bennett *et al*, 2009).

Of equal importance are studies on the response of ecosystem functions and the supply of ESs to multiple anthropogenic drivers, yet is scarce in peatland ESs studies (Evans *et al*, 2014). Drivers are unlikely to produce homogenous or static responses in ESs

(Mouchet *et al*, 2014), as depicted by a domed peatland's carbon store in Figure 1-1. Capturing the impacts of different drivers on ecosystem functions that underlie the supply of ESs can help isolate disturbances that produce greater trade-offs. The potential interactions between concurrently operating drivers, which can be competing or non-rival uses, may also impact the supply of ESs (Mouchet *et al*, 2014).

The local social-ecological setting and historical interactions between humans and the environment partly influences the current supply of ES and constrains its potential future states (Belyea, 2009; Tomscha and Gergel, 2016). This may produce distinct responses or relationships between ESs and other considerations that are unique to a given site and/or period. However, local ecological and social processes also interact with those operating at other spatial and temporal scales (Clark, 1985; Cash *et al*, 2006; Mouchet *et al*, 2014; Scholes *et al*, 2013). Thus, a better balance of both site-specific considerations and broader commonalities is needed to appropriately compare factors affecting ES trends between sites and studies. Ecosystem-specific examinations that consider both the geographic and historical specificities of a site or landscape, as well as relevant events at broader levels may improve this balance (Evans *et al*, 2014; Tomscha and Gergel, 2016).

1.4 Purpose statement and thesis objectives

This thesis examines the impacts of multiple anthropogenic drivers on a domed peatland's reduction over 200 years. It explores the use of an ES approach to capture long-term changes in the supply of intact² and disturbed peatland ESs using available secondary sources. This was accomplished through a case-study at Alfred Bog. This 7100-year-old

² The carbon stored in peat, a major component of climatic regulation, was the focus of intact peatland ESs.

domed peatland near Ottawa, Ontario (see Figure 1-2) (Aylsworth, Guertin and Lawrence, 2000) has been disturbed since the 19th century (Bird and Hale, 1984a; Mosquin, 1991).

The study's objectives were to:

- 1) Assess Alfred Bog's areal versus volumetric responses to disturbances;
- 2) Characterize the impacts of distinct anthropogenic drivers, including by area and volume;
- 3) Approximate changes in the supply and value of three ESs (food production, peat production and carbon storage) to examine the relative trade-offs of two main drivers on the carbon store.

These changes were assessed both for 11 selected³ dates and cumulatively over the most recent 200 years.

The case-study required first establishing the peatland's pre-disturbance area and volume. Then, land-cover changes were mapped over 11 dates between 1800 and 2014. The data from these maps were used with other sources to capture changes in the peatland's areal and volumetric reduction, the impacts of different drivers and the supply of the selected ESs, as the peatland was reduced from its pre-disturbance conditions to its present, highly altered state. A sub-objective of examining multiple drivers was to explore the effects of competing drivers on the peatland's reduction and changes in ESs. Thus, the study assesses Alfred Bog's areal and volumetric reduction, the specific impacts of drivers on these changes and the implications for ESs analyses in domed peatlands.

The case-study trends were linked with broader events that influenced local human-environmental interactions, and were compared against the distribution of peatlands and

³ Mapped dates, listed in chronological order, are: 1800, 1806-1820, 1830-1860, 1880, 1909, 1928, 1947, 1964, 1991-1994, 2008 and 2014.

drivers at other sites and administrative levels (*e.g.* region, province, country). This grounds the study's results in a larger context. It also enables a preliminary exploration of site-specific trends and more general findings that may extend to other social-ecological settings.

1.5 Thesis structure

The literature review and methods are presented in Chapters 2 and 3 respectively. Subsequently, the results and discussion are presented successively for individual research objectives, with each presented as a separate chapter. Chapters 4 through 6 cover the case-study trends, examining Alfred Bog's areal versus volumetric responses to disturbances (4), the impacts of individual drivers (5) and the changing supply of ESs (6) respectively. Chapter 7 then compares the case-study trends with those at other sites and broader levels and Chapter 8 discusses the challenges of the historical case-study and broader level trends using available secondary sources. The thesis concludes with an integrated summary of the research findings and implications for future peatland ES studies in Chapter 9.

Figure 1-2 – Location and boundary of the historical case-study at Alfred Bog.

Note: A digital elevation model (DEM) (top) and imagery (bottom) of Alfred Bog's location relative to Ottawa (Sources: Ontario Ministry of Natural Resources [OMNR], 2006 and Environmental Systems Research Institute [ESRI], 2014). The DEM shows the meltwater channel in which Alfred Bog formed.

2 Chapter: Literature review

2.1 Overview

Aside from the overview and summary, the literature review is divided into two main sections: an overview of the ecosystem service (ES) approach in examining the effects of anthropogenic disturbances on ecosystems (§2.2), including scalar complications arising from its interdisciplinary focus; and its specific application to peatlands (§2.3). The chapter concludes with a summary of the current gaps in peatland ESs research (§2.4).

2.2 Ecosystem services

Although earlier studies exist, the 2005 United Nation's mandated Millennium Ecosystem Assessment (MA) popularized the ES approach. The three main ES categories are shown in Table 2-1. The ES approach is a multidisciplinary research tool for examining interactions both within and between social and ecological systems. Its multidisciplinary use has led to diverse, sometimes disparate research applications and variations in the applied definitions, terminologies and methodologies (Mouchet *et al*, 2014). ES research areas include mapping, future scenarios development (Carpenter *et al*, 2006), valuation (Glenk *et al*, 2014; Hein *et al*, 2006) and examining relationships among multiple ESs (Bennett *et al*, 2009; Mouchet *et al*, 2014). This thesis addresses gaps within the latter, namely on the relationships between three selected ESs, which are tied to both intact and disturbed peatland uses (see §2.3).

Table 2-1 – Three main ES categories outlined by the MA.

#	Type	Definition	Examples
1	Provisioning	Material goods from ecosystems.	Food, timber, fibre
2	Regulating	Services from ecosystem functions that moderate other processes.	Climate regulation, water filtration, pollination
3	Cultural	Nonmaterial benefits of ecosystems.	Knowledge, recreation

A shift from global to sub-global analyses since the MA's publication (Scholes *et al*, 2013) has fostered greater attention to factors affecting geographic (spatiotemporal) variations in ES trends. Landscape-level ESs analyses may focus on the ecological capacity to produce an ES (*i.e.* supply), its distribution to and use by beneficiaries (*i.e.* flow) or the societal demand for that ES (Figure 2-1) (Mouchet *et al*, 2014; Villamagna, Angermeier and Bennett, 2013). Figure 2-1 shows that ES supply and demand are driven by biophysical and human factors respectively and may fluctuate independently of one another at a given level (Raudsepp-Hearne *et al*, 2010a; Villamagna *et al*, 2013). Comparatively, landscape fragmentation and ES flows are influenced by the combined social and ecological setting.

Figure 2-1 – Components of landscape ESs dynamics (*i.e.* supply, flow, demand) and influential factors (Source: Mitchell *et al*, 2015).

2.2.1 Scale and the interactions between social and ecological systems

ESs are supplied, valued, used and managed over distinct, yet interconnected spatial and temporal scales, making comprehensive ES analyses challenging (Hein *et al*, 2006;

Scholes *et al*, 2013). Single-level ESs studies (*e.g.* one spatial extent or a snapshot of ESs trends) have a limited ability to capture the multi-level processes that operate within social and ecological systems or the cross-scalar interactions that occur between them (Cash *et al*, 2006, Cumming, Cumming and Redman, 2006). For example, carbon sequestration occurs diurnally in individual plants, while a peatland's carbon store develops over centuries through peat accumulation over the entire ecosystem. Yet, the resulting climate regulating ESs are valued globally over decades (Scholes *et al*, 2013), as is depicted in a space-time plot in Figure 2-2. The shown disturbances operate over shorter timespans than peatland development and climate regulating ESs. This highlights the unsustainability of exploitative site uses and the temporal lag and spatial mismatch in their trade-offs with climate regulating ESs. Disturbances produce short-term, local and tangible returns in material products, while the loss in climate regulating ESs are abstract (global and long-term) and cumulative (Evans *et al*, 2014; Glenk *et al*, 2014).

Sub-global analyses of ESs may overlook incremental impacts of localized events on global processes (Scholes *et al*, 2013), such as the cumulative releases of GHGs from recurrent peatland exploitation on climate regulation (Page and Baird, 2016). They may also miss the influence of broader events, distant actors and global processes on local land-use dynamics and ES supply (Cumming *et al*, 2006). For example, the greatest releases of carbon and reduction in regional air quality from peat swamp clearing in Indonesia coincides with El-Niño Southern Oscillation events, which delay monsoon rains and result in expansive and uncontrolled fires (Page and Baird, 2016). The interaction between global climatic events and the amplified regional impacts of peatland exploitation may be missed with single-level or strictly spatial analyses.

Figure 2-2 – Generalized operational scales of select peatland ESs (green), anthropogenic uses (red) and factors affecting their supply (dotted).

Note: Figure created by author. General operational scales were derived from peatland literature (Joosten and Clarke, 2002; Webster *et al.*, 2015). The space-time plot, used to conceptualize multi-scalar processes, is based off similar plots found in Clark (1985) and Scholes *et al.* (2013).

Comparatively, global studies are less suited to capturing geographic variations in social-ecological interactions, settings and conditions that result in the varied supply, flow or demand for ESs in similar systems. They are also prone to greater uncertainties and generalizations with data amalgamation. For example, a global peatland assessment required addressing the inconsistent national classification criteria, such as minimum peat depths, used to define peatlands, as well as the varied completion and resolution of national wetland inventories (Joosten and Clarke, 2002). The general findings of global ES studies are less also applicable in regional or local land-use and ES management decisions (Scholes *et al.*, 2013). Sub-global, ecosystem-specific analyses can better reflect the particular social-ecological setting and associated factors affecting ES dynamics (Evans *et al.*, 2014).

Thus, social and ecological processes at a given level can interact with each other, as well as those operating at other levels (Clark, 1985). Further, a study's analytical boundaries can directly impact which influential factors or processes are identified, as well as the strength or significance of trends (Clark, 1985; Scholes *et al*, 2013). Since research findings may be sensitive to the applied spatial and temporal scale, studies advocate multi-scalar ESs analyses and greater scale-awareness in research design (Carpenter *et al*, 2009; Scholes *et al*, 2013). Yet, the logistical constraints on data collection and existing long-term records that impede the wider adoption of multi-scalar and temporal ES analyses are seldom explicitly discussed in studies (Carpenter *et al*, 2009).

2.2.2 Relationships between anthropogenic drivers and ESs

Relationships between ESs arise from shared ecological functions or responses to a common driver, as well as indirectly through interactions (Bennett *et al*, 2009; Mouchet *et al*, 2014; Tomscha and Gergel, 2016). Relationships are categorized as trade-offs or synergies based on whether the co-variation in two or more ESs is negative or positive. Relationships may be tied to social (demand-demand), ecological (supply-supply) or social-ecological (supply-demand) interactions (Mouchet *et al*, 2014). Studies aim to improve the understanding and management of multi-functional landscapes by identifying the relationships between multiple ESs, their recurrence over space and time and the influential factors⁴ (Bennett *et al*, 2009; Mouchet *et al*, 2014). However, due to the multiple operational scales of processes that underlie the supply or demand of different ESs, as well as data constraints, the assessment of their relationships is rarely a holistic representation

⁴ The ESs bundling method outlined by Raudsepp-Hearne *et al* (2010b) and expanded upon by Mouchet *et al* (2014) is used to establish recurrent relationships between selected ESs.

of the diverse ESs associated with a specific ecosystem or landscape (Evans *et al*, 2014).

Anthropogenic exploitation can alter both the relationships between multiple ESs and their individual supply, often producing trade-offs. Although there is no universal definition of ES trade-offs (Mouchet *et al*, 2014), examining the capacity of humans to intervene and alter undesirable relationships (*i.e.* reversibility), as well as characterizing the spatial and temporal traits of trade-offs are common in ES studies (Rodriguez *et al*, 2006). The latter may refer to the spatial and temporal lags in trade-offs between ESs or the inequitable changes in ES distribution between beneficiaries (Mouchet *et al*, 2014). Valuation can also be included in trade-off analysis⁵, such as applying cost-benefit analyses to ES supply under different land-use scenarios (Glenk *et al*, 2014).

2.2.3 Temporal dynamics in ES relationships and responses

Studies on changes in ESs relationships over time are less common than those that assess their spatial variations and recurrence (Mouchet *et al*, 2014; Renard, Rhemtulla and Bennett, 2015). Inconsistencies in long-term data records (*e.g.* changes in reported variables, definitions, intervals between reports and boundaries over which data is recorded) and discrepancies between the scale of interest and that of available data complicate temporal analysis (Raudsepp-Hearne *et al*, 2010b; Tomscha and Gergel, 2016). Existing studies often use a limited number of samples over time or cover shorter timespans (Renard *et al*, 2015). Increasing the examined timespan may limit the number of ESs that can be assessed, the spatial and temporal resolution of trends and the appropriateness of

⁵ In this thesis, ES valuation is included to examine another dimension of the trade-offs between ESs. Thus, it is applied as an analytical tool and is not a literal statement of the ESs' monetary values. The author recognizes that ES valuation is a contentious area of research, as well as the limitations of commodifying ecosystems and their functions in addressing present unsustainable interactions between humans and the environment. An in-depth discussion on ES valuation is beyond the scope of this study.

available data for research objectives (Evans *et al*, 2014; Renard *et al*, 2015).

The relationships between ESs can change over time (Renard *et al*, 2015) and past social-ecological interactions influence current ESs trends (Tomscha and Gergel, 2016). Yet studies that explicitly examine the temporally varied impacts of different drivers or responses of ESs remain scarce (Evans *et al*, 2014). While the cumulative impacts of disturbances may be implicitly included in ES baselines, there have been difficulties in capturing variations in their impacts at finer temporal resolutions over extended periods. For example, studies on past variations in anthropogenic peatland exploitation (Pellerin, 2003) and changes in ESs (Evans *et al*, 2014) rarely exceed 50 to 70-year timespans (Swindles *et al*, 2016).

2.2.4 Anthropogenic impacts on ecosystems and ES supply

The MA's key findings highlight that anthropogenic alterations to ecosystems have expanded and accelerated at unparalleled rates since the mid-1900s with technological advances, increased interconnectivity and population growth; significantly shaping the Earth's surface and trade-offs in ESs (MA, 2005). For example, growth in farmland area is the main driver of global land-use changes and ES trade-offs. Farmland covers 38% of the ice-free terrestrial surface, with its expansion and intensification tied to the degradation of other ESs (*e.g.* habitat support, water regulation) (Foley *et al*, 2005). The amplified supply of a few provisioning ESs and resulting decline or loss in other ESs that tend to be more temporally diffuse and spatially dispersed in their benefits, such as cultural and regulating ESs, is typical of human-induced ecosystem alterations (Carpenter *et al*, 2009; Rodriguez *et al*, 2006). Recurrent trade-offs in regulating ESs may reduce the resilience of ecosystems to changing conditions and their capacity to supply life-supporting ESs in the future

(Cumming *et al*, 2006; Raudsepp-Hearne *et al*, 2010a; Villamagna *et al*, 2013).

As a result, quantifying the response of ecosystem functions and the supply of ESs to human-induced disturbances and specific drivers (*i.e.* distinct development pressures) is outlined as a critical area for further research (Evans *et al*, 2014; Mouchet *et al*, 2014). The impacts of different drivers on ecosystem alterations and changes in ES supply are not equal or static (Evans *et al*, 2014; Mouchet *et al*, 2014). The physical characteristics of a driver and its relationships with ESs may change over time, such as the industrialization, commercialization and other advances in farming practices (*e.g.* tile drainage and nutrient inputs) which have intensified yields, as well as its ecological impacts and trade-offs in ESs (*e.g.* water quality and flow regulation), far beyond that which was previously possible (Foley *et al*, 2005). Thus, the distinction of individual drivers is necessary to understand their specific relationships with the supply of ESs and how they have changed over time.

Societal demands are also diverse and potentially competing in their interests. Since multiple drivers often operate simultaneously in altering ecosystems and the supply of ESs (Evans *et al*, 2014), feedbacks between competing demands or site uses may accelerate or stall changes in the supply of ESs (Mouchet *et al*, 2014). For example, certain exploitative peatland uses may be exhaustive yet compete for overlapping sites within the peatland, such as farmland conversion and commercial extraction, which may, in turn, accelerate the remaining ecosystem's exploitation. Thus, characterizing the impacts of individual drivers, as well as capturing interactions between them with their concurrent operation, are both essential to advance empirical understandings of the effects of multiple drivers on the supply of different ESs (Evans *et al*, 2014).

The drivers of landscape alterations and their impacts on ESs supply are influenced by site and time specific factors, as well as external processes operating at other levels (Belyea, 2009; Evans *et al*, 2014). External processes include common factors that influence ESs trends in similar social-ecological settings (*e.g.* atmospheric pollutant deposition in peatlands, market values of exploited products or changing exploitation techniques). Variations in the geographic setting and past alterations may result in differing current ecosystem conditions, configuration with surrounding landscape structure or regulatory considerations. Ecosystem-specific and sub-global ES assessments are fundamental to distinguish common trends and influential factors on ES supply from those that are site, time or context specific (Cash *et al*, 2006; Tomscha and Gergel, 2016).

The general and context specific factors affecting ES dynamics are exemplified by peatland drainage, a common step in exploitation and a nearly universal feature of disturbed peatlands (Grand-Clement *et al*, 2015). However, the age, depth and density of ditches, as well as their maintenance and regulation, determines their effect on the water table levels, degradation in adjacent peatland areas and changes in the supply of ESs (Monenco, 1981). These factors vary both within and between peatlands. For example, Alfred Bog's deepest drainage ditches, installed a century ago (Anrep and Nyström, 1909; National Air Photo Library [NAPL], 1928), are municipal drains (OMNR, 1990). Despite the later recognition as a 'Class 1' Provincially Significant Wetland (PSW) and the acquisition of remaining peatland areas by conservationists, these drains must be maintained in accordance with Ontario's *Drainage Act*. This prevents the deepest drains from being blocked to mitigate further peatland degradation. Thus, although drainage is common in disturbed peatlands, their physical properties and management regulations

involve site-specific considerations.

2.3 Peatland ecosystem services

2.3.1 From wetland to peatland ESs: A shift to ecosystem-specific analyses

Wetlands are characterized by hydric soils, which are seasonally or perennially saturated, and hydrophytic vegetation adapted to the water-logged, anaerobic conditions (National Wetland Working Group [NWWG], 1997). Yet, individual wetland classes have distinct ecological functions and biophysical properties, which may lead to differences in their supply of ESs. As such, generalizing wetland ESs may lead to inaccurate estimates of the capacity or flow of ESs from different wetland classes. Certain ESs may even be exclusive to a specific wetland group, such as peat products from peatlands.

Peatlands are organic wetlands, comprised of bog and fen classes, which gradually accumulate peat⁶ ($\approx 0.5 \text{ mm yr}^{-1}$), have a near-surface ($\leq 0.5 \text{ m}$) water table and are nutrient-poor (Gorham, 1991; Joosten and Clarke, 2002; NWWG, 1997). They have the highest carbon density and one of the largest carbon stores (270 to 455 billion metric tons of carbon) of all terrestrial ecosystems (Belyea, 2009; Joosten and Clarke, 2002; Price and Waddington, 2000). Conversely, mineral wetlands, such as swamp and marsh classes, do not accumulate peat, exhibit greater seasonal water table fluctuations and may be more nutrient rich. Thus, applying proxies for water filtration or flow regulation ESs derived from a riparian marsh to a raised bog would be inappropriate⁷, as would be applying proxies for carbon storage from peatlands to mineral wetlands that lack the former's carbon density (Evans *et al*, 2014; Holden, 2005).

⁶ In Canada, peatlands have a minimum peat depth of 0.4 m (NWWG, 1997).

⁷ Peatlands exhibit flashier runoff responses to rainfall events than mineral wetlands and also release dissolved and particulate organic carbon (Holden, 2005).

Joosten and Clarke's (2002) global assessment of peatlands, their services and varied human uses, was a seminal publication. The distinction of peatlands from wetlands emphasized their specific biophysical properties and ecological functions on their supply of ESs (Chapman *et al*, 2003). The assessment includes ESs associated with intact and exploitative peatland uses (Table 2-2), highlighting the impact of human activities on the distribution of peatlands and their ESs. Their findings match those of the MA, with anthropogenic alterations intensifying the supply of food (50%), timber (30%) and raw peat (10%), at the reduction of ESs supplied by intact peatlands (Joosten and Clarke, 2002). These findings have been supported by subsequent regional peatland ESs analyses (Chapman *et al*, 2003; Evans *et al*, 2014; Glenk *et al*, 2014).

Table 2-2 – Select ESs derived from peatlands and their exploited uses (Source: Joosten and Clarke, 2002).

Intact Site Uses (<i>In-situ</i>)	Altered Site Uses (<i>In-situ</i>)	Extracted Peat (<i>Ex-situ</i>)
Food production	Crop/vegetable production	Energy production
Animal products	Grazing	Agricultural fertilizer
Medicinal uses of plants	Forestry (timber)	Horticultural applications
Water filtration	Absorption/Filtration (<i>e.g.</i> landfill, water treatment)	Absorption/Filtration (<i>e.g.</i> surgical dressing, bedding)
Water regulation (<i>i.e.</i> store, supply, attenuation)	Infrastructure (<i>e.g.</i> utility corridors, dams)	Flavouring (<i>e.g.</i> whiskey, beer)
Climate regulation (<i>i.e.</i> carbon store, sequestration)	Industry (<i>e.g.</i> resource extraction)	Peat textiles
Habitat support	Urbanization	Insulation materials
Knowledge functions	Military training	Therapeutic

Exploitation disrupts key conditions that enable peatland self-regulation and long-term development, most commonly tied to drainage and its effects on the water table (Belyea, 2009; Grand-Clement *et al*, 2015). As such, disturbances may switch previously accumulating peatlands from net carbon sinks to sources and accelerate degradation in others (Joosten and Clarke, 2002). Many exploitative uses remove the accumulated peat,

which leads to the release of its stored carbon and step changes in land-cover. Even disturbances that leave a site partly intact, such as forestry, may surpass thresholds that cause rapid degradation with peat oxidation, compaction and subsidence (Page and Baird, 2016; Swindles *et al*, 2016). Aside from enhanced decay with drainage, peat can become hydrophobic when exposed to aerobic conditions (Belyea, 2009) and promote the formation of soil pipes; decreasing water retention and amplifying the effects of initial disturbances (Holden, 2005). The cumulative effects of exploitation can also alter these thresholds (Belyea, 2009). Disturbances may also trigger degradation in adjacent peatland areas (Price *et al*, 2003). Given the greater timescales of accumulation versus exploitation, as well as the differing present climatic conditions from those under which peatland development initiated (Holden, 2005; Price, Heathwaite and Baird, 2003), disturbances often lead to irreversible ecological alterations and losses in ES supply.

The scalar mismatch between the general, coarser resolution findings of earlier global ESs assessments (*e.g.* MA, 2005) and typical land-use management decision-making presented gaps that influenced a broad shift to sub-global, ecosystem or landscape specific ES analyses (Evans *et al*, 2014; Scholes *et al*, 2013). This shift produced a greater awareness of the influence of landscape and ecosystem structure on the flow of ESs, as well as the social and ecological conditions on ES supply and demand at a specific site.

A special publication of Ecosystem Services (2014) with peatland-specific ESs studies in the United Kingdom exemplifies this transition. Evans *et al* (2014) and Glenk *et al* (2014) emphasized the influence of variations in peatland structure between subclasses (*e.g.* blanket bogs versus raised bogs) and the geographic setting of specific sites (*e.g.* disturbed and undisturbed blanket bogs) on the supply of ESs. These distinctions, both

between peatland subclasses and specific sites, are valuable in advancing scientific understanding of variations in peatland functions and supply of ESs (Evans *et al*, 2014). For example, the formation of blanket bogs over extensive upland areas means they generally have a greater capacity to supply water regulation and filtration ESs to downstream beneficiaries than topographically confined and less extensive subclasses, such as raised bogs. However, the greater peat depths in raised bogs suggests they have a greater carbon density (*i.e.* weight per unit area) than blanket bogs. As such, the structure and landscape setting of different peatland subclasses can produce distinct considerations in their supply of ESs, which vary according to the ESs of interest and research objectives of a study.

In general, certain peatland ESs may be more sensitive to changes in a peatland's area (*e.g.* habitat support, wild food production, recreation), while others are more strongly tied to peat volume (*e.g.* carbon and water storage) (Joosten and Clarke, 2002). Consequently, peatland subclasses with non-uniform distributions in peat depths may yield divergent areal versus volumetric responses to disturbances⁸. This, in turn, indicates that the response of ESs sensitive to changes in area versus volume may also deviate. Thus, the supply of ESs and their response to anthropogenic exploitation may vary not only between peatland subclasses and sites, with changes in structure and setting (Glenk *et al*, 2014), but within sites as well.

2.3.2 Peatlands' carbon stores and climate regulating ESs

A major benefit of peatlands to human well-being is their influence on climate

⁸ The divergence is a lesser concern for peatland forms with relatively uniform depths, such as flat bogs, as the volumetric changes can be approximated through applying the site's average peat depths.

regulation (Zelder and Kercher, 2005). Its supply is based both on the peatland's existing carbon store and current carbon balance (Joosten and Clarke, 2002). The carbon stored in peat⁹ is by far the most distinctive and influential aspect of peatlands' climate regulating ESs. Part of the carbon dioxide fixed via photosynthesis is effectively immobilized with much slower anaerobic decay, as it is buried and saturated with successive accumulation and the rise of the water table respectively. Over long timespans (>500 years), this stored carbon offsets the warming effects of carbon dioxide and methane releases with aerobic and anaerobic decay respectively (Joosten and Clarke, 2002). The net accumulation of peat in peatlands over past millennia has resulted in both their moderating climatic effect and their unmatched carbon density. However, the carbon store and its changes with disturbances over time has been omitted from spatially explicit examinations of peatland ESs, with greater focus on their present carbon balance and sequestration. The carbon store's omission is linked to the broader gaps in ESs literature outlined in §§[2.2.3](#) and [2.2.4](#).

Peatlands' carbon stores are relevant when there are detectable changes in the mass and volume of peat (Joosten and Clarke, 2002). As noted, anthropogenic disturbances can produce rapid and substantial volumetric changes to peatlands (Page and Baird, 2016; Swindles *et al*, 2016). Changes through natural accumulation or degradation are much slower and, as such, may be negligible over shorter timespans (*e.g.* annual measurements), with average accumulation rates often less than one millimetre per year (Gorham, 1991). Thus, the minimal examination of temporal changes in the response of ecosystem functions

⁹ Peatlands' carbon stores are divided into three components: biomass, litter and peat (Joosten and Clarke, 2002). Despite minor variations between subclasses and sites (*e.g.* open versus treed bog), peat is consistently the largest component of the carbon store in peatlands (98.5%) (Gorham, 1991).

and ESs to multiple anthropogenic disturbances partly explains the absence of the carbon store in current peatland ESs studies.

Data limitations also impede the carbon store's inclusion. The carbon balance is more readily derived from and applied to existing data sets, often as an areal proxy (*e.g.* average weight of carbon per unit area per unit time [t C ha⁻¹ yr⁻¹]) to different land-cover classes (Evans *et al*, 2014; Glenk *et al*, 2014). Further, the seasonal and annual variations in the carbon balance are more amenable to typical timescales of scientific studies. Conversely, data on the spatial variations in peat depths and volume needed to approximate the carbon store's distribution both within and between peatlands is relatively scarcer (Gorham, 1991; Joosten and Clarke, 2002). Further, where data is available at a sufficient resolution, it may require greater effort to include in analysis. Thus, gaps in both historical and present peat depth records may contribute to its omission in studies (Gorham, 1991; Webster *et al*, 2015). This is compounded by the disparate timescales over which detectable changes in peatlands' carbon stores versus most research and site monitoring occurs.

Finally, the transition to sub-global ES studies and the scalar mismatch in trade-offs with peatland's climate regulating ESs (*i.e.* negligible impacts of a single peatland's exploitation on global atmospheric carbon levels), results in a tendency to focus on the non-marginal changes in local peatland ESs (Glenk *et al*, 2014). This emphasizes the tangible local benefits of peatland conservation or rehabilitation, a prevalent theme of many studies, but indirectly contributes to the underrepresentation of the carbon store and their climate regulating ESs. Since reinitiating peat accumulation and a negative carbon balance are integral to peatland rehabilitation the carbon balance may be assessed, while excluding changes in the carbon store (Chapman *et al*, 2003; Price *et al*, 2003).

2.4 Summary

The shift to ecosystem-specific and landscape-level ES analyses is critical to identify factors affecting geographic variations in ES dynamics (Scholes *et al*, 2013). This transition is reflected in peatland ES studies, with the initial distinction from wetland ESs (Chapman *et al*, 2003; Joosten and Clarke, 2002) and subsequent studies on the morphology and landscape setting of specific peatland subclasses and sites to further contextualize variations in ES supply (Evans *et al*, 2014; Glenk *et al*, 2014). However, the effect of peatland structure on ESs has not yet been applied to the carbon store within domed peatlands (*e.g.* raised bogs).

Despite the carbon store's sensitivity to changes in peat volume and the varied distribution of peat in many subclasses, both have been excluded from spatially explicit examinations of anthropogenic impacts on peatland ESs. Thus, for subclasses with large spatial variations in depth and volume, such as domed peatlands, the potential for disturbances of equal area to yield differing impacts on volume and the carbon store based on their location relative to the depth profile has not yet been examined. Divergence in the areal versus volumetric impacts of specific drivers would suggest that multidimensional analyses are necessary to fully assess their trade-offs with the integrated supply of peatland ESs (*e.g.* more extensive disturbance could have greater impact on habitat support, recreation or wild food production, but lesser impact on carbon and water storage).

Further, data constraints have limited historical examinations of multiple anthropogenic drivers on changes in land-use and the supply of ESs (Evans *et al*, 2014; Mouchet *et al*, 2014), with peatland-specific studies mostly limited to the past 50 to 70 years (Swindles *et al*, 2016). As such, changes in the response of ESs to different drivers,

over multiple periods, from their pre-disturbance to present conditions are seldom captured. Yet, examining temporal variations in the relationships and responses of ESs to multiple drivers is fundamental to improve understanding of social-ecological interactions on ES dynamics. It can help address knowledge gaps on the response or relationships of ESs with distinct anthropogenic drivers, factors affecting their changes over time and identify any feedbacks between concurrently operating drivers (Mouchet *et al*, 2014).

3 Chapter: Methods

3.1 Overview

Since no one data source covered the study's 200-year timespan, addressing the research objectives required processing, amalgamating and interpreting multiple sources. For the case-study, the peatland's pre-disturbance extent and subsequent land-cover changes were established using cartographic, photographic and textual sources. Alfred Bog's depth profile and volumetric distribution were estimated using a predictive function derived from two maps with systematically sampled peat depths of independent sites within the raised bog. Land-cover maps were then reused to quantify the areal and volumetric impacts of individual drivers, as well as the peatland's associated reduction. Using this information and a few other sources, changes in the supply and value of the three selected ecosystem services (carbon storage, food production and peat production) were estimated. The case-study trends were established over 11 dates: 1800, 1806-1820, 1830-1860, 1880, 1909, 1928, 1947, 1964, 1991-1994, 2008 and 2014. The 1806-1820, 1830-1860 and 1991-1994 dates are respectively referred to as 1820, 1860 and 1991 hereafter.

Multiple sources were also used to isolate the periods in which competing site uses (CSUs) operated simultaneously and to compile broader level trends for comparing the case-study results. The periods of CSUs were identified using local sources, with particular emphasis on governmental, private and non-governmental organization reports. Broader trends in peatland distribution and the impacts of anthropogenic drivers were also gathered from governmental and private reports, as well as academic sources. Agricultural censuses and mining reports were used to establish broader trends in food and peat production. The specific methods used to address the research objectives are presented separately for the

case-study (§3.2) and broader level analysis (§3.3), in greater detail below. The methods are presented in the general order of the project's workflow.

3.2 Case-study: Alfred Bog

3.2.1 Data source collection and preparation

The combined interpretation of photos, maps and texts documenting local human-environmental interactions was needed to delineate changes in land-cover and peatland extent within Alfred Bog's pre-disturbance boundaries. Sources were gathered from both digital and physical archives. From 1800 to 1928, historical maps and texts were used. From 1928 onward, aerial imagery was also used. For consistency, all created, referenced and downloaded geospatial data was projected to NAD83, UTM Zone 18N. A complete list of sources is found in [Appendix A](#).

3.2.1.1 Cartographic and photographic sources

A total of 16 historical maps and 634 panchromatic air photos were collected, digitized and georeferenced to map land-cover changes. Sources were digitized on a flatbed scanner using a scanning resolution of 600 or 1200 dots per inch. Georeferencing links unreferenced data to a known coordinate system through ground control points (GCPs) (*i.e.* x,y coordinates) with common features in a reference geospatial dataset. The Ontario Ministry of Natural Resources' (OMNR) "Geographic Townships" and "Lot Fabric" shapefiles, which show the pre-1995 township boundaries and lots and concessions respectively, and its 2008 (Digital Raster Acquisition Project for the East [DRAPE]) imagery were used as reference sources and were downloaded from Scholar's Geoportal (OMNR, 2008a; OMNR, 2008b; OMNR, 2013).

Aside from its use as a reference dataset, OMNR's DRAPE imagery, also available for 2014, was used to map land-cover changes in 2008 and 2014. The orthorectified (*i.e.* corrected for geometric and positional errors with variations in elevation) imagery sets were mosaicked in ArcMap 10.2 (ESRI, 2014) with the 'Mosaic to New Raster' tool.

Historical maps were georeferenced manually using the 'Georeferencing' toolbar in ArcMap. Four to twelve GCPs were collected for each map. The number of GCPs collected and the selected reference dataset were affected by the abundance and types of features shown, which varied based on the spatial scale and thematic content of the maps.

Historical air photos were georeferenced using semi-automated referencing software. 326 air photos were actively used to map land-cover changes from 1928¹⁰ to 1991. Another 308 photos helped evaluate land-cover maps¹¹. PCI's Historical Airphoto Processing (HAPs) software was used for all photosets except 1947 and 1978, which used Agisoft's Photoscan (Agisoft, 2015; PCI Geomatics, 2015).

To process photos using HAPs, metadata on flight and photo parameters such as the roll and photo number, focal length, image coordinates and altitude were compiled in an excel spreadsheet. After running photosets through preliminary referencing stages, they were run through the "Alignment" stage iteratively. The mosaicked 2008 imagery and a tiled provincial digital elevation model (DEM) from OMNR were used as the reference image and DEM to establish GCPs and tie points (TPs) for the unreferenced photosets. Hundreds of GCPs and TPs were collected per photo. GCPs and TPs with excessive error

¹⁰ 68 photos from 1927 and 1928 were accessed at the National Air Photo Library, but not acquired. These photos were not digitized, referenced or mosaicked, but were consulted in approximating land-cover in 1928.

¹¹ The additional 308 photos made up four photosets (1946, 1954, 1969 and 1978) with partial site coverage. They were used to get another perspective of landscape features and evaluate the interpreted boundaries in maps, but were not actively used in delineation.

were removed between runs and if needed, a few were manually collected, to successively improve the overall model and positional accuracy of the air photos. This process was repeated until the root mean square error was less than one pixel for each photoset. Photosets were then mosaicked in PCI Geomatica's OrthoEngine (PCI Geomatics, 2015).

3.2.1.2 Textual sources

Textual sources with sufficient spatial reference and detail, as well as any included photos, plans and sketches were incorporated in land-cover delineation. Plans and sketches were georeferenced using the above-described methods for maps.

Field notes of provincial land surveyors (PLSs) were the earliest records (1806-1858) with detailed landscape descriptions (Mosquin, 1991). Traits such as vegetation, topography and soils were recorded as lots, concessions and road allowances were demarcated in Alfred and Caledonia townships. Observations were spatially referenced by lot and concession or measured as a distance in links, chains and miles from a reference point with a particular bearing. Five PLS notebooks were transcribed in total.

Inconsistent wetland terminology between individual surveys and to the current national classification system required identifying peatland sites and other land-cover classes through their landscape descriptions¹². Sites described as '*low*', '*sunken*', '*shaking*' or '*barren*' '*swamps*' and '*marshes*', with '*stunted*' or '*small*' '*spruce*' and/or '*tamarack*' timber were included as part of the original peatland. '*High*', '*dry*' and '*upland*' sites, with '*fine*' or '*drained*' soils and predominantly deciduous timber were excluded as potential peatland sites. '*Burned*', '*cleared*' or '*improved*' lands were classified as 'Cleared Lands'

¹² Field note interpretations from other historical studies on Alfred Bog, especially Mosquin (1991), were also considered. Classification errors, such as identifying black spruce as "red spruce" in Fortune's 1806 field notes, were noted (Bird and Hale, 1984a; Mosquin, 1991).

and occupied lots were classified as ‘Farmland’ in accordance with the mapping assumptions and land-cover classification scheme discussed in §3.2.2. The PLSs’ field notes were then digitized as a point shapefile, with abbreviated summaries of their descriptions and the interpreted land-cover class included in the attribute table, so they could be used with other geospatial data in ArcMap 10.2 to map land-cover changes.

Other textual sources included government, private and non-governmental organization reports, which were used throughout the study to establish and evaluate mapped land-cover changes. For example, reports from the Department of Mines during the joint governmental peat fuel experiments, as well as those by Bird and Hale (1984a) and Mosquin (1991) provided spatially explicit and detailed accounts of Alfred Bog’s ecological conditions and anthropogenic alterations. Sources documenting broader spatial changes or with useful information for contextualizing general sites, timing and drivers of land-cover changes were still considered even when delineation was not possible. For example, promotional texts on the Caledonia Springs Hotel detailed the village’s settlement and growth, peatland clearing and drainage with the hotel’s establishment and the changing transportation networks from 1800 to 1900. Similarly, 14 newspaper articles from 1899 to 2001 provided supporting evidence for events documented elsewhere and captured changes absent from other sources, but were seldom spatially explicit.

3.2.1.3 Identifying periods of concurrently operating competing site uses

A timeline was created to record events identified from sources that influenced Alfred Bog’s reduction. Changes in policies, market values, extraction techniques and perceived uses of both peat and peatlands at broader levels were recorded separately. From these detailed timelines, generalized trends and drivers of peatland alterations, as well as

broader changes in human-environmental interactions were identified.

The timeline of events, in part, helped identify competing site uses (CSUs) and the periods in which they operated simultaneously at Alfred Bog. Three major CSUs were identified: ‘Direct Farmland Conversion’, ‘Commercial Peat Extraction’ and ‘Conservation’. There were two periods in which two or more CSUs operated concurrently. The first period (*i.e.* CSU Period 1), between direct farmland conversion and commercial extraction, was from 1904 to 1964. CSU Period 2, from 1982 to 2004, involved commercial peat extraction and conservation. The three CSUs are exclusive and exhaustive, yet overlap in the potential sites for their production and, thus may compete. Areas directly converted to farmland cannot be commercially extracted or conserved. The case-study trends (*i.e.* peatland’s reduction, impacts of drivers and changes in ESs supply) were then assessed during the CSU periods to explore the potential feedbacks between concurrently operating CSUs on ecosystem alterations.

3.2.2 Mapping land-cover changes

3.2.2.1 Establishing Alfred Bog’s pre-disturbance extent

Alfred Bog’s pre-disturbance area was mapped first, as it was the spatial extent over which subsequent changes in land-cover, peatland area and volume, impacts of drivers, and ES supply were examined. Based upon settlement records, the year 1800 was selected to depict its pre-disturbance boundaries¹³. The first land patents in Alfred and Caledonia townships were issued in 1801 and 1808 respectively (Thomas, 1896). These lots were outside of Alfred Bog’s historical extent, indicating that prior anthropogenic disturbances,

¹³ Prescott County formed in 1800 from part of Glengarry County. PLSs demarcate the lots and concessions of its townships within the next decade.

if any, were unrecorded.

Historical sources and physical confining features were used to map Alfred Bog's pre-disturbance area. Having prepared sources for mapping, its areal extent in 1800 could be roughly estimated, yet conflicting observations between historical sources had to be addressed. Physical confining features such as topography, soils and surficial drainage were used to eliminate conflicting observations and select the most likely boundaries. The interpretation of sources in establishing Alfred Bog's 1800 extent are included below.

1) Digital Elevation Model (DEM):

Raised bogs develop in topographic depressions, with Alfred Bog situated in an abandoned post-glacial meltwater channel. Thus, areas external to the meltwater channel were excluded as potential peatland sites using a DEM (OMNR, 2006).

2) Soils Map:

Clay and fine marine soils deposited by the Champlain Sea (12-10 kya) created the water-logged conditions that initiated Alfred Bog's development (Charron, 1978; Ottawa Field Naturalists Club [OFNC], 2008). Thus, Ontario Ministry of Agriculture, Food and Rural Affairs' (OMAFRA) Soil Survey Complex was used (OMAFRA, 2003) to identify 'Clay' or 'Organic' soils found within the low-lying channel and supported by historical sources, which were then classified as part of the peatland complex. Other soil classes within the low-lying area were also considered, since Alfred Bog is located in a regional groundwater discharge area (Charron, 1978) and may have expanded onto adjacent ecosystems (paludification).

3) Surficial Drainage

The pre-disturbance surface drainage was used to identify boundaries between peat domes and the total peatland's extent. Based on available peat depth samples and reports, three domes were found within the peatland complex. Horse Creek separated the deeper northern and southern domes, while the shallower northwest dome formed around a historical pond (Mosquin, 1991). Hydrological boundaries to the peatland's formation included the South Nation River (west), Caledonia Creek (south) and tributaries of the Ruisseau des Atocas (north). Surface drainage was extensively modified and existing drains deepened with settlement and exploitation (Mosquin, 1991).

4) Aerial Photography:

Alfred Bog's extent prior to disturbances, as well as in following mapped dates (1820 to 1909), cannot be smaller than the 'Peatland' and 'Peat Extraction' boundaries observed in air photos from 1928 onwards.

5) Field Notes and Maps from Earliest Surveyors

The land-cover classes derived from Joseph Fortune's 1806 field notes and William Browne's 1820 map of Caledonia and Alfred townships respectively were also used to approximate the peatland's pre-disturbance extent.

6) Reports estimating historical extent of Alfred

Other reports estimating the peatland's pre-disturbance extent were also used. Specifically, maps and descriptions of Alfred Bog's historical extent in Mosquin (1991) and Bird and Hale (1984a) were used to assess potential peatland sites.

7) Department of Mines (1909) Map

Finally, a 1909 Department of Mines' map was also used to establish the peatland's north-eastern boundaries. These boundaries were supported by surficial geology and soils maps (Fraser, 1976; OMAFRA, 2003).

3.2.2.2 Mapping assumptions

Basic assumptions were also used to address incomplete site coverage and conflicts between sources in delineating land-cover changes in following maps. For conflicting observations, the relevance, reliability and consistency with the observations of other sources was considered. The assumptions were as follows:

- 1) Alfred Bog can only decrease or maintain its extent between dates. Disturbances produce step changes in land-cover (*i.e.* once a site transitioned to a non-peatland class it cannot be reclassified as 'Peatland' in subsequent maps). This assumption was broadly applied to quantify the impacts of individual drivers and the peatland's reduction, discussed further in §3.2.4 and §3.2.5 respectively.
- 2) Commercial peat extraction begins in 1904 (Anrep and Nyström, 1909; Bureau of Mines, 1905) and becomes a prominent driver by the 1940s (Bird and Hale, 1984a; Mosquin, 1991). 'Direct Farmland Conversion' ceases to be a major driver of peatland reduction in the mid-20th century (NAPL, 1964; Richardson, 1948).
- 3) Areas without data coverage in a given map default to the land-cover boundaries of the more recent, nearest map with coverage.
- 4) Maps that span multiple years (*e.g.* 1806-1820 and 1830-1860) assume land-cover boundaries are consistent over that period. For example, it assumes land-cover classes derived from Joseph Fortune's field notes for Caledonia Township in 1806 are stable until William Browne's map of Alfred Township in 1820.

- 5) Lots occupied by settlers, were considered to be completely cleared and converted, unless otherwise noted or if this conflicted with preceding assumptions.

3.2.2.3 Land-cover classification and interpretation

Nine land-cover classes were used to capture changes in landscape structure and the impacts of different drivers within its pre-disturbance boundaries. Classes were based on what could be interpreted from existing sources by applying basic photographic, cartographic and textual analyses. The traits of the selected land-cover classes and their associated drivers are described in Table 3-1 and samples shown in Figure 3-1.

The resolution and relevance of interpretable spatial information varied between data types (*e.g.* photos > maps > texts) and individual sources (*e.g.* map of county roads versus peat bog). The relevance of maps and texts varied based on the alignment of their original purpose and the research objectives. For example, the reports on Alfred Bog by the Department of Mines were more relevant and readily applied in land-cover mapping, than the tourist pamphlets for Caledonia Springs' Grand Hotel. In general, sources in the 1800s were scarcer and not explicitly focussed on the peatland.

The interpretability of historical maps in delineation were affected by their thematic content and physical condition. Legends, labels and supporting texts helped interpret map features. Certain texts documented features in greater detail, such as the field notes versus maps of PLSs. The peatland was not always explicitly depicted, with certain maps roughly outlining the peatland through shaded lots (*e.g.* Cattnach, 1829) or a generic label (*e.g.* 'Marsh' in Lloyd, 1928). However, its extent could often be approximated, such as identifying unoccupied lots or planned versus constructed roads. Similar solutions, and the assumptions outlined above (§[3.2.2.2](#)), were used to classify other land-cover classes.

Table 3-1 – Land-cover classification scheme and associated anthropogenic drivers.

#	Land-Cover Class	Description	Anthropogenic Driver	Air Photo Traits
1	Peatland	Bog, fen and swamp areas, known as “Alfred Bog”.	Conservation (‘Peatland’ in 2014)	Dark tone, variable texture (<i>e.g.</i> treed fen = rough versus open bog = smooth)
2	Peat Extraction	Sites of commercial peat extraction	Commercial Peat Extraction	Frequent drainage ditches (20-50 m), dark tone, smoother texture than bog
3	Cleared Lands	Burned, cleared or altered peatland areas for agricultural conversion.	Direct Farmland Conversion	Variable tone and texture. Burnt areas are dark with rougher texture.
4	Farmland	Cropland, pasture or sites with farming structures.	Direct Farmland Conversion	Lighter tone, access paths, plough patterns, smooth surface texture.
5	Forest	Forested sites external to the remaining peatland core.	Degraded Peatland ¹⁴	Dark to light tone, rough texture
6	Other	Areas not captured by other land-cover classes.	Other (<i>e.g.</i> roadside, riparian, residential and commercial areas)	No consistent traits.
7	Water	Main hydrological features.	Drainage ¹⁵	Darkest tone, smooth texture
8	Roads	Roads and historical railway.	Transportation	Paved roads: bright tone, smooth texture. Gravel and dirt roads: darker tone, rougher texture.
9	Structures	Houses, barns, stores, other anthropogenic structures	Not Applicable ¹⁶	Distinctive shadows. Tone and texture vary between structures and with lighting

¹⁴ ‘Degraded Peatland’ was primarily attributed to anthropogenic drainage and land-use changes that isolated small peatland areas from remaining domes.

¹⁵ ‘Drainage’ only captured the impacts of drains that were not explicitly tied to any other driver. For example, the impacts of field and perimeter drains in extracted deposits were attributed to ‘Commercial Peat Extraction’, as opposed to ‘Drainage’. This avoided diluting the impacts of specific drivers affecting peatland drainage.

¹⁶ ‘Structures’ were excluded from maps prior to 1928, due to insufficient spatial accuracy and non-planimetric depictions in earlier sources.

Figure 3-1 – Air photo and map samples of the interpreted land-cover classes. (Sources: ¹ OMNR, 1991; ² McConnell, 1858; ³ NAPL, 1964; ⁴ Department of Scientific and Industrial Research, 1923; ⁵ Department of Planning and Development, 1947; ⁶ Walling, 1862; ⁷ Browne, 1820; ⁸ Cattnach, 1829)

Air photos offered more detailed and objective representations of landscape features. Land-cover classes were interpreted through tonal and textural variations, as well as other unique traits of specific classes. For example, ‘Structures’ and ‘Forest’ classes created distinctive shadows, while tillage and grazing patterns aided identify ‘Farmland’. The differing tones of ‘Farmland’ and ‘Peat Extraction’, associated with their differing moisture content, and the latter’s high drainage ditch density facilitated their distinction. Broadly, disturbances produced clear divisions between adjacent land-uses and the remaining ‘Peatland’, facilitating the latter’s delineation (Bird and Hale, 1984a). Maps and texts helped classify landscape features in the air photos (*e.g.* Alfred Station).

Each land-cover class had an inferred driver (Table 3-1). Sources indicated that ‘Direct Farmland Conversion’ and ‘Commercial Peat Extraction’ were the main drivers of Alfred Bog’s reduction (Bird and Hale, 1984a; Mosquin, 1991; OFNC, 2008). As such, excluding ‘Transportation’, the drivers tied to other land-cover classes were more generic, rather than distinct development pressures. For example, ‘Degraded Peatland’ and ‘Drainage’ are common features of exploited peatlands. Similarly, ‘Other’ categorized land-cover not captured by other classes, although its subclasses may represent distinct drivers (*e.g.* urbanization, resource extraction or infrastructural development).

3.2.2.4 Delineating land-cover changes

Land-cover changes were manually delineated in ArcMap 10.2 (ESRI, 2014). A polygon shapefile was created for each land-cover class. Interpreting the available sources, sites were designated according to the classification scheme and their extent traced using ArcMap’s ‘Editor Toolbar’ functions. Changes in land-cover configuration were mapped to capture broader trends within classes, such as changing farm field sizes or peat extraction

techniques. A “Class” field was added to each land-cover shapefile and populated using the ‘Field Calculator’. Once the land-cover classes were established for a date they were merged (Geoprocessing). Individual land-cover files were then reused and their boundaries modified accordingly to map land-cover changes in the following date.

Configurational land-cover changes were mapped in reverse chronological order from 2008 to 1820. Imagery for 2014 was delineated later once released. The 2008 orthorectified imagery had minimal geometric or positional errors. Thus, the combined reuse of land-cover shapefiles and reverse chronological mapping reduced the effects of small positional errors from georeferencing sources on the generated land-cover maps.

Since land-cover classes were not delineated as mutually exclusive or exhaustive, allowing for overlap (*e.g.* forest patches and hedgerows on farmland, water under roads or structures on residential sites), shapefiles were clipped to standardize the study site area between maps. The individual polygons of each class were aggregated using ‘Merge’ in the ‘Editor Toolbar’. Classes were then clipped in the following order in each map: ‘Roads’, ‘Structures’, ‘Forest’, ‘Farmland’, ‘Water’, ‘Peat Extraction’, ‘Cleared Lands’, ‘Peatland’ and ‘Other’. An “Area” field was added and quantified using the ‘Calculate Geometry’ function. This enabled changes in land-cover composition to be captured, a prerequisite to quantify changes in the peatland’s reduction, impacts of drivers and the selected ESs over the 11 examined dates.

3.2.3 Determining Alfred Bog’s pre-disturbance volume

3.2.3.1 Data preparation

Alfred Bog’s volume was determined using peat depth samples recorded on two maps: Anrep and Nyström (1909, $n=317$) and Bird and Hale (1984, $n=117$). The maps

covered separate areas within the peatland complex, the former located in the northwest dome and parts of the northern dome, while the latter was confined to the southern dome. Incomplete site coverage excluded the possibility of interpolating peat depths. Instead, the study site's pre-disturbance volume was determined by establishing and extrapolating the relationship between peat depths and their distance from the peatland's edge.

The peat depth samples were digitized in a point shapefile and the reported depths were standardized to metric units. Using the "Near" tool, the distance of depth samples from delineated 'Peatland' boundaries in different maps were quantified to explore the relationship. Ultimately, Alfred Bog's 1860 extent was used to calculate the distance of samples in deriving the predictive function for peat depths.

A 10×10 m point grid, to which the predictive function would be applied, was generated using the "Create Fishnet" tool. The peatland's 1800 extent was input as the "Template Extent" and "Create Labels" was checked. Easting and northing coordinates were added to the attribute table. The label point file was then clipped to the 1860 boundaries and the "Near" tool applied to calculate each point's distance from the peatland's edge. Points outside of the 1860 boundaries, but within the pre-disturbance (1800) boundaries of the peatland complex were also exported as a separate shapefile.

3.2.3.2 Establishing the peat depth-distance predictive function

The attribute tables of the peat depth sample and the clipped 10×10 m were exported as comma-separated values files (.csv) for use in Excel and R Studio. Depths were plotted against their distance from the peatland's edge in 1860 in Excel. After different relationships were examined (visual fit, plot diagnostics, R^2), a power law function was used to curve fit the depth-distance data. Coefficients were optimized in R studio, running

them through a non-linear least squares function. The resulting predictive function was:

$$y=a(x^b)$$
$$y=0.15831(x^{0.46984}) \quad \text{[EQ 1]}$$

The function was applied to the clipped 10×10 m point grid within the 1860 boundaries, using the distance column to predict the corresponding depths. Depths were then multiplied by 100 m^2 ($10 \text{ m} \times 10 \text{ m}$) to determine the peat volume at each point. The .csv file, with calculated depths and volumes, was reimported into ArcMap (Add XY data) to be used in determining the rates and drivers of volumetric reduction.

Points external to the 1860 boundaries were classified as peat swamp or lagg areas. These are transitional areas between a domed peatland and adjacent lands (*e.g.* upland forest or low-lying mineral soils) (NWWG, 1997). Although peat depths are commonly less than 0.5 m (Howie and Meerveld, 2011), an ecohydrological model of these areas for a boreal peatland used an average depth of 0.9 m^{17} (Dimitrov, Bhatti and Grant, 2014). Using these values and assuming a peat depth of zero at the peatland complex's edge, an average depth of 0.3 m (rounded to nearest decimeter) and volume of 30 m^3 was assigned to each point within the 1800 to 1860 boundaries. The distinction of 'Peat Swamp' and 'Domed' areas within the peatland complex led to the separate examination of the case-study results over the 'Entire Complex' (1800-2014) and 'Domed' sites (1860-2014).

3.2.4 Quantifying the impacts of anthropogenic drivers

The impacts of drivers were quantified using the land-cover maps and volume point grid. Broadly, the area and volume¹⁸ of a site was considered fully removed in the map

¹⁷ 0.9 m was the average depths of 'Forest Margin' and 'Mid-Transition' in Dimitrov *et al* (2014), excluding 'Fen Margins', which was assumed to be captured by the predictive function applied in 'Domed' sites.

¹⁸ Assumption that the entire peat deposit was removed at exploited peatland sites for Alfred Bog was supported by field visits, air photos (OMNR, 2008a) and additional sources (Bird and Hale, 1984a), in which

where it switched from ‘Peatland’ to a non-peatland class, and the specific class affecting the change was the driver. Exceptions to this assumption are detailed below.

The impacts (ha and m³) and rates (ha⁻¹ yr⁻¹ and m³ yr⁻¹) of drivers were calculated in their respective units and as percentages of the baseline area and volume values (% and % yr⁻¹). This was to facilitate comparing the correspondence in their impacts on area versus volume both within and between the two examined extents (‘Entire Complex’ and ‘Domed’ sites). The impact rates were calculated to account for the irregular time intervals between maps. To help assess the influence of area versus depth on the volumetric impacts of drivers, variations in their average volumetric impacts per unit area and depths were also included. These trends were quantified both in each of the 11 dates and cumulatively, over the entire historical study.

Sites that transitioned from ‘Peatland’ to ‘Farmland’ classes may have been directly converted or driven by intermediary drivers (*e.g.* commercial extraction). To determine the driver, the second mapping assumption (§[3.2.2.2](#)) was applied. Until 1964, sites that transferred directly to ‘Farmland’ were classified as ‘Direct Farmland Conversion’, with widespread agricultural conversion from the 1800s to the mid-1900s (Richardson, 1948; NAPL, 1928). Only peatland areas adjacent to peat extraction sites that switched directly to ‘Farmland’ after 1947 were classified as ‘Commercial Peat Extraction’.

3.2.4.1 Areal impacts

Land-cover classes, excluding ‘Peatland’, were copied into a corresponding shapefile labeled “Drivers[Year]”. Hydrological features in 1800 were clipped to isolate

the mineral substrate (clay layer) visible at many sites after exploitation. Thus, residual peat layers and carbon stored after disturbances were likely negligible for most examined drivers.

human-induced alterations to the peatland and drainage network. The timing and drivers of disturbances were then determined by clipping land-cover classes chronologically across maps to remove extraneous changes in land-cover (*e.g.* reforestation of previously cleared sites or the transition to farmland and other site uses after peat extraction is complete). To isolate the main drivers and remove transitional classes and drivers (*e.g.* ‘Forest’/‘Degraded Peatland’) (Pellerin, 2003), ‘Peat Extraction’, ‘Farmland’ and ‘Cleared Lands’ classes were clipped first across all maps. This was then repeated for ‘Road’ classes, followed by ‘Water’ and ‘Other’ classes and finally, ‘Forest’.

3.2.4.2 Volumetric impacts

The volumetric impacts of drivers were isolated using ‘Select by Features’ and ‘Select by Location’ tools with the “Drivers[Year]” and depth shapefiles. Using the ‘Field Calculator’, both the driver and date associated with selected points were included in “Class” and “Year” fields. This was repeated for all drivers in each map; enabling both the volumetric impacts of drivers to be quantified and examined.

‘Commercial Peat Extraction’ was an exception to the assumption that peat was completely removed in the first map that its disturbances are registered. Commercial operations remove peat gradually, over years and decades, through successive extraction (Environmental Commissioner of Ontario [ECO], 2005; Monenco, 1981). At Alfred Bog extraction was intermittent, with certain sites cleared, partly extracted and then left idle for long periods. Thus, applying this assumption would overestimate the volumetric impacts of extraction in earlier dates and underestimate more recent impacts.

To capture its gradual volumetric impacts, points classified as ‘Commercial Peat Extraction’ were exported as a separate file and a “Year2” field added. Air photo mosaics

and land-cover maps were used to estimate the date when peat deposits were exhausted, at which point the volume was considered completely extracted. By averaging the two methods, which placed the entire volumetric impacts at the beginning (“Year”) and completion (“Year2”) of extraction, the gradual volumetric impacts of ‘Commercial Peat Extraction’ were captured over the examined dates. This averaged value was used to calculate the peatland’s volumetric reduction rates.

3.2.5 Quantifying Alfred Bog’s reduction

The site’s natural hydrological features (*i.e.* pre-disturbance ponds and streams) were clipped to determine the peatland’s total area and volume in 1800. The remaining peatland area or volume in each date was quantified by subtracting the cumulative impacts of all drivers (*i.e.* across all maps up to and including that being calculated) from the total in 1800. Having determined the area and volume remaining in each map, the reduction rates were calculated by taking the difference in area or volume between two maps divided by the difference in years. As with the individual drivers, the average volumetric losses per unit area and depths of exploited deposits were calculated for each date and cumulatively.

3.2.6 Approximating the selected ecosystem services

3.2.6.1 Supply

Using the land-cover and driver data in conjunction with other proxies the supply of the three examined ecosystem services (ESs) were quantified. ‘Farmland’ area was used to establish changes in the area available for food production. Carbon storage and peat production are weight-based ESs. Thus, the volume of undisturbed and commercially extracted peat in each date was established. Since peat’s *in-situ* moisture content is often near saturation (85% to 95% water by volume) (Monenco, 1981), further conversions were

applied to determine the weight in tonnes of commercially produced peat at 30% moisture and the dry weight of stored carbon. Their specific calculations and conversions are detailed in [Appendix B](#). Where possible, proxies were derived from local sources.

To determine the weight of peat commercially produced at Alfred Bog required accounting for peat losses with production. Losses were considered for drainage (field and perimeter ditches) and surface levelling in site preparation, and a shallow residual peat layer left after extraction (Haanel, 1926; Monenco, 1981). After these losses were subtracted from the volumetric impacts of ‘Commercial Peat Extraction’, the remaining peat volume was that available for production in each date. This was converted to a weight at 30% moisture; reflecting common industry practices (Monenco, 1981).

Using the dry bulk densities reported for different ranks of peat humification (von Post scale) and the average depths of these ranks reported for Alfred Bog (Bird and Hale, 1984, p.22-23), a weighted average of the peat’s dry bulk-density was calculated. This was multiplied by the volume of undisturbed peat in each date¹⁹ to quantify its dry weight. The peat’s average organic carbon content was determined to be 51.4%, was derived from the reported chemical composition of peat samples in Alfred Bog (Bird and Hale, 1984a, p.62). Thus, the dry weight of peat was multiplied by 0.514 to quantify the total carbon stored in tonnes and its reduction with exploitation.

3.2.6.2 Value

To determine the value of the selected ESs, per unit area and weight values were established for the ESs and multiplied by their supply. The historical market values of peat

¹⁹ Using the averaged volumetric impacts of ‘Commercial Peat Extraction’ over time (described in [§3.2.4.2](#)).

and food production were compiled to assess their changes over time. Carbon storage, which lacks historical market values, was assigned a value of \$49 per tonne (\$ t C). This was the averaged maximum and minimum quasi-market values of carbon reported in Kulshreshtha *et al* (2000, p. 70) adjusted to their 2015 value.

The value of food production per hectare (\$ ha⁻¹) at Alfred Bog was calculated by dividing value of farmland and buildings by total farmland area reported for Prescott County in Census of Agriculture records from 1861 to 2011. The misalignment between land-cover maps and census records led to the value for farmland per unit area being first adjusted to the mapped date and then adjusted to its 2015 value. The timespan of the GDP deflator index (1871-2010) and changing boundaries over which census values were reported limited the analysis of food production's value from 1880 to 2014. The unadjusted and inflation-adjusted average values of farmland per hectare used in each date and the specific census years from which they were derived are listed years in Table 3-2.

Table 3-2 – Historical and inflation-adjusted (2015) value of farmland per hectare.

Census Year	Map Year	\$ ha⁻¹ (Census)	\$ ha⁻¹ (2015)
1861	1880	\$85	\$3,249
1911	1909	\$135	\$3,949
1921-1931	1928	\$146	\$2,533
1951	1947	\$131	\$1,326
1961	1964	\$336	\$2,938
1991	1991	\$2,813	\$4,518
2001-2011	2008	\$9,430	\$11,363
2011	2014	\$11,251	\$12,120

Suppression of provincial and local peat records required using the adjusted national value per tonne to determine the value of peat production at Alfred Bog. The weight of peat produced since the previous map was multiplied by the averaged national per tonne values over that timeframe.

3.3 Broader trends

Broader level trends in the distribution of peatlands and impacts of anthropogenic drivers on their reduction were established using a variety of sources. Farmland and peat production trends were also compiled to compare with trends at Alfred Bog. Historical units were standardized to metric units and market values associated with food and peat production were adjusted to their value in 2015 using the Gross Domestic Product (GDP) deflator index. Sources used to establish broader trends are recorded in [Appendix C](#).

3.3.1 Peatland distribution: Area, volume and carbon storage

The estimates of peatland area, volume and carbon storage were compiled from government reports; providing regional, provincial and national baselines for comparing the case-study results. A range of reported values existed at a given administrative level. Where possible the methods used to derive estimates was noted. This information was used to determine the appropriateness of an estimate in comparing it with the case-study results. For example, studies deriving estimates strictly from in-field validated sites vastly under-predicted peatland resources and were excluded from the comparison. With the remaining values, Alfred Bog's volume, area and carbon storage were then calculated as percentages of their distribution at other levels. This helped indicate the study site's influence on peatland trends at other levels and evaluate some of the site estimations.

3.3.2 Anthropogenic drivers of peatland reduction

The impacts of anthropogenic drivers on peatland reduction at other sites and broader levels were gathered from academic studies, as well as governmental and non-governmental reports. The sources only reported on the areal impacts of drivers, excluding their volumetric impacts. Certain sources did not clearly identify the methods used in

quantifying the impacts of drivers. All sources were used due to the scarcity of available data, while recognizing their limitations.

3.3.3 Food production and farmland expansion

Municipal, county, provincial and national data on farmland area and food production was derived from Canada's Censuses of Agriculture. The total farmland area, number of farms as well as the market value of farmland and buildings were compiled in an excel spreadsheet. Areal measurements prior to 1976 were converted to metric units for consistency across the study. The reported farmland area was divided by the value of land and buildings to calculate farmland's value per hectare. This per unit value was subsequently adjusted to 2015 Canadian dollars. To compare across levels, farmland area was plotted as a percentage of the total area.

3.3.4 Peat production

Provincial and national data on commercial peat extraction was derived from various mining reports. The weight, use (*e.g.* Fuel, Moss) and market value of peat were compiled in an Excel spreadsheet. Weight units were standardized to metric tons. The total peat extracted was determined by summing reported weights of peat moss (before 1941=0) and peat fuel production (after 1956 = 0). Subsequently peat's nominal market value was divided by the total weight to determine its value per tonne in a given year. The suppression of peat extraction data for Ontario after 1986 required using the adjusted national value of peat per tonne to quantify the value of peat production ESs at Alfred Bog over time.

3.3.5 Adjusting nominal market values for inflation

Reported historical market values of food and peat production had to be adjusted for inflation. All historical market values reported have been adjusted to their value in 2015

using the GDP Deflator index (2012, Table 383-0027). This index was selected over others due to its greater timespan; covering from 1871 to 2010. The index was extended to 2015 using reported GDP from 2010 to 2015 (2016, Table 380-0064) and the 2010 GDP deflator index value to determine the GDP for 1926, $n=100$ (Equation 2). The reported GDP values for 2011 to 2015 were then divided by the 1926 GDP and multiplied by 100 to determine their values on the index (Equation 3). Historical market values could then be adjusted to their 2015 value (\$CDN 2015) by dividing the 2015 GDP deflator index value by the index value of the year being adjusted and multiplied by the historical market value (Equation 4).

$$\text{a) } \mathbf{GDP_{1926} = Index_{1926} / Index_{2010} \times GDP_{2010}} \quad \text{[EQ 2]}$$

$$\text{b) } \mathbf{Index_{(Year)} = GDP_{Year} / GDP_{1926} \times 100} \quad \text{[EQ 3]}$$

$$\text{c) } \mathbf{Value_{2015} = Index_{2015} / Index_{(Year)} \times Value_{(Year)}} \quad \text{[EQ 4]}$$

3.4 Overview of Alfred Bog's history

Alfred Bog is one of, if not, the largest domed peatland in southern Ontario, both by area and volume (Bird and Hale, 1984a; Canadian Peat Society, 1916). It has developed over the past 7000 years in an abandoned glacial meltwater channel, 75 km southeast of Ottawa (Figure 1-2) (Aylsworth *et al*, 2000; Mosquin, 1991). Covering roughly 111 km² in 1800, the peatland complex at Alfred was composed of three connected peat domes and surrounding 'Peat Swamp' at the periphery. The same meltwater channel contains the smaller but better known Mer Bleue Bog. The clay substrate underlying both peatlands was deposited by the Champlain Sea which occupied the region after deglaciation (12-10 kya) and then retreated with isostatic rebound. This led to the water-logged conditions that catalyze the peatlands' initial development. Alfred Bog and Mer Bleue Bog, are typical features of boreal landscapes, but rarer in temperate areas of southern Canada; providing a

unique habitat for many rare and endangered species (Cuddy, 1983; Mosquin, 1991).

Roughly two centuries of anthropogenic exploitation, predominantly agricultural conversion and commercial extraction, have significantly altered its extent, configuration and ecological conditions (Bird and Hale, 1984a; Mosquin, 1991). Farmland conversion dominated local and regional land-cover changes in the 19th and early 20th century (Richardson, 1948). Yet interests in commercial peat extraction increased in the 1900s, exemplified by the joint provincial and federal government peat fuel tests from 1909 to 1914 and 1918 to 1923 (Haanel, 1926). Although commercial peat fuel extraction was sporadic from 1904 to 1928 (Anrep and Nyström, 1909; Haanel, 1926), peat moss for agricultural and horticultural uses after 1941 became profitable and widespread at Alfred Bog and throughout southern Canada (Leverin, 1944; Monenco, 1981; Warner and Buteau, 2000). Commercial extraction continues at Alfred Bog's margins presently.

Conservation at Alfred Bog began in 1982, as various actors²⁰ formed The Alfred Bog Committee. The committee sought to ensure the remaining peatland's protection through policy and property ownership (F. Pope, personal communication, July 14, 2015). It first acquired a 20 ha parcel in 1983 to gain 'stakeholder' status and appeal a zoning reversal that permitted further exploitation (OFNC, 2008). Two major property acquisitions of 1500 and 1300 ha in 1988 and 2001, combined with minor purchases led to roughly 3000 ha or 90% of the remaining peatland (area) being owned (OFNC, 2008). With the peatland's redrawn provincially significant wetland (PSW) boundaries also recognized in local zoning, over 95% of Alfred Bog's remaining extent is protected (OFNC, 2008).

²⁰ Included the Ottawa-Field Naturalist Club, Nature Conservancy of Canada, South Nation Conservation, Vankleek Hill Nature Society and many others (F. Pope, personal communication, July 14, 2015).

4 Chapter: Alfred Bog's multidimensional response to disturbances

4.1 Overview

This chapter presents the results and discussion of Alfred Bog's responses (*i.e.* losses and reduction rates) to disturbances, in both area and volume. These trends are examined over two distinct spatial extents, the 'Entire Complex' (EC) and 'Domed' sites (DS), due to their differing areal and volumetric baselines (Table 4-1). The baseline values influenced the calculated percentages of area and volume, and by extension the magnitude of their divergence in the 'Entire Complex' (EC) versus 'Domed' sites (DS).

Changes in the remaining area and volume, as well as the corresponding reduction rates are shown in Figure 4-3 (EC) and Figure 4-4 (DS) respectively. The specific values, as well as the average volumetric losses per unit area ($\text{m}^3 \text{ ha}^{-1}$) are found in [Appendix E.1](#). Average depths (m) of disturbances are included in Appendix E.5. They helped assess the relative influence of area versus depths on the peatland's volumetric response. For example, although the volumetric losses in 1860 (3.8%) and 1947 (4.0%) are similar, the losses in 1860 were tied to the extent of disturbances (1860: 29.1 km^2 (26.2%); 1947: 6.9 km^2 (6.2%)), while those in 1947 were tied to greater depths (1860: 0.3 m; 1947: 2.3 m) and volume per hectare (1860: $3.00 \times 10^3 \text{ m}^3 \text{ ha}^{-1}$; 1947: $2.35 \times 10^4 \text{ m}^3 \text{ ha}^{-1}$).

The results are divided into three major sections:

[§4.2.1](#) pre-disturbance conditions of the peatland complex and its components, 'Peat Swamp' and 'Domed' sites.

[§4.2.2](#) reports the general spatial progression of disturbances from 1800 to 2014.

[§4.2.3](#) covers the peatland's areal and volumetric reduction over the following 10 dates and cumulatively over the entire historical study.

The discussion is divided into two sections:

[§4.3.1](#) factors affecting the peatland's divergent responses.

[§4.3.2](#) the implications of the peatland's divergent reduction with disturbances in relation to their impacts on ecosystem stability and the carbon store.

4.2 Results

4.2.1 Pre-disturbance conditions at Alfred Bog

Alfred Bog's pre-disturbance area and volume is listed in Table 4-1 for the entire complex and its components: 'Peat Swamp' and 'Domed' areas. The three domes (northwest, northern and southern), within the 1860 boundaries, are labeled in Figure 4-1. 'Domed' sites made up 65% and 95% of the complex by area and volume.

Table 4-1 – The pre-disturbance area and volume of the peatland complex and its subcomponents.

Spatial Extent	Boundaries	Area (ha)	Volume (m ³)
Peat Swamp	1800-1860	3.85×10^3 (35%)	1.16×10^7 (5%)
Domes	1860-2014	7.26×10^3 (65%)	2.22×10^8 (95 %)
Entire Complex	1800-2014	1.11×10^4 (100%)	2.34×10^8 (100%)

Figure 4-2 shows the predictive function used to determine the spatial distribution of depths and volume in 'Domed' sites. Both the depth samples and the power function capture the domed peatland's curved depth profile, with depths increasing towards the centre. The disproportionate distribution of peat volume in 'Domed' sites is tied to its much greater average depth (3.1 m) and volume per unit area (2.41×10^4 m³ ha⁻¹) than that in 'Peat Swamp' areas (0.3 m and 3.00×10^3 m³ ha⁻¹). Combined, the average depth and volume per unit area in the 'Entire Complex' was 2.1 m and 1.35×10^4 m³ ha⁻¹.

Since disturbances were mostly in 'Domed' sites after 1860, the trends of the 'Entire Complex' and 'Domed' sites largely overlap. In their areal and volumetric units, the reduction rates, depths of disturbances and volumetric losses per unit area are of equal

or similar values over both spatial extents (EC and DS). The peak volumetric reduction rate ($9.24 \times 10^5 \text{ m}^3 \text{ yr}^{-1}$), maximum average depth (3.0 m) and volumetric loss per unit area (EC: $3.00 \times 10^4 \text{ m}^3 \text{ ha}^{-1}$; DS: $3.03 \times 10^4 \text{ m}^3 \text{ ha}^{-1}$) in 1964 are similar in the ‘Entire Complex’ and ‘Domed’ sites. However, their results are presented separately to compare the magnitude of divergence in the peatland’s response over both extents. For example, although the same area (35.0 km^2) and volume ($1.32 \times 10^8 \text{ m}^3$) remains in 2014, the percentages varied with 31.5% and 56.2% of the pre-disturbance area and volume remaining in the ‘Entire Complex’ versus 48.2% and 59.2% in ‘Domed’ sites.

Figure 4-1 – Reduction in Alfred Bog’s extent over the 11 dates between 1800 and 2014.

Note: The 1860 border is thicker to distinguish ‘Peat Swamp’ and ‘Domed’ areas of the peatland complex.

Figure 4-2 – The power function (red), derived from peat depth samples (black), to predict depths and volume in ‘Domed’ sites.

4.2.2 Incremental peatland reduction and spatial progression of disturbances

Figure 4-1 depicts Alfred Bog’s shrinking areal extent and the broad progression of disturbances over the 11 dates. Disturbances progressed inwards from the peatland’s margins, moving rapidly from ‘Peat Swamp’ areas prior to 1860 to ‘Domed’ sites thereafter. By 2014, the ‘Peat Swamp’ and northwest dome were fully exploited. The remaining peatland overlaps with the northern and southern domes.

Disturbances were visibly slowed with the exploitation of deeper deposits in the 20th century. The greater volumetric response to disturbances in the 1900s is corroborated by larger average volumetric losses per unit area and depths of disturbances, which were less than $2.00 \times 10^4 \text{ m}^3 \text{ ha}^{-1}$ and 2 m respectively prior to 1909 and greater thereafter (see Appendices [E.5](#) and [E.6](#)).

4.2.3 Alfred Bog's areal versus volumetric reduction

4.2.3.1 Reduction in the peatland complex (1800-2014)

Figure 4-3 – Alfred Bog's area (solid) versus volume (dotted) remaining (pink), and associated reduction rates (brown), in the 11 dates over the 'Entire Complex'.

Solid versus dotted lines also distinguish areal versus volumetric trends in other figures. The vertical red line broadly separates disturbances in 'Peat Swamp' (1800-1860) and 'Domed' areas (1860-2014).

Alfred Bog's extent was reduced from 111.1 km² (100%) to 73.2 km² (65.9%) between 1800 and 1860. This produced the greatest decline in the remaining peatland area and corresponding peak in areal reduction rates in 1860 (0.65% yr⁻¹). By 1909, 62.3 km² (56.1%) of the peatland remained. Areal losses continued in the 20th century at a lesser intensity, decreasing another 27.3 km² (24.6%) to 35.0 km² (31.5%) by 2014. Thus, areal losses of the 19th century were double those of the 20th century.

In contrast, volumetric reduction rates were negligible prior to 1880 (<0.10% yr⁻¹). In 1909, the site contained 2.02×10^8 m³ or 86.2% of its original volume. As of 2014, this

was further reduced to $1.32 \times 10^8 \text{ m}^3$ (56.2%)²¹; representing net losses of $3.23 \times 10^7 \text{ m}^3$ (13.8%) from 1800 to 1909 and $7.01 \times 10^7 \text{ m}^3$ (30.0%) from 1909 to 2014. Contrary to areal losses, volumetric losses in the 20th century were double those of the 19th century. Further, the peak volumetric reduction rate occurred in 1964 (0.39 % yr⁻¹), which was smaller and a century later than that of areal reduction.

Thus, the peatland's areal versus volumetric responses to disturbances diverged. Approximately $\frac{2}{3}$ (64.1%) of total areal losses occurred between 1800 and 1909 (48.8 km² of 76.1 km²), while $\frac{2}{3}$ (68.4%) of total volumetric losses occurred from 1909 to 2014 ($7.01 \times 10^7 \text{ m}^3$ of $1.02 \times 10^8 \text{ m}^3$). The peatland's cumulative losses also diverged, with more than $\frac{1}{2}$ (56.2%) of its volume intact in less than $\frac{1}{3}$ (31.5%) of its pre-disturbance area after two centuries of exploitation.

4.2.3.2 Reduction in domed sites (1860-2014)

Figure 4-4 – Remaining peatland and reduction rates, by area and volume, in 'Domed' sites.

²¹ Includes the volume from actively extracted, but not yet exhausted peat deposits in 2014.

As with the ‘Entire Complex’, areal losses and reduction rates initially outpaced those of volume. For example, 64.4% (24.3 km² of 37.7 km²) and 48.5% (4.41×10^7 m³ of 9.08×10^7 m³) of the total areal and volumetric losses in ‘Domed’ sites occurred from 1860 to 1947. Cumulative losses also diverged, with 48.2% and 59.2% of the original area and volume remaining in 2014.

In 2014, the difference in the areal versus volumetric losses ($|\Delta_{A-V}|$) was 11.0% compared to 24.7% in the ‘Entire Complex’. The peak areal and volumetric reduction rates showed a stronger correspondence; differing by only 0.09 % yr⁻¹, compared to 0.26 % yr⁻¹. Both the areal and volumetric reduction rates peaked in 1964.

4.2.4 Summary of the peatland’s areal versus volumetric reduction

The peatland’s responses to disturbances were divergent in each date and cumulatively over 200+ years, in both the ‘Entire Complex’ and ‘Domed’ sites. Further, the magnitude of divergence varied between examined dates. The difference between the remaining area and volume widens from the 1800s until it peaks in 1947 (32.5%) (EC) and 1964 (15.2%) (DS) (see [Appendix E.7](#)). The gap subsequently narrows, as the volumetric response to disturbances increases.

4.3 Discussion

Since certain ESs are more affected by volume than area, a multidimensional analysis is necessary to capture the integrated response of ESs to disturbances in peatland complexes and domed subclasses. Thus, spatially explicit analyses of depth and volume variations within domed peatlands are required to fully assess the response of certain ESs to disturbances and individual drivers. This is demonstrated specifically with Alfred Bog’s carbon store in this case-study (Ch. 6).

4.3.1 Factors affecting areal and volumetric divergence

4.3.1.1 Spatial distribution of disturbances and peat depths

The main factor shaping the areal versus volumetric divergence was the distribution of disturbances relative to spatial variations in the depth profile. The case-study demonstrated that the peatland's volumetric response, a combined function of area and depth, could deviate from its areal response to disturbances. Capturing the divergence in areal versus volumetric reduction requires incorporating the spatial distribution of peat depths and disturbances. The peatland's divergent reduction demonstrates the importance of multidimensional analyses in examining the response of their ESs to disturbances, something which is not yet commonly done.

The range in peat depths also affects the magnitude of divergence in the peatland's areal versus volumetric response. Divergence will be less pronounced at sites with smaller variations in depth. There is likely a minimum range in peat depths above which incorporating the depth profile is necessary to approximate the volumetric impacts and losses in the carbon store with disturbances. For sites below the threshold, the efforts in incorporating depth and volume will outweigh the benefits of improved accuracy. Further studies would be needed to identify the threshold and explore whether subclasses are grouped above or below such a threshold.

Since Alfred Bog is not completely exploited, the areal versus volumetric losses in 2014 were divergent. The remaining peatland coincides with deeper sections of the northern and southern domes. As such, the percentage of volume left intact is greater than that of area, with over 50% of the peatland's volume remaining in less than half of its original area. Thus, the divergence in areal versus volumetric reduction in domed peatlands

that remain partly intact has important implications for evaluating both the present and future supply of ESs.

Although the case-study focussed on the peatland's past responses to disturbances, the findings and implications are not limited to historical analyses. Multi-dimensional analyses can also be applied to pristine and partly disturbed peatlands presently in examining spatial variations in the response of the ecosystem and its ES supply to future disturbances. This may help isolate, prioritize and protect sites with greater influence on ecosystem stability and the integrated supply of ESs in land-use zoning, policy and management decisions. Thus, the analysis can also be extended to intact peatlands to preemptively identify priority sites and prevent or reduce undesirable changes in ESs supply.

4.3.1.2 Incremental reduction: Changing distribution of disturbances over time

Although the main factor affecting divergence is spatial, the peatland's incremental reduction led to changes in the extent and depths of disturbances over time. As a result, the relationship between areal and volumetric responses and the magnitude of their divergence was temporally dynamic, varying between examined dates. Incremental reduction is common, particularly in larger domed peatlands, where many exploitative uses operate gradually over years and decades (*e.g.* successive burning or extraction with farmland conversion and commercial peat extraction respectively) (Monenco, 1981; Swinnerton and Ripley, 1947). Further, the cumulative impacts from incremental exploitation may alter the quality or condition of the remaining peatland resources and ESs. This, in turn, can affect the distribution of further exploitation and the continued supply of peatland ESs. Thus, capturing variations in the magnitude of divergence and peatland conditions at finer intervals are relevant considerations both at Alfred Bog and in other domed peatlands.

The manner in which disturbances progressed, namely inwards from the peatland's margin, shaped the changing magnitude of divergence in both examined spatial extents. Areal reduction exceeded volumetric losses in the 19th century, with the latter increasing in the 20th century. Shallower depths on the peatland's edge facilitated greater areal reduction in the 19th century, while the exploitation of deeper deposits in the 20th century produced greater volumetric impacts. Thus, the areal impacts of manual exploitation in the 1800s exceeded that of mechanized techniques in the 1900s due to the changes in the depth and volume of exploited deposits. A spatially explicit analysis of the depth profile readily contextualizes this trend, which may remain counterintuitive or unidentified in areal examinations only.

The peatland's divergent responses were partly intensified after 1909 due to the delayed volumetric impacts of 'Commercial Peat Extraction'. For example, the time lag produced both the decline in volumetric reduction rates in 1947 and their intensification in 1991. The delay also amplified the maximum divergence in the peatland's areal versus volumetric losses; occurring in 1947 (EC) and 1964 (DS)²². However, the peatland's responses remained divergent in the affected dates even if the delayed volumetric impacts were excluded.

The dates in which the maximum deviation in areal versus volumetric losses occurred were transitional phases in the peatland's reduction. In general, earlier disturbances produced greater areal impacts, while later disturbances led to greater

²² These dates broadly align with the peak areal impacts of 'Commercial Peat Extraction'. The change in the maximum deviation of the peatland's areal versus volumetric losses was minimal when the delayed volumetric impacts of peat extraction were removed, being reduced by 2.4% (EC) and 4.2% (DS). The shift in the timing of the maximum deviation was more substantial, moving to 1909 (EC) and 2014 (DS).

volumetric responses even though their areal extent was in decline. Capturing the peatland's temporally varied divergence in response to disturbances is useful for understanding and strategically managing land-use changes and their impacts on ES supply. For example, restricting further disturbances prior to reaching the maximum divergence in areal versus volumetric losses would have minimized volumetric losses for substantial gains in area available for alternative uses. Thereafter, volumetric losses were intensified while the area for alternative uses with exploitation diminished.

4.3.2 Implications: Varied volumetric impacts across the depth profile

Based on the divergence in areal versus volumetric response, area is insufficient to estimate the volume in domed peatlands. The divergence reinforces that peatland structure (variations in depth and volume) in complexes and certain subclasses may considerably shape the response of certain ESs and the ecological impacts of disturbances (Evans *et al*, 2014; Glenk *et al*, 2014). Volumetric changes are more relevant indicators of a domed peatland's state and future stability than changes in area. Although the shallower peat swamp areas at the edge of domed peatlands are important to self-regulation and buffer against external pressures (*e.g.* nutrient intrusion from groundwater or adjacent farms), they are also more sensitive to disturbances and short-term changes than deep deposits at centre of domed peatlands (Howie and Meerveld, 2011). The resistance of domed peatlands and the associated supply of ESs to external pressures tend to be greater in deeper deposits. Ecological functions in areas beyond the influence of drains can persist over extended time periods. As such, the continued supply of peatland ESs is more likely at sites where marginal areas are exploited but deeper deposits remain intact.

In domed peatlands multidimensional analyses is essential to fully assess the

ecological effects of disturbances, as well as changes in ES supply (discussed further in §6.3.6). As seen at Alfred Bog, despite substantial areal reduction, the general progression of disturbances (*i.e.* inwards from the margins) yielded less impacts on peat volume and the carbon store. Combined with the configuration of its remaining domes, there is a greater capacity for its continued functioning and supply of ESs.

Past divergence in areal versus volumetric reduction is relevant to assess the present state and supply of ESs in partly exploited peatlands (Belyea, 2009; Tomscha and Gergel, 2016), as well as their capacity to maintain this supply in the future. Cumulative effects can reduce the resistance of peatlands to future changes (Belyea, 2009; Webster *et al*, 2015). For exploited peatlands where central deposits remain undisturbed, such as at Alfred Bog, multidimensional analyses can reveal the enduring supply and value of ESs, which may be undetected with areal analyses alone.

5 Chapter: Anthropogenic drivers of peatland reduction

5.1 Overview

In the previous chapter, Alfred Bog's response to disturbances was examined with respect to its historical areal and volumetric reduction. This chapter deconstructs these areal and volumetric impacts in relation to specific anthropogenic drivers (Table 3-1) in the 11 maps and cumulatively, over the entire historical study. The impacts of drivers are examined both over the 'Entire Complex' and in 'Domed' sites. The delineated land-cover maps, in conjunction with other sources, made the assessment of selected drivers possible.

Within each map, the location of individual drivers were distinct. While disturbances generally progressed inwards from the peatland's margins (Figure 4-1), the location of specific drivers relative to the depth profile and the divergence in their areal versus volumetric impacts were more varied between maps, with certain drivers moving back and forth from shallower to deeper deposits. Consequently, the trends associated with individual drivers (*e.g.* average depth, volumetric impacts per unit area and deviation in areal versus volumetric impacts) were quantitatively and temporally distinct from one another and the peatland's responses to disturbances.

The results are divided into three sections:

[§5.2.1](#) land-cover changes at Alfred Bog.

[§5.2.2](#) areal and volumetric impacts of drivers.

[§5.2.3](#) impacts of competing site uses (CSUs) on peatland reduction.

The discussion is divided into four sections:

[§5.3.1](#) areal and volumetric impacts of drivers. Land-cover changes are not discussed separately, but assist in assessing the trends of drivers.

[§5.3.2](#) effects of CSU periods on peatland reduction.

[§5.3.3](#) distribution of drivers within Alfred Bog.

[§5.3.4](#) summary on the benefits of a driver-specific approach.

5.2 Results

5.2.1 Land-cover changes

A sample of the created land-cover maps, used to determine changes in the land-cover composition (*i.e.* areal coverage) over the 11 dates, is shown in Figure 5-1. The remainder are found in [Appendix D](#). Non-peatland classes were defined as either major or minor, according to whether their peak areal coverage exceeded a threshold of 5% of the study site (5.6 km²). In descending order of peak areal coverage, the major non-peatland classes were: 'Farmland', 'Cleared Lands', 'Peat Extraction' and 'Forest'. Minor classes were 'Other', 'Water', 'Roads' and 'Structures'. Aside from 'Other', minor classes covered less than 1%, or 1.1 km², of the study site. Figure 5-2 and Figure 5-3 show the changing extent of major and minor classes. Their trends are reported below, in descending order.

'Farmland' was the dominant change in land-cover. Increasing in area each map, it expanded rapidly in the 1800s, covering 43.9 km² (39.2%) by 1909, and grew more slowly in the 1900s, expanding a further 14.9 km² (13.3%) from 1909 to 2014. After 1860, 'Farmland' had the greatest area of non-peatland classes. In 1964, it overtook 'Peatland' as the most extensive class. By 2014, it occupied 58.9 km² (52.5%) of the study site.

'Cleared Lands' was the most extensive non-peatland class from 1800 to 1860 and second thereafter until 1947. It covered 21.0 km² (18.8%) at its peak in 1860. Its coverage then declined gradually and after 1964, it covered roughly 1% of the study site.

Figure 5-1 – Selected delineated maps depicting changes in landscape composition over the study period.

Figure 5-2 – Changing areal coverage of major land-cover classes between 1800 and 2014.*

Figure 5-3 – Changing coverage of minor land-cover classes between 1800 and 2014.*

*Vertical red line broadly separates land-cover changes in 'Peat Swamp' and 'Domed' areas.

'Peat Extraction' was exclusively located in 'Domed' sites and the only class absent in the 1800s. It began in 1904 with a focus on peat fuel production until 1928 (Anrep and Nyström, 1909; Haanel, 1926; Smith, 1927). Extraction resumed in 1941 with a focus

on peat moss for horticultural and agricultural use (Leverin, 1944; Warner and Buteau, 2000). In 1947, it surpassed 'Cleared Lands' as the third largest class. Its coverage peaked at 9.6 km² (8.6%) in 1964. Its coverage then declined, as older sites were exhausted and transitioned to alternative classes, and as conservation initiatives increased.

'Forest' covered less than 5% of the study site until 1991, when it surpassed 'Peat Extraction' as the third most extensive class. Its coverage grew rapidly after 1947, from less than 2 km² to above 6 km² by 1991, and peaked at 6.8 km² (6.1%) in 2014. Its coverage rose with the afforestation of detached peatland sites and reforestation of abandoned 'Farmland' and 'Cleared Lands' areas.

'Other' rose from 1800 to 1860, aligned with the rise of 'Farmland' and linked to increased roadside and residential areas. After a stable period from 1860 to 1991, it grew again from 1991 until its peak in 2014, at 3.5 km² (3.2%). Its secondary rise was tied to a few large changes, such as the solar-power plant constructed in the northwest dome.

'Water' declined from 1800 to 1860, as large ponds were drained and converted to farmland with increased settlement. From 1909 to 2014 its coverage increased slightly, with drainage ditches cut through 'Domed' sites between 1909 and 1947 and sewage lagoons constructed near Alfred Village between 1969 and 1984.

The coverage of 'Roads' also rose rapidly from 1800 to 1909 and then remained stable; occupying roughly 0.5 km² (0.5%) from 1909 to 2014. Although initially concentrated in 'Peat Swamp' areas, some roads were installed through 'Domed' areas in the 1900s. For example, the Canadian Pacific Railway's Ottawa-Montréal line cut through the northwest dome, operating from 1898 to 1986, and was integral to the joint governmental peat fuel tests (*e.g.* import machinery and export peat fuel briquettes).

5.2.2 Impacts of anthropogenic drivers

‘Direct Farmland Conversion’, ‘Commercial Peat Extraction’ and to a lesser extent, ‘Degraded Peatland’, were major drivers. In combination, they accounted for at least 96% of the areal and volumetric disturbances in each date²³ and cumulatively. The impacts of others, classified as minor drivers, each accounted for 1% or less of losses in the pre-disturbance area and volume over both examined spatial extents. Despite the link between the major land-cover classes and drivers, their trends are not interchangeable. For example, the peak coverage of ‘Peat Extraction’ (land-cover class) is 9.6 km² in 1964, while its peak areal impact of ‘Commercial Peat Extraction’ (driver) is 5.7 km² in 1947.

As with the peatland’s reduction, the areal versus volumetric impacts of individual drivers were divergent and the magnitude of divergence changed over time. Similarly, in ‘Domed’ sites there were smaller differences in a driver’s areal versus volumetric impacts and a greater temporal correspondence in its peak impacts.

5.2.2.1 Changing distribution and impacts of drivers over the 11 dates

Figure 5-4 depicts the varied spatial distribution of drivers in selected maps. Variations in the areal and volumetric impacts of major drivers, as well as their rates, over the 11 dates are shown for both the ‘Entire Complex’ and ‘Domed’ sites in Figure 5-5. The trends of minor drivers are displayed in Figure 5-6. The specific values are in Appendices [E.3](#) (area) and [E.4](#) (volume), while changes in the average depths and volumetric impacts per unit area of drivers are reported in Appendices [E.5](#) and [E.6](#). The trends of major and minor drivers are presented successively below.

²³ Except for ‘Domed’ sites in 1860, where ‘Transportation’ and ‘Other’ accounted for 50% and 65% of areal and volumetric disturbances.

Figure 5-4 – Spatial distribution of drivers in select years, with underlying land-cover maps at 50% transparency.

Figure 5-5 – The areal and volumetric impacts (top) and impact rates (bottom) of major drivers in the ‘Entire Complex’ (left) and ‘Domed’ sites (right). For trends over the ‘Entire Complex’, the vertical red line broadly separates the impacts of drivers in ‘Peat Swamp’ (1800-1860) and ‘Domed’ areas (1860-2014).

Figure 5-6 – The areal and volumetric impacts (top) and impact rates (bottom) of minor drivers in the ‘Entire Complex’ (left) and ‘Domed’ sites (right). For trends over the ‘Entire Complex’, the vertical red line broadly separates the impacts of drivers in ‘Peat Swamp’ (1800-1860) and ‘Domed’ areas (1860-2014).

Except for 'Direct Farmland Conversion', the trends of major drivers were largely consistent over both examined spatial extents. The primary difference in their trends was the timing and magnitude of the peak impacts of 'Direct Farmland Conversion'. The trends of other major drivers, concentrated in 'Domed' sites, were less affected. As such, the described trends apply to the 'Entire Complex' and 'Domed' sites, unless otherwise noted.

'Direct Farmland Conversion' was the main driver until 1947. From 1800 to 1909, it accounted for 90% of areal and volumetric losses. Its impacts declined in the 20th century. In 1928, it accounted for roughly 70% of disturbances. After 1947, 'Direct Farmland Conversion' comprised less than a third of anthropogenic impacts. Similarly, in 1947 its impacts dipped below 5% of both the pre-disturbance area and volume and were less than 1% in each date after 1964.

'Direct Farmland Conversion' had the largest areal and volumetric impact in one date; occurring in 1860 and 1909 in the 'Entire Complex' and both occurring in 1909 in 'Domed' sites. Its peak areal impact was reduced from 28.0 km² (25.2%) in 1860 (EC) to 6.8 km² (9.4%) in 1909 (DS), while its peak volumetric impact, 1.46×10^7 m³ (EC: 6.2%, DS: 6.6%) in 1909, remained consistent. The difference in the peak areal versus volumetric impacts of 'Direct Farmland Conversion' was reduced from 18.2% (EC) to 2.8% (DS). In 'Domed' sites, there was also a greater balance between the peak impacts of 'Direct Farmland Conversion' and 'Commercial Peat Extraction'. The difference between their respective peak areal impacts declined from 20.0% (EC) to 1.5% in 'Domed' sites, while the difference in their peak volumetric impacts increased by 0.2%.

The initial impacts of 'Commercial Peat Extraction' in 1909 were negligible (<0.1% of baseline area and volume), but by 1928 it accounted for roughly 25% of

disturbances. From 1947 to 2014 it was the main driver²⁴ and accounted for roughly 70% of disturbances. It had the second greatest peak impacts of the examined drivers; occurring in 1947 for area (5.7 km²) (EC: 5.2%, DS: 7.9%) and 1991 for volume (8.86×10^6 m³) (EC: 3.6%, DS: 4.0%). The latter coincided with the depletion of older deposits, shown by the sharp decline in the land-cover area of 'Peat Extraction' in 1991 (Figure 5-2). In contrast, the volumetric impact rates of 'Commercial Peat Extraction' were stable from 1947 to 1991, increasing until its peak in 2014.

The impacts of 'Degraded Peatland' were less intense and consistent than 'Direct Farmland Conversion' and 'Commercial Peat Extraction'. The latter were the main drivers of disturbances over two or more dates. 'Degraded Peatland' was only the main driver of volumetric losses during its peak areal (EC: 1.4%; DS: 2.2%) and volumetric (EC: 2.5, DS: 2.7%) impacts in 1964, which were the smallest of the major drivers. In other dates, its impacts were no more than 0.5% of the pre-disturbance area and volume. As such, it often had the smallest impacts of the major drivers, despite having a greater depth (3.8 m) and volumetric impact per unit area (3.81×10^4 m³ ha⁻¹) in one date (1964).

The areal and volumetric impacts of minor drivers were each consistently less than 0.8% (EC) and 0.2% (DS) of the baseline values. They were also temporally concentrated. All three peak prior to 1947 and recede thereafter. In the 'Entire Complex', 'Other' had the largest areal impact (0.8 km² or 0.7%), which occurred in 1860. In 'Domed' sites, its peak areal impact, 0.1 km² (0.1%) in 1909, was matched by 'Transportation' in 1928. 'Drainage' had the greatest peak volumetric impact (0.2%) of minor drivers, in 1928, despite

²⁴ Except in 1964, when its volumetric impact (5.72×10^6 m³) was slightly less than 'Degraded Peatland' (5.96×10^6 m³).

commonly having the smallest areal impact. It also had the greatest average depth (EC: 3.9 m; DS: 4.0 m) and volumetric impact per unit area (EC: $4.13 \times 10^4 \text{ m}^3 \text{ ha}^{-1}$; DS: $8.54 \times 10^4 \text{ m}^3 \text{ ha}^{-1}$) in one date of all examined drivers.

Variations in the impacts versus impact rates of drivers were tied the latter's sensitivity to the timespan between maps. For example, despite smaller volumetric impacts of 'Commercial Peat Extraction' after it peaked in 1991, its volumetric impact rates rose after 1991 and peaked in 2014, due to the smaller intervals between dates (1964-1991: 27 yrs, 1991-2008: 17 yrs, 2008-2014: 6 yrs). Similarly, in 'Domed' sites, the areal and volumetric impacts of 'Direct Farmland Conversion' peak in 1909, while the peak impact rates occur in 1928. Another notable difference is that, in 'Domed' sites 'Commercial Peat Extraction' had the greatest areal impact rate, despite the greater absolute impacts of 'Direct Farmland Conversion' in 1909. These were the main differences in the impacts versus impact rates of major drivers.

5.2.2.2 Cumulative impacts of drivers

The cumulative areal and volumetric impacts of drivers from 1800 to 2014 are shown in Table 5-1 (EC) and Table 5-2 (DS). The tables also include their average volumetric impacts per unit area ($\text{m}^3 \text{ ha}^{-1}$) and depths (m). Figure 5-7 is a visualized ranking of individual drivers according to these four traits (*i.e.* total areal and volumetric impacts, as well as the average volumetric impact per unit area and depths). Figure 5-8 shows the cumulative spatial distribution of drivers and illustrates the transition between the two main drivers: 'Direct Farmland Conversion' and 'Commercial Peat Extraction'. The former comprised the older, larger outer-ring of disturbances on shallower deposits, while the latter formed the more recent inner-ring of disturbances. The combined impacts of 'Direct

Farmland Conversion’ and ‘Commercial Peat Extraction’ accounted for 90% of the total areal and volumetric losses in both the ‘Entire Complex’ and ‘Domed’ sites.

Rank	Cumulative Impacts				Volume Per Unit Area		Depths	
	Complex		Domed Sites		Complex	Domed Sites	Domed Sites	
	Area	Volume	Area	Volume				
1	DFC	C	C	C	C	D	C	
2	C	DFC	DFC	CPE	D	C	DP	
3	CPE	CPE	CPE	DFC	DP	DP	D	
4	DP	DP	DP	DP	CPE	CPE	CPE	
5	O	O	O	O	T	DFC	T	
6	T	D	T	D	DFC	O	DFC	
7	D	T	D	T	O	T	O	

Figure 5-7 – Ranked cumulative impacts of drivers on different dimensions of peatland reduction.

Note: The table is colour coded and labeled to facilitate interpretation. Abbreviations are as follows: C – Conservation; DFC – Direct Farmland Conversion; CPE – Commercial Peat Extraction; DP – Degraded Peatland; O – Other; T – Transportation; D – Drainage.

Figure 5-8 – The cumulative distribution of drivers at Alfred Bog (1800-2014).

Table 5-1 – The cumulative impacts of individual drivers in the ‘Entire Complex’.

Drivers		Area (ha)		Volume (m ³)		Per Unit	Depth
Class(es)	Driver	ha	%	m ³	%	m ³ ha ⁻¹	M
Farmland and Cleared Lands	Direct Farmland Conversion	5.51×10^3	49.6	5.03×10^7	21.5	9.13×10^3	0.9
Peat Extraction	Commercial Peat Extraction	1.59×10^3	14.3	4.13×10^7	17.6	2.59×10^4	2.6
Forest	Degraded Peatland	3.11×10^2	2.8	8.92×10^6	3.8	2.87×10^4	2.9
Water	Drainage	1.90×10^1	0.2	5.60×10^5	0.2	3.02×10^4	2.7
Roads	Transportation	4.72×10^1	0.4	4.49×10^5	0.2	9.52×10^3	0.9
Other	Other	1.32×10^2	1.2	9.43×10^5	0.4	7.12×10^3	0.7
Peatland (2014)	Conservation	3.50×10^3	31.5	1.32×10^8	56.2	3.76×10^4	3.8
Total		1.11×10^4	100.0	2.34×10^8	100.0		

Table 5-2 – The cumulative impacts of individual drivers in ‘Domed’ sites.

Drivers		Area (ha)		Volume (m ³)		Per Unit	Depth
Class(es)	Driver	Ha	%	m ³	%	m ³ ha ⁻¹	m
Farmland and Cleared Lands	Direct Farmland Conversion	1.82×10^3	25.0	3.91×10^7	17.6	2.15×10^4	2.2
Peat Extraction	Commercial Peat Extraction	1.59×10^3	21.9	4.13×10^7	18.6	2.59×10^4	2.6
Forest	Degraded Peatland	2.85×10^2	3.9	8.85×10^6	3.7	3.11×10^4	3.1
Water	Drainage	1.15×10^1	0.2	5.58×10^5	0.3	4.85×10^4	3.1
Roads	Transportation	2.18×10^1	0.3	4.49×10^5	0.2	1.60×10^4	2.2
Other	Other	3.57×10^1	0.5	9.43×10^5	0.3	1.83×10^4	1.9
Peatland (2014)	Conservation	3.50×10^3	48.2	1.32×10^8	59.2	3.76×10^4	3.8
Total		1.11×10^4	100.0	2.22×10^8	100.0	N/A	N/A

The cumulative impacts of drivers in the ‘Entire Complex’ and ‘Domed’ sites are presented separately below. The main difference in their trends is attributed to the inclusion or exclusion of the large area and lesser volumes in ‘Peat Swamp’ areas. Its exclusion intensified the average volumetric impacts per hectare and depths of drivers, while reducing the magnitude of divergence in their areal versus volumetric impacts.

In the ‘Entire Complex’, ‘Direct Farmland Conversion’ and ‘Commercial Peat Extraction’ exploited 71.0 km² and removed 9.16×10^7 m³ of peat or 63.9% and 39.1% of the pre-disturbance area and volume. Other drivers comprised the remaining 5.1 km² (4.6%) and 1.09×10^7 m³ (4.6%) of anthropogenic losses. ‘Direct Farmland Conversion’ had the greatest areal and volumetric impacts; converting roughly 55.1 km² (49.6%) and removing 5.03×10^7 m³ (21.5%) of peat. ‘Commercial Peat Extraction’ exploited 15.9 km² (14.3%) and 4.13×10^7 m³ (17.6%). Despite the wide gap in the areal impacts of ‘Direct Farmland Conversion’ and ‘Commercial Peat Extraction’, their impacts on volume differed by only 3.9%.

The cumulative areal impacts of ‘Direct Farmland Conversion’, ‘Transportation’ and ‘Other’ exceeded their respective volumetric impacts. Conversely, ‘Commercial Peat Extraction’, ‘Degraded Peatland’, ‘Drainage’ and ‘Conservation’ had greater impacts on volume than area. These differences were further supported by their average volumetric impacts per hectare and depths.

The average volumetric impacts per hectare of drivers ranged from 7.12×10^3 to 3.76×10^4 m³ ha⁻¹. ‘Direct Conversion’, ‘Other’ and ‘Transportation’ were less than 1.00×10^4 m³ ha⁻¹, while ‘Drainage’, ‘Degraded Peatland’ and ‘Commercial Extraction’

exceeded $2.50 \times 10^4 \text{ m}^3 \text{ ha}^{-1}$. Similarly, the average depths of the former drivers were less than 1 m, while the latter were above 2.5 m; ranging from 0.7 to 2.9 m²⁵.

Comparatively, in ‘Domed’ sites the areal impacts of all examined drivers were greater than or equal to their volumetric impacts, with the exception of ‘Drainage’. There was also a greater correspondence in their areal versus volumetric impacts. The narrowed divergence was most apparent for ‘Direct Farmland Conversion’, which was reduced from 28.1% (EC) to 7.4% (DS)²⁶. There were also minor variations in the ranked impacts (ha^{-1} , m^3 , $\text{m}^3 \text{ ha}^{-1}$ and m) of drivers. Notably, despite occupying a lesser area (21.9%) than ‘Direct Farmland Conversion’ (25.0%), the volumetric impacts of ‘Commercial Peat Extraction’ (18.6%) were slightly (1.0%) greater in ‘Domed’ sites.

The volumetric impacts per unit area of most²⁷ drivers also increased in ‘Domed’ sites, ranging from $1.50 \times 10^4 \text{ m}^3 \text{ ha}^{-1}$ to $4.90 \times 10^4 \text{ m}^3 \text{ ha}^{-1}$. For example, although ‘Commercial Peat Extraction’ maintained a greater volumetric impact per hectare ($2.59 \times 10^4 \text{ m}^3 \text{ ha}^{-1}$) than ‘Direct Farmland Conversion’, their differences were substantially reduced, with the latter rising from $1.07 \times 10^4 \text{ m}^3 \text{ ha}^{-1}$ (EC) to $2.15 \times 10^4 \text{ m}^3 \text{ ha}^{-1}$ (DS). Further, the ranked volumetric impacts per unit area of ‘Drainage’ surpassed ‘Conservation’ and ‘Direct Farmland Conversion’ exceeded ‘Transportation’ (Figure 5-7).

The average depths of drivers in ‘Domed’ sites ranged from 1.9 m to 3.2 m, increasing the minimum and maximum depths by 1.2 m and 0.3 m compared to the ‘Entire Complex’. ‘Degraded Peatland’ and ‘Drainage’ are tied for the greatest depth of exploitative drivers at 3.2 m. Of the main drivers, ‘Commercial Peat Extraction’ (2.6 m)

²⁵ Excludes ‘Conservation’ in 2014 with a depth of 3.8 m (EC and DS), since it is not an exploitative site use.

²⁶ The divergence in ‘Conservation’ area versus volume was also reduced from 24.7% (EC) to 11.0% (DS).

²⁷ ‘Conservation’ and ‘Commercial Peat Extraction’, already restricted to domed sites, are unchanged.

occurs on deeper deposits than ‘Direct Farmland Conversion’ (2.2 m). The only driver with lesser average depths than the latter is ‘Other’.

5.2.3 Competing Site Use Periods: Accelerated Alterations at Alfred Bog

A sub-objective of examining specific drivers was to identify periods where two or more competing site-uses (CSUs) operated concurrently and explore the potential effects on Alfred Bog’s exploitation and changes in ES supply. The two identified CSU periods are outlined against the peatland’s reduction rates and impacts of relevant drivers in Figure 5-9²⁸. CSU Period 1, from 1904 to 1964, was characterized by competition between ‘Direct Farmland Conversion’ and ‘Commercial Peat Extraction’. CSU Period 2, from 1982 to 2004, was between exploitation and conservation initiatives. ‘Commercial Peat Extraction’ was the main driver during this period and thus, CSU Period 2 was defined by the competition between commercial extractors and conservationists.

5.2.3.1 Peatland reduction during CSU periods

The CSU periods coincide with the peatland’s accelerated areal and volumetric losses. The areal and volumetric reduction rates rise continually throughout CSU Period 1, excluding the latter in 1947. After 1991, reduction rates continue to rise until 2014, roughly matching CSU Period 2. Based on the link between peat volume and the carbon store, periods of accelerated losses in the carbon store are roughly aligned with CSU periods and the intensification of the two provisioning ESs after 1909, discussed further in Chapter 6.

²⁸ *Note:* The impacts of relevant drivers and the peatland’s response in the CSU Periods were only quantified for ‘Domed’ sites. This is because ‘Commercial Peat Extraction’, which is involved in both CSU Periods, is exclusively located in ‘Domed’ sites. As such, its competition with ‘Direct Farmland Conversion’ (Period 1) and ‘Conservation’ (Period 2) is also restricted to these areas.

Figure 5-9 – The two CSU periods shown against the case-study trends in domed areas.

The net areal and volumetric impacts of drivers associated with the CSU periods are summarized in Table 5-3. The impacts of commercial extraction and direct conversion in CSU Period 1 were 4.6 (area) and 2.3 (volume) times greater than those of extraction in CSU Period 2. However, CSU Period 2 yields a greater volumetric impacts per hectare and per year than CSU Period 1.

Table 5-3 – The areal and volumetric impacts of drivers associated with the CSU periods.

Note: The reported volumetric impacts and impact rates per year include the lagged impacts of ‘Commercial Peat Extraction’, while it was removed for volumetric impacts per unit area to reflect the average peat volume in exploited deposits in both CSU Periods.

CSU Period #	Area (ha)	Volume (m ³)	m ³ ha ⁻¹	m ³ yr ⁻¹
1 (1904-1964)	2.43×10^3 (34%)	4.62×10^7 (21%)	2.35×10^4	8.40×10^5
2 (1982-2004)	5.34×10^2 (7%)	2.01×10^7 (9%)	2.72×10^4	8.73×10^5

5.2.3.2 Impacts of competing drivers during CSU Periods

In CSU Period 1, the trends of direct conversion and commercial extraction are inversely related. One would expect competition between two exploitative uses to intensify their respective disturbances. Their combined presence accelerates the peatland’s reduction, but at no point between 1909 and 1964 do farmland conversion and commercial extraction co-vary positively. While ‘Commercial Peat Extraction’ rises, ‘Direct Farmland Conversion’ decreases and *vice versa*. These trends also applied to their impact rates, except from 1909 to 1928, where both rose simultaneously. CSU Period 1 ends after 1964, with the areal and volumetric impacts of direct conversion declining to less than 1%.

CSU Period 2 is roughly captured by ‘Commercial Peat Extraction’ points from 1991 to 2014. In 1991 its volumetric impacts peak, while its areal impacts continue to decline after peaking in 1947. The areal impacts rise again in 2008 and the volumetric impacts remain elevated. As noted, despite the decline in the volumetric impacts of

‘Commercial Peat Extraction’ in 2014, its associated impact rates rose from 1991 and peaked in 2014; corresponding strongly with CSU Period 2. By 2014, over 95% of remaining peatland was protected by ownership and zoning (OFNC, 2008), marking the end of CSU Period 2 and roughly two centuries of direct anthropogenic exploitation.

5.3 Discussion

5.3.1 Distinct impacts of individual drivers

The areal versus volumetric impacts of individual drivers were divergent in each of the 11 dates and cumulatively. There were considerable variations in the impacts and spatial distribution of drivers in the 11 maps. The respective progressions of drivers relative to the depth profile were unique. Many were non-linear, despite a general progression onto deeper deposits. Thus, the magnitude of divergence in the impacts of individual drivers impacts were distinct and temporally dynamic, based on changes in their respective distributions relative to depth profile. Thus, examining individual drivers was necessary to capture the specific response of ESs to their respective disturbances, and how these responses varied both spatially and temporally within the peatland complex.

5.3.1.1 Temporally varied impacts of drivers

In the 19th century, drivers impacted area more than volume. Volumetric impacts generally increased in the 20th century as they moved from the ‘Peat Swamp’ and edge of ‘Domed’ sites onto deeper deposits. This is reflected by the greater correspondence between their areal and volumetric impacts from 1909 to 2014 (Figure 5-5 and Figure 5-6). Further, the difference in the areal versus volumetric impacts of drivers (Δ_{A-V}) were only negative in the 20th century (EC), as volume exceeding the area impacted with the exploitation of deeper deposits.

The non-linear progression of individual drivers relative to the depth profile resulted in more erratic variations in their divergence between maps, despite the greater magnitude of divergence observed for the peatland's response to disturbances²⁹. Unlike the maximum divergence in the peatland's areal versus volumetric losses which grew until their peak in 1947 (EC) and 1964 (DS) and subsequently narrowed, the divergence of individual drivers did not necessarily have a single clear transition point associated with their areal versus volumetric impacts. For example, in 'Domed' sites, the difference in the areal versus volumetric impacts of 'Degraded Peatland' is positive in 1928 (0.4%), negative in 1964 (-0.5%) and then roughly equal in following maps ($|\Delta_{A-V}| \leq 0.1\%$) (see [Appendix E.7](#)). Thus, its location on deeper deposits in 1964 led to its greatest impacts on peat volume and the carbon store, exceeding those on the shallower northwest dome's edge in 2014.

The non-linear progression of drivers is particularly exemplified by the average depths of 'Other' in 'Domed' sites, which were at or above 2 m in 1860, 1909, 1964 and 2008, but not in other dates (1880, 1928, 1947, 1991 and 2014). This highlights the inconsistent relation between the areal and volumetric impacts of specific drivers in the 11 examined dates. Temporal variations in the magnitude of divergence are further attested by the volumetric impacts of certain drivers exceeding their areal counterpart in one date, but not in others, such as 'Drainage' in 1928, as well as 'Degraded Peatland' and 'Other' in 1964. Thus, examining individual drivers provides a clearer understanding of their

²⁹ The maximum divergence (Δ_{A-V}) in the peatland's response was -32.5% (EC: 1947) and -15.2% (DS: 1964), compared to a peak divergence of 21.6% (EC: 1860) with 'Direct Farmland Conversion' and 4.8% (DS: 1947) with 'Commercial Peat Extraction' for individually examined drivers.

distinct impacts on the peat volume and the carbon store than that which can be inferred from the ecosystem's aggregate response to disturbances.

Analysis at finer temporal resolution identified trends that would not have been detected by strictly assessing their cumulative impacts. Examining drivers over shorter time intervals not only captured changes in their respective distribution and divergence, it was critical to detect and differentiate their specific impacts. For example, 'Farmland' was the dominant end-use of disturbances at Alfred Bog (Bird and Hale, 1984a; Mosquin, 1991), but its expansion was tied to direct conversion, commercial extraction or other intermediary drivers. Cumulative analysis alone would not be able to partition or distinguish the differing roles of these intermediary drivers on the growth in 'Farmland' area. The other major land-cover classes, such as 'Cleared Lands' and 'Peat Extraction', were transitional site uses, occupying the landscape for less time than 'Farmland'. As such, their detection was more sensitive to the timespan between maps.

Using longer time intervals can inflate the impacts of more stable drivers and understate the impacts of transitional drivers. For example, had the cumulative impacts of 'Commercial Peat Extraction' versus 'Direct Farmland Conversion' been approximated using the two land-cover maps in 1800 and 2014, the impacts of extraction would have been significantly underestimated. Thus, minimizing timespans between land-cover maps improved the detection of intermediary drivers.

Longer intervals may also dilute the impacts and rates of disturbances. If an intense, yet brief disturbance occurred immediately after a mapped date and then remained idle until the next, its registered intensity would lessen over longer periods. Further, it could lead to a lag in the actual timing of a disturbance and it being recorded. This could affect

the correspondence between the impacts of drivers and known events. For example, the correspondence between the peak areal impacts of ‘Commercial Peat Extraction’ in 1947 with the spike in peat moss value in 1941, or its peak volumetric impacts in 1991 with the implementation of vacuum extraction and pressures from conservationists (in CSU Period 2) may have been missed using longer intervals between maps.

The transition between ‘Direct Farmland Conversion’ (1800-1928) and ‘Commercial Peat Extraction’ (1947-2014) as the main driver illustrates the temporally varied impacts of different drivers. Prior to 1900, shallow peat depths, as well as broader social and economic factors were favourable for agricultural conversion, but not commercial extraction. From 1909 to 1964, these conditions gradually reversed, with the emergence (1909) and eventual dominance (1947) of ‘Commercial Peat Extraction’. Their temporally dynamic impacts and links with broader events are discussed separately below. The trends of ‘Degraded Peatland’ and other minor drivers are then examined briefly.

5.3.1.1.1 Direct Farmland Conversion

The greatest divergence in the areal versus volumetric impacts of ‘Direct Farmland Conversion’ occurred in 1820 (5.8%) and 1860 (19.0%) in the ‘Entire Complex’, while it was in ‘Peat Swamp’ areas. Although smaller in ‘Domed’ sites, the greatest divergence occurred in 1880 (2.5%) and 1909 (2.8%). In both cases, the peak divergence involved area exceeding volume, with its impacts concentrated in shallower deposits. This indicates it produced smaller volumetric impact per unit area with ‘Farmland’ growth than ‘Commercial Peat Extraction’ in later maps.

The peak volumetric impacts ‘Direct Farmland Conversion’ in 1909 occurred as it moved from the edge to deeper deposits in ‘Domed’ sites. Its depths exceeded 2 m from

1909 to 1991, peaking in 1991 (EC: 2.8 m; DS: 3.0 m). Yet, its impacts on area and volume declined throughout the 1900s. Thus, its greater depths and volumetric impacts per unit area had a lesser effect on the peatland's reduction and the cumulative trends of 'Direct Farmland Conversion' than its earlier impacts.

The trends of 'Direct Farmland Conversion' were shaped by local depth variations and regional trends in population, farming and land-use. Its greatest impacts occurred with rapid population growth from the mid-1800s to early 1900s. 'Direct Farmland Conversion' rose rapidly with the widespread clearing of shallow deposits, as settlement and land-clearing spilled over from surrounding upland regions (Richardson, 1948). As population growth waned in the county and declined in townships in the early 1900s, its impacts also diminished. Its reduced impacts also paralleled the decline in the number of farms and farmland area at municipal and county levels, which had peaked in the early to mid-1900s.

The widespread drainage and uncontrolled burning that typified 'Direct Farmland Conversion' in the 19th and early 20th centuries was increasingly regulated and contained to mitigate their social, economic and ecological impacts (Richardson, 1948, p.32-33). For example, a summary recommendation in a 1948 South Nation Valley Interim Report is that all agricultural burning practices in peatlands cease immediately (Richardson, 1948). The decline in 'Direct Farmland Conversion' was further precipitated by the depth of remaining deposits, which made it less suitable, and the rise in 'Commercial Peat Extraction' as an intermediary driver. As a result, after the mid-1900s direct conversion was mostly confined to smaller detached and degraded 'Peatland' sites.

5.3.1.1.2 Commercial Peat Extraction

The temporally varied impacts of 'Commercial Peat Extraction' were tied to

changes in the *ex-situ* uses of peat, its value and extraction techniques in the 20th century. From 1904 to 1928, there were sporadic attempts at commercial peat fuel extraction. Peat fuel faced high production costs and lower yields. They were unable to consistently outcompete coal prices. These factors led to intermittent, small scale and often short-lived operations (Swinerton, 1945; Warner and Buteau, 2000), shown by the smaller impacts of peat fuel extraction at Alfred Bog in 1909 and 1928³⁰.

The peak areal impact of ‘Commercial Peat Extraction’ in 1947 and its emergence as the main driver coincided with the switch to peat moss production after 1941 (Leverin, 1944; Monenco, 1981). This was linked to the dramatic rise in the value of peat moss with its demand in the United States and loss of European suppliers during World War II (Swinerton, 1945; Warner and Buteau, 2000). Despite its peak areal impact, its volumetric impacts remained relatively small in 1947 and 1964.

From 1941 to the 1960s, early mechanized extraction techniques remained dominant (Leverin, 1944; Swinerton and Ripley, 1947; Swinerton, 1958). These techniques were labour intensive, involving many manual steps (*e.g.* prepare the surface, extract the peat and move machinery). Vacuum-extraction, developed in the early 1960s, combined production steps and amplified the industry’s output. As such, it rapidly became the dominant extraction technique in Canada, being used in roughly 90% of operations by the 1980s (Cleary *et al*, 2005). Vacuum-extraction was implemented at Alfred Bog sometime between 1964 and 1991, partly influencing its peak volumetric impact and

³⁰ Impacts in these dates are associated with the operation of the Montréal and Ottawa Peat Company in 1904 and the joint governmental tests from 1909 to 1923 respectively (Anrep and Nyström, 1909; Bureau of Mines, 1905; Haanel, 1926). The government test site was transferred to a private owner (Globe and Mail, 1923), but commercial extraction failed; ending peat fuel production at Alfred Bog in 1927 (Smith, 1927).

impact rates in following years.

Figure 5-10 and Figure 5-11 show plans for early mechanized and vacuum extraction techniques respectively. The included air photos show the government test site in 1928 and 1994 to contrast their differing impacts at Alfred Bog. Early mechanized extraction was comprised of two working trenches, with the surrounding peatland left largely intact in its use as drying fields³¹ (Haanel, 1922; Haanel, 1926). These drying fields were then vacuum extracted in later periods. The area was segmented into narrow elongated working fields separated by drainage ditches every 20 to 30 metres (Monenco, 1981) and gradually depleted through successive extraction. As a result, the ecological impacts of vacuum-extraction were much more extensive and less reversible than earlier methods (Price *et al*, 2003; Price *et al*, 2005).

The trends of ‘Commercial Peat Extraction’ highlight that the changing practices, techniques and technologies with a specific driver may alter:

- 1) The rates of a driver’s impacts and of ecosystem alterations more broadly.
- 2) The reversibility of alterations (*e.g.* manual and early mechanized extraction versus vacuum extracted techniques), and;
- 3) The relationships between a driver and ESs (*e.g.* impacts of early mechanized extraction on carbon store with surrounding peatland left intact versus the complete depletion of the working field with vacuum extracted techniques).

³¹ Surface vegetation was still cleared and levelled, but the peat was not extracted. This technique resulted in an exaggeration of natural topographic variations in domed peatlands microforms (Price *et al*, 2005).

Figure 5-10 – Field plan for peat fuel extraction at Alfred Bog in 1922 (Source: Haanel, 1922, p.23).

Note: A 1928 photo showing the government test site with features depicted in the field plan labelled (Source: HA239-87, NAPL, 1928).

The effects of these changes (techniques, practices, policies and market values) applies to other drivers, but was most clearly observed with ‘Commercial Peat Extraction’. Intensified farming practices, such as increased land-inputs and drainage, could amplify its ecological impacts on the remaining peatland and its relationships with the supply of ESs. Similarly, variations in the market values of food products had increasing influence over agricultural and landscape biodiversity after the mid-20th century. Thus, these factors can change a driver’s ecological impacts and its relationship with different ESs over time; underscoring the benefits of finer resolution analyses which can capture the dynamic response and relationships of ESs to specific drivers.

5.3.1.1.3 Degraded Peatland and Minor Drivers

‘Degraded Peatland’ was tied to the progression of disturbances. As ‘Peatland’ sites were separated from the remaining core, they gradually became afforested with the drawdown of the water table, subsidence and degradation. For example, a large peatland area that was isolated by ‘Direct Farmland Conversion’ in 1928 and 1947 led to the peak impacts of ‘Degraded Peatland’ in 1964. The discrepancy between the peak coverage of ‘Forest’ (6.8 km² in 2014) and the total areal impacts of ‘Degraded Peatland’ (3.1 km²) indicates most degraded peatland areas were subsequently converted to other uses and that most ‘Forest’ areas in 2014 were reforested, rather than degraded sites.

The greatest impacts of minor drivers occurred from the mid-19th to the early 20th century, broadly paralleling the rise and decline in ‘Direct Farmland Conversion’. The rise in ‘Other’ and ‘Transportation’ was tied to infrastructural expansion, such as the rise in residential areas and the regional transportation network, with the growth in population and ‘Farmland’ area. Farmland expansion also led to the drainage of historical ponds within

Alfred Bog, shown by the decline in the coverage of 'Water' between 1800 and 1860 in Figure 5-3. The deep drains cut through 'Domed' areas between 1909 and 1947, to facilitate further exploitation, led to the peak impacts of 'Drainage' in 1928 and the greatest average depth of all drivers in the 11 dates in 1947 (EC: 3.9 m; DS: 4.0 m).

5.3.1.2 Divergent cumulative impacts of drivers

The cumulative areal versus volumetric impacts of individual drivers highlights that disturbances of similar extent could produce differing volumetric impacts, based on their distribution relative to the depth profile. This was shown by the minor variations (± 1) in their ranked impacts on area versus volume (Figure 5-7). For example, the spatial distributions of the main drivers in 'Domed' sites led to 'Commercial Peat Extraction' having greater volumetric impacts, despite 'Direct Farmland Conversion' occupying a greater area. This was even more pronounced in the 'Entire Complex', where despite their similar volumetric impacts, 'Commercial Peat Extraction' occupied an area 3.5 times smaller than 'Direct Farmland Conversion'.

The divergence was also apparent between minor drivers, with the greater aggregate areal impacts of 'Transportation' but the larger volumetric impacts of 'Drainage', over both examined extents. 'Transportation' was mostly confined to shallower deposits, while 'Drainage' was concentrated in deeper deposits of 'Domed' areas, given its purpose of facilitating further exploitation.

Additionally, the larger variations in the ranked average depth and volumetric impact per unit area of drivers may also help identify drivers that tend to produce greater volumetric impacts and consequently are in greater direct conflict with the carbon store. For example, the greater depths and volumetric impacts per hectare of 'Drainage' and

‘Commercial Peat Extraction’ indicates that they were concentrated on deeper peat deposits and produced larger trade-offs per unit area in the carbon store.

These examples highlight the benefits of both a driver-specific and multi-dimensional analysis of the peatland’s reduction in distinguishing their respective impacts and relationships with ESs supply. Solely examining the drivers of a domed peatland’s reduction using areal proxies to estimate their respective trade-offs in the carbon store would overlook these distinctions.

5.3.2 Competing Site Uses: Accelerated peatland reduction and losses in ESs

Feedbacks between competing drivers during CSU periods, may have affected their individual impacts, as well as the peatland’s reduction and changes in ES supply. Sources supported the competition between the identified CSUs (Anrep and Nyström, 1909; Haanel, 1926; ECO, 2005; OFNC, 2008).

The peatland’s accelerated reduction during CSU Period 1 and 2 initially suggests that interactions between CSUs intensified ecosystem alterations and losses in ESs. However, when examining the impacts of relevant drivers, their direct competition is less clear, particularly in CSU Period 1. Further, peatland reduction may have been affected by non-rival drivers in CSU Periods. For example, the peak in the peatland’s volumetric reduction rates in 1964 at the end of CSU Period 1 also coincides with the peak impacts of ‘Degraded Peatland’, a non-rival driver.

The greater areal and volumetric reduction in CSU Period 1 is expected, since it is associated with the concurrent operation of two exploitative site uses, while CSU Period 2 involves conservationists trying to prevent further disturbances. CSU Period 1 is also 38 years longer than CSU Period 2, providing more time for impacts to occur.

Interestingly, CSU Period 2 had a greater volumetric impact per unit area and per unit time, with the extraction of deeper deposits and the switch to vacuum extraction. Although the rates of areal impact rates ($\text{ha}^{-1} \text{yr}^{-1}$) of ‘Direct Farmland Conversion’ and ‘Commercial Peat Extraction’ in CSU Period 1 are double those of CSU Period 2, the volumetric impacts per hectare and per year of ‘Commercial Peat Extraction’ alone in CSU Period 2 were slightly greater. Thus, the volumetric impacts rates were more intense with the competition between conservationists and extractors than between two exploitative uses in CSU Period 1.

5.3.2.1 CSU Period 1: Competing exploitative peatland uses (1904-1964)

The negative co-variation between the impacts of ‘Direct Farmland Conversion’ and ‘Commercial Peat Extraction’ from 1909 to 1964 suggests that there is a transition in their dominance, rather than mutual intensification. As the remaining peatland became less suited to direct farmland conversion, commercial peat extraction became increasingly practicable in response to both local depth variations and broader events. The positive co-variation in their impact rates from 1909 to 1928, indicates certain sites were suitable to both commercial extraction and farmland conversion, and some competition occurred during the transition from shallow to deeper deposits (Haanel, 1922; Haanel, 1926). Yet, their distinct spatial distribution (Figure 5-8) suggests they mostly targeted different areas.

The fires used in farmland conversion were not restricted to the target sites and often spread throughout the peatland (Haanel, 1926; Richardson, 1948). Existing commercial operations, with stacks of drying peat fuel briquettes or piles of peat moss were highly susceptible to fires (Haanel, 1922; Swinnerton, 1958). The damages to existing and

future operations was a source of tension between extractors and farmers, with extractors recommending the burning practices be banned (Haanel, 1926).

5.3.2.2 CSU Period 2: Conservation versus commercial extraction (1982-2004)

The peatland's accelerated losses during the competition between extractors and conservationists seems counterintuitive, but is indicative of regulatory gaps in peatland management. As conservation initiatives expanded both locally and more broadly in the 1980s, the threat of changes in local zoning laws and provincial regulations that would restrict further extraction increased. Owned but not yet extracted sites were moved into production and extraction at existing sites was accelerated in the 1980s and 1990s (ECO, 2005). The latter is supported by residents who reported extraction beginning as early as 2:00 AM in the summer of 1999 ("Toughen Protection for Wetlands", 1999). This maximized extraction prior to zoning changes which restricted further disturbances.

Further, extractors correctly anticipated that sites already under extraction may be grandfathered with changes in zoning or legislation. After the zoning changes were appealed by extractors (2002) and resolved by the Ontario Municipal Board (OMB) (2004), the new Provincially Significant Wetland (PSW) boundaries drawn by OMNR excluded sites that had been extracted since its original designation in 1984. Thus, throughout the competition between conservationists and extractors, extraction continued unabated, leading to further irreversible ecosystem alterations and losses in its supply of ESs.

The losses during CSU Period 2 underscore the gaps in Ontario's peatland policies. For example, despite Alfred Bog's designation as a Class 1 PSW and Area of Natural and Scientific Interest by OMNR in 1984, without being recognized in municipal zoning laws, extraction continued (ECO, 2005; OFNC, 2008). The release of the United Counties of

Prescott and Russell's Official Plan in 1999, which zoned Alfred Bog as a 'Natural Heritage Policy Area', partly addressed this discrepancy. Under the *Planning Act* lower-tier municipalities must conform their zoning laws to higher-tier (*i.e.* county) plans (ECO, 2005). Even so, the zoning changes were appealed and extraction was not prevented until the OMB's ruling in 2004.

The reversibility of local zoning laws and inconsistent provincial policies (Schulte-Hostedde *et al*, 2010) highlights the vulnerabilities of protecting peatlands solely through policy. In fact, it was the 1982 reversal of an earlier (1978) zoning change that switched Alfred Bog from "Agricultural-Rural" to "Conservation" was the catalyst for competition between conservationists and extractors (Cuddy, 1983; ECO, 2005). The Alfred Bog Committee formed in response (OFNC, 2008). The acquisition of private properties within the peatland over the following 24 years proved the most secure means of conserving Alfred Bog, while additionally securing a stakeholder position in future proposed zoning changes (F. Pope, personal communication, July 14, 2015; OFNC, 2008). As property owners they had much greater control over the remaining peatland's use (Cuddy, 1983).

5.3.2.3 Interpreting the case-study results against the CSU periods

Four factors impacted the interpretability of the case-study trends against the identified CSU periods.

First, the temporal misalignment between CSU periods and land-cover maps meant trends in CSU periods could not be independently assessed from periods without CSUs. For example, between the 1964 and 1991 maps, CSU Period 1 ended (1964) and CSU Period 2 begun (1982). This meant that trends from 1964 to 1982 versus those from 1982 to 1991 at the beginning of CSU Period 2 could not be differentiated.

Second, only cumulative impacts and trends are registered between maps, which may be lagged and diluted compared to the actual timing and intensity of impacts. Consequently, the changes in case-study trends between the 1991 map and the end of CSU Period 2 in 2004, are only registered in the 2008 map.

Third, the precise start or end of CSU periods may be ambiguous or unclear in historical records, potentially involving some degree of interpretation or subjectivity in their identification.

Finally, the local competition between drivers cannot be fully separated from broader events and factors that may have impacted the local competition between drivers or indirectly contributed to accelerated peatland losses.

Although these issues and the case-study approach limit any conclusive statements on the competition between drivers the results suggest that, in addition to distinguishing the impacts of individual drivers, the interactions between competing drivers should be considered in assessing the impacts of multiple drivers on ecosystem alterations and ES supply. Further, the potential for competition not only between drivers, but between actors should be considered. For example, the spike in peat moss value and emergence of many commercial extractors in the 1940s may have resulted in competition between extractors for optimal sites both within and between peatlands, while the influx of settlers in the 19th century may have further accelerated ‘Direct Farmland Conversion’ at Alfred Bog. That competition between conservation and exploitation could accelerate peatland disturbances, and even exceed the volumetric impacts per year and per hectare of the competition between two exploitative uses in CSU Period 1, highlights the need for further exploration of the interactions between competing societal demands.

5.3.3 Selective distribution of individual drivers

The spatial distribution of ‘Commercial Peat Extraction’ and ‘Direct Farmland Conversion’ at Alfred Bog highlighted their opposing sensitivities to depth variations (Figure 5-8). Farmland conversion was largely confined to the shallower deposits where manual drainage was most effective (Anrep and Nyström, 1909; Haanel, 1926), while extraction was restricted to deeper and more expansive deposits in domed sites where extraction was profitable (Bird and Hale, 1984a). Other drivers were less sensitive, with ‘Degraded Peatland’, ‘Drainage’ and ‘Other’ distributed independently of depth variations.

Thus, the distribution of certain drivers are a function of variations in the peatland’s physical properties that in turn affect the accessibility and profitability of exploitation. For example, the selective distribution of commercial extraction according to depth variations applies to all peatland sites (Joosten and Clarke, 2002; Monenco, 1981; Price and Waddington, 2000; Swinnerton and Ripley, 1947). Commercial extraction must exceed minimum area and depth requirements to be profitable³². Further, the quality and properties of peat (*e.g.* stump/root content, decomposition, chemical composition) can affect the distribution of commercial extraction, according to the type and intended use of extracted peat (Swinnerton and Ripley, 1947; Monenco, 1981).

The concentration of agricultural conversion on shallower deposits at Alfred between 1800 and 1909 (Anrep and Nyström, 1909), may also extend to past farmland conversion in other domed peatlands. The smaller return in farmland and increased effort

³² Minimum requirements cited for extraction were between 1 and 2 metres for depth and 50 ha for area (Monenco, 1981; Price and Waddington, 2000; Swinnerton and Ripley, 1947). However, extraction techniques can influence the minimum depth and extent requirements. For example, vacuum-extracted techniques enabled production to be profitable on deposits of lesser depths.

and time to manually convert deeper deposits through successive drainage and burning likely restricted agricultural conversion to shallower sites prior to mechanization.

Considering the influence of variations in the peatland's physical properties on the spatial distribution of specific drivers may help identify commonalities in their location, divergent impacts and ES trade-offs between domed peatlands. For example, commercial peat extraction operates on deeper peat deposits, suggesting it produces greater impacts on volume and the carbon store than manual farmland conversion for disturbances of equal area. Further, the potential for two drivers, which are both selectively distributed based on the peatland's physical properties, to compete will be affected by the degree to which these properties overlap. Thus, considering within-site variations in peatland conditions that affect specific drivers may help identify recurrent trends in their distribution and trade-offs in ES between sites, as well as assess the potential for competition between drivers.

5.3.4 The benefits of a driver-specific approach

The impacts of drivers on the peatland's volume and carbon store were divergent from their corresponding areal extents. The spatial progression and cumulative distribution of individual drivers were unique and exhaustive; resulting in their quantitatively and temporally distinct impacts. The magnitude of areal versus volumetric divergence varied both between individual drivers and dates (Evans *et al*, 2014; Mouchet *et al*, 2014). Differing magnitudes of divergence between drivers are exemplified by the cumulative impacts of 'Commercial Peat Extraction' and 'Direct Farmland Conversion' on volume relative to their extents (Table 5-1 and Table 5-2), while differences between dates are shown by the smaller impacts on volume per hectare of 'Direct Farmland Conversion' in 1880 than in 1928 (Figure 5-5). Further, given the study's timespan, the relationship

between ESs and drivers could be altered by changes in their specific practices. Solely examining the ecosystem's responses to alterations overlooks the differing impacts of specific drivers on ecosystem processes, properties and supply of ESs and how their relationships with ESs may have changed over time.

The finer temporal resolution analysis was essential to accurately detect and distinguish the impacts of different drivers, in addition to capturing the changes in their magnitude of divergence and respective trade-offs with the carbon store. Longer intervals may miss the impacts of intermediary drivers and ascribe their impacts to more stable land-uses or drivers. This could lead to the relationships or trade-offs of a specific driver with ES being incorrectly tied to a different driver and, if incorporated in land management, could result in the wrong driver being targeted in policies or other suboptimal decisions.

6 Chapter: Changes in the supply and value of selected ESs

6.1 Overview

This chapter examines the variations in the supply and value of the selected ESs (food production, peat extraction and carbon storage) at Alfred Bog over the 11 dates. Food and peat production represent the main provisioning ESs derived from exploitation. Conversely, the carbon store, an integral component of peatlands' climate regulating ESs, is tied to the volume of undisturbed peat. As such, examining the carbon store's response to drivers and, specifically, its trade-offs with the rise in provisioning ESs, was a primary thesis objective.

Of the three selected ESs, peat production and carbon storage were tied to site variations in the depth, volume and weight of peat (at varying % moisture contents). Food production was more strongly tied to the area of 'Farmland', as well as the yield and weight of food products derived annually. Variations in yield, types and total weight of food products at the study site could not be interpreted from historical sources; complicating the comparability of food production against other ESs. As a result, trends in its supply and value are presented on secondary axes in Figure 6-1 through Figure 6-3.

The examined ESs were limited by available sources and proxies for approximating their variations in supply from pre-disturbance to present conditions. Although the primary ESs associated with exploitation were included, intact peatland ESs were underrepresented. Incorporating other peatland ESs, particularly those sensitive to changes in peatland area (e.g. habitat support), would have been ideal to compare the response of ESs tied to peatland area versus volume in the 11 dates.

The variations in ESs supply and value are presented successively in §[6.2](#). The

impacts of the two main drivers and their associated ESs on Alfred Bog's carbon store are then discussed in §6.3.

6.2 Results

6.2.1 ESs supply: Loss in regulating ES with anthropogenic exploitation

The changing supply of the examined ESs at Alfred Bog is shown in Figure 6-1. In 1800, Alfred Bog contained approximately 10.7 million tonnes of carbon (t C), 95% of which was distributed in 'Domed' sites. The carbon store declined between each map, with greater losses in the 20th century. From 1800 to 1909 and 1928 to 2014, 1.5 and 3.2 million t C, or 13.8% and 30.0% of the entire store, was mobilized by exploitation. Losses exceeded rates of 20 000 t C yr⁻¹ from 1909 to 1964 and 2008 to 2014, paralleling the peatland's volumetric reduction and coinciding with CSU periods. Thus, the intensification of provisioning ESs with exploitation was juxtaposed by persistent losses in Alfred Bog's carbon store throughout the study.

Figure 6-1 – Changing supply of the three selected ESs from 1800 to 2014.

Vertical red line broadly separates ES changes in 'Peat Swamp' and 'Domed' sites respectively.

Alfred Bog's exploitation for food production began in the early 1800s, with 'Farmland' present in all land-cover maps after 1800, while peat production began roughly a century later in 1904. Direct conversion for food production produced a greater loss in the carbon store in the 'Entire Complex', mobilizing roughly 2.70×10^6 t C compared to 1.88×10^6 t C removed by peat production. However, in 'Domed' sites, 'Commercial Peat Extraction' yielded greater losses, as 'Direct Farmland Conversion' was reduced to 1.78×10^6 t C. Commercial extraction also produced greater losses in per hectare (1.18×10^3 t C ha⁻¹) and per year (1.71×10^4 t C yr⁻¹) than 'Direct Farmland Conversion' (4.91×10^2 t C ha⁻¹ and 1.18×10^4 t C yr⁻¹)³³. After two centuries, 56.2% (6.00×10^6 t C) of Alfred Bog's original carbon store remains intact, exceeding its losses with food and peat production (39.1% or 4.18×10^6 t C) and other drivers (4.7% or 4.96×10^5 t C).

Temporal variations in the effects of 'Direct Farmland Conversion' and 'Commercial Peat Extraction' on the carbon store match their volumetric trends, reported in §5.2.2.1. As such, 'Direct Farmland Conversion' is the main driver of carbon store losses until 1928 and accounts for roughly 95% of losses until 1909. Thereafter (1947 to 2014), 'Commercial Peat Extraction' accounts for the majority (70%) of losses in the carbon store.

6.2.2 ESs value: Rise in provisioning ESs and decline in regulating ES

Figure 6-2 shows changes in the value of the three selected ESs from 1800 to 2014. The carbon store's value exceeds that of both food and peat production ESs in each date. Yet, the cumulative value of the provisioning ESs over the 200-year study was \$1.24 billion, more than twice the value of the pre-disturbance carbon store (\$541 million). Thus,

³³ In calculating their impacts on carbon store losses per unit time, 'Direct Farmland Conversion' and 'Commercial Peat Extraction' were considered to have operated for 194 and 110 years respectively.

despite more than half of the original carbon store remaining intact, provisioning ESs acquired through exploitation were of comparatively greater value.

Figure 6-2 – Changes in the total value of the selected ESs.
Vertical red line separates changes in ES value in ‘Peat Swamp’ and ‘Domed’ sites.

Figure 6-3 depicts the changes in the adjusted value per unit of the two provisioning ESs. The average value of farmland per hectare and peat production per tonne over the 200-year study was \$5,028 ha⁻¹ and \$215 t respectively. Although excluded from the figure due to its lack of historical market values and variations, the adjusted per unit value applied to the carbon store was notably lower than the provisioning ESs at \$49 t C.

To improve the comparability of the two provisioning ESs the average weight and value of both food and peat products generated per hectare were considered (Table 6-1). Present food production trends were used to select specific food products to compare with peat. The comparison highlights that price per tonne of typical food products derived from the region are greater than the value of peat, although the value of crop-based products were more comparable to peat moss than dairy products.

Figure 6-3 – Changes in the per unit value with food and peat production ESs.

Table 6-1 – Average value per tonne and value per hectare of food and peat products.

Note: The yield and value of crop food products were from OMAFRA ([OMAFRA, 2016](#)). Dairy products were gathered from the Canadian Dairy Information Centre ([CDIC, 2016](#)). Both values were from 2016.

Product	Weight Value (\$ t)	Yield (t ha ⁻¹)	Value per Area (\$ ha ⁻¹)
Peat Moss	213	2,936.0	626,289
Soybean	495	3.1	1,566
Grain Corn	229	9.9	2,264
Hay	175	5.6	978
Butter	8,876	N/A	N/A
Cheese	14,040	N/A	N/A

The average weight of peat (30% moisture) produced per hectare at Alfred Bog was $2.93 \times 10^3 \text{ t ha}^{-1}$, far exceeding the yields of crop-based food products. Thus, despite the lesser value per tonne of peat moss, its average value per hectare (\$626,289 ha⁻¹) was unmatched by food products. However, food products are generated annually, while peat is depleted over years and decades, the latter requiring longer for benefits to be realized.

For comparison, the average carbon stored in peat per hectare was $1.00 \times 10^3 \text{ t ha}^{-1}$, yielding an average value of \$48,716 ha⁻¹ in the ‘Entire Complex’. In ‘Domed’ sites these values were $1.40 \times 10^3 \text{ t ha}^{-1}$ and \$68,094 ha⁻¹ respectively. With only the deeper domes

remaining in 2014, both the average carbon store and value per unit area were even greater at $1.72 \times 10^3 \text{ t ha}^{-1}$ and $\$83,636 \text{ ha}^{-1}$. The value of deposits in terms of both peat production and the carbon store varied spatially across the depth profile.

6.3 Discussion

6.3.1 ES supply: Trade-offs in the carbon store with disturbances

The changing supply of the selected ESs with Alfred Bog's exploitation mirrors the general trends identified in ESs literature (MA, 2005; Raudsepp-Hearne *et al*, 2010a; Rodriguez *et al*, 2006) and peatland ESs studies (Chapman *et al*, 2003; Evans *et al*, 2014; Grand-Clement *et al*, 2015; Joosten and Clarke, 2002). The rise in 'Direct Farmland Conversion' and 'Commercial Peat Extraction', with food and peat production, led to irreversible trade-offs in the carbon store. The disparate timescales of exploitation, confined to the past two centuries, versus Alfred Bog's development over several millennia, epitomizes the unsustainability of anthropogenic disturbances in peatlands and the irreversible losses in their carbon stores and supply of other ESs.

The two main drivers had the greatest impacts on Alfred Bog's reduction and supply of ESs. In relation to the carbon store, both drivers represent spatial and temporal trade-offs in ESs, through the loss of global, long-term climate regulating ESs for local, short-term gains with the intensified supply of local, material goods. Similarly, both drivers result in the peatland's complete exploitation. First, the peatland's self-regulating properties are disrupted through drainage and clearing living surface vegetation. Subsequently, peat is removed through successive burning ('Direct Farmland Conversion') or extraction ('Commercial Peat Extraction'). These alterations lead to step changes in ecosystem conditions (Swindles *et al*, 2016). Further, advances in technology and

techniques, as well as increased interconnectivity and commercially-oriented exploitation after the mid-20th century influenced the rates and beneficiaries of ecosystem alterations. The specific properties, processes and impacts of the two main drivers on the carbon store are examined below.

6.3.2 Food production ESs³⁴

As presented in the results, direct conversion to farmland for food production produced the greatest net impact on Alfred Bog's carbon store over the entire complex. Further, burning peat in direct agricultural conversion immediately mobilizes stored carbon to the atmosphere (Cleary *et al*, 2005). These fires could spread throughout the peatland until they were extinguished by autumn rain (Haanel, 1926, p.149). The fires also sometimes spread to and damaged existing infrastructure and farmland in adjacent areas (Richardson, 1948). Including the loss in other ESs, from both the peatland, as well as adjacent ecosystems and land-uses, would further amplify the trade-offs associated with 'Direct Farmland Conversion'. Sites that were burned and cleared, but then abandoned when found to be unsuitable for agriculture presented particularly acute trade-offs in peatland ESs with the negligible gains from altered site uses.

However, the sustainability of food production is an important consideration for assessing its relative trade-offs with the peatland's carbon store. Further, the concentration of direct conversion on shallower peat deposits at Alfred Bog produced a smaller impact on the carbon store in 'Domed' sites, as well as per unit area or time in the 'Entire Complex'

³⁴ As noted, both drivers ('Direct Farmland Conversion' and 'Commercial Peat Extraction') led to the growth in 'Farmland' area (§5.3.1.1). Food production was tied to the area of 'Farmland' in each map. As such, food production was not tied to any one specific driver. However, for the discussion, the impacts of food production on the carbon store were attributed to sites that were directly converted to farmland, while those that were commercially extracted prior to conversion were attributed to peat production.

when compared against peat production. Thus, direct farmland conversion produced a greater return in available farmland area for food production with lesser per unit impacts on the carbon store. This is particularly illustrated by the minimal losses in the carbon store (1.48×10^6 t C or 13.8% of original store) with the rapid expansion in 'Farmland' area in the 19th century, which covers 4.39×10^3 ha⁻¹ or 39.2% of the study site in 1909.

6.3.3 Peat production ESs

Peat production led to greater trade-offs in the peatland's carbon store per unit area and time, as well as cumulatively in 'Domed' sites. Further, peat extraction is in greater direct conflict with the carbon store since both are volume-based ESs, with the former tied to active exploitation, with peat removed, processed and transported for sale elsewhere. With all other conditions equal, a peatland of greater depth and volume is more profitable for extraction, but is also a site of greater carbon storage (Monenco, 1981).

The carbon released to the atmosphere with peat moss extraction is less immediate than its combustion through either the use of peat fuel or in direct farmland conversion, but is still mobilized in following years (Cleary *et al*, 2005). Further, modern extraction is a finite and unsustainable process, with peat removed at rates vastly exceeding accumulation, until the deposit is exhausted (Cleary *et al*, 2005; ECO, 2005; Price *et al*, 2003).

6.3.4 Relations between peat and food production ESs

The two provisioning services have a unidirectional, synergistic relationship. Peat extraction sites can be subsequently transferred to farmland and produce food (Monenco, 1981), but not *vice versa*. This was shown at Alfred Bog, with the rise in commercial extraction resulting in the expansion of 'Farmland' and food production in subsequent

maps. This led to the continued rise in ‘Farmland’ area (Figure 5-2), despite the decline in ‘Direct Farmland Conversion’ after 1964 (Figure 5-5).

Some may represent this synergistic relationship (*i.e.* the combined gains in food and peat production from a single disturbance) as an intensification in the returned ESs and an optimal trade-off for the change in land-use. However, the exploitation of deeper peat deposits mobilizes substantially greater amounts of carbon for a diminishing return in the area for post-extraction uses. Therefore, it is a larger trade-off in the peatland’s carbon store than if disturbances were restricted to the shallower and more expansive deposits, mostly associated with manual ‘Direct Farmland Conversion’ at Alfred Bog.

Although ‘Direct Farmland Conversion’ and ‘Commercial Peat Extraction’ are distinct drivers, the proliferation of Canada’s commercial peat industry is tied to increasing commercial demand for peat in agriculture and horticulture in the mid-20th century. Farmland growth in temperate regions has been limited over the past 50 years, yet intensified practices have led to greater yields (Foley *et al*, 2005). A part of intensification involves the increased use of soil amendments, which includes large quantities of peat moss (Joosten and Clarke, 2002; Swinnerton and Ripley, 1947). Thus, peat production after 1941 at Alfred Bog is partly linked to its demand for use in food production elsewhere.

6.3.5 Broader factors affecting ES trade-offs at Alfred Bog

The mechanization and advancing techniques in farming and peat extraction practices, as well as the transition to commercially-oriented production over the course of 100 years intensified the trade-offs in ESs and rates of volumetric losses (*e.g.* greater carbon store losses from 1909 to 1964 and 2008 to 2014). This was exemplified by differing properties of early mechanized peat extraction versus vacuum-extracted techniques

(discussed in §[5.3.1.1.2](#)), as well as the greater trade-offs with modern farming practices, such as enhanced nutrient inputs, tile drainage and crop homogenization (Foley *et al*, 2005). Thus, commercially-driven decision-making and technological advances increased the frequency and magnitude of ecosystem alterations with food and peat production; maximizing their yield and profitability.

Further, these factors combined with greater interconnectivity, resulted in the rising influence of distant events and factors shaping local anthropogenic alterations over the course of the study. In the 19th and early 20th centuries, the benefits derived from peatland exploitation were mostly affected and consumed within the region. Peat fuel produced during the government tests at Alfred Bog was sold locally in Alfred Village and in the Ottawa and Montréal regions, connected to Alfred by the Canadian Pacific Railway line (Haanel, 1920; Haanel, 1922). However, by the mid-20th century, landscape alterations and trade-offs in ESs were increasingly affected by factors and gained by beneficiaries beyond the study site and surrounding region.

The switch from peat fuel to peat moss production in 1941 exemplifies the transition from a domestic, secure and cost-effective fuel source for regional and national energy needs (Bureau of Mines, 1891; Haanel, 1918) to an export-oriented industry driven by market values and international trade³⁵. Further, despite the opposition of many residents to commercial extraction in the 1980s and 1990s, an international company with large land-holdings was able to reverse a 1978 zoning change and enable exploitation to persist (Cuddy, 1983; OFNC, 2008). These broader developments after the mid-20th

³⁵ Peat production for horticulture and agriculture continues as the major focus of Canada's peat industry (Warner and Buteau, 2000). Domestic use accounts for roughly 10% of extracted peat in Canada and 90% of peat exports are to the United States (Keys, 1992).

century can lead to situations in which local gains in ESs from exploitation are negligible, while simultaneously bearing the losses in peatland's ESs. This can complicate incentivizing non-disruptive site uses, with decision-makers and beneficiaries increasingly removed from the trade-offs in ESs with exploitation.

6.3.6 Estimating the carbon store: Peat depth, volume and density

The peatland's divergent areal versus volumetric responses shows that areal proxies are insufficient to approximate the spatial distribution of domed peatland's volume and carbon store. Thus, incorporating variations in peat depths and volume, as well as the average dry bulk density into analyses are required to estimate the carbon store's distribution and response to disturbances in domed peatlands (Joosten and Clarke, 2002).

Many ES studies quantify ecosystem and ES dynamics using land-cover maps and areal proxies, even when the proxies remain empirically untested for a given ecosystem or specific site (Bennett *et al*, 2009). The case-study demonstrates this approach would misrepresent the impacts of exploitation on the carbon store in domed peatlands, both in magnitude and timing. In such peatlands, the carbon store's losses to disturbances and its relationships with specific drivers cannot be accurately or confidently inferred using two-dimensional analyses; necessitating a spatially explicit analysis of both the areal and volumetric impacts of disturbances.

Although specific considerations vary for each ES, incorporating the spatial variations in peat depths and volume may also help capture other susceptible ESs in domed peatlands, such as water storage and flood attenuation. Further, the differentiation between areal and volumetrically sensitive ESs may also be relevant in examining other ecosystems with divergent distributions of area versus volume. For example, water storage and flow

regulation ESs in glaciers will also vary with changes in volume, density and mass, while other ESs, such as tourism may be tied to area. Similarly, the paleo-environmental records stored in peatlands and glaciers are broadly tied to depths. Thus, in addition to capturing the carbon store's distribution, a multidimensional analysis may be useful for estimating the supply of other ESs, both in domed peatlands and other ecosystems more generally.

6.3.7 Changing value of the selected ESs

Valuing the selected ESs was affected by data limitations, complicating their comparability and comprehensive assessment. Constraints on ESs valuation related to the:

- 1) The timespan of available inflation adjustment indices.
- 2) Consistency of reported variables (for use as proxies) and reporting boundaries.
- 3) Mismatching spatial extent of reporting boundaries (administrative) and case-study (ecological).

The GDP deflator index was selected due to its longer timespan (1871-2010) over other available inflation adjustment indices, such as the Consumer Price Index (1914-2017). As such, reported values for the selected ESs were only comparable after 1871, as earlier values could not be inflation adjusted. Further, different reporting boundaries used for agricultural census data prior to 1851³⁶ meant regional farmland trends, including values, could only be established thereafter.

This was less problematic for peat production at Alfred Bog, which only began in 1904. Similarly, the lack of historical market values for the carbon store led to its estimation

³⁶ Prescott County was amalgamated and reported with other counties in the Lunenburg district (renamed Eastern district in 1792) from 1788 to 1816. From 1816 to 1849 its trends were reported under the Ottawa district. Subsequently, the districts are replaced by county and municipal boundaries. Municipal trends were established from 1851 to 1996, prior to municipal amalgamation in the late 1990s which altered the township boundaries. The county's boundary was not impacted and its trends were established from 1851 to 2011.

using a value per tonne (\$ t C) proxy. The proxy was adjusted to its 2015 value and multiplied by the total dry weight of stored carbon remaining in the 11 dates, enabling its value to be extended earlier than 1871. The historical valuation of ESs faced challenges with the changing administrative boundaries over which trends were reported; the consistency of reported variables and the proxies available to estimate the value of ESs; as well as the absence of an inflation adjustment index that covered the study's timespan.

Accurately valuing past food production was particularly challenging. This was partly influenced by the array of harvested food products, which changed in composition, yield and value over time. Present food production trends (*e.g.* food types, yields and values) cannot accurately capture its historical variations, especially given the study's length. Further, even if historical food production trends were consistently reported and compiled from agricultural censuses, it cannot be assumed that food production trends scale down to the study site's ecological extent. The proxy used in food production valuation captured average farmland property values, and not that of the annually harvested food products. As such, the comparability of food production ESs against peat and carbon storage ESs was limited, having an area as opposed to a weight based per unit value and capturing a limited aspect of its total value. The cumulative value of food production (*i.e.* total food products sold from 'Farmland' areas between 1800 and 2014) could not be established or compared against peat production. Thus, the value of selected ESs cannot be relied upon and are loose comparisons at best.

6.3.7.1 Provisioning ESs: Greater value in exploitation

It is likely that food production had a greater total value, despite the results indicating peat production was of greater value. The longer duration and larger areal extent

of 'Farmland' at Alfred Bog suggests that the weight of food produced in a year and in aggregate likely outweighs that associated with peat production. Combined with its greater average value per tonne, the aggregate value of food products likely exceeded that of peat production. This is particularly applicable from 1909 to 1964, with the use of early mechanized peat extraction techniques resulting in lesser total volumes being extracted, and prior to 1941 with the lesser value of peat fuel. The annual harvest of food products from farmland, compared to the finite amount of peat available for extraction, further supports the greater cumulative and long-term value of food production at Alfred Bog.

Thus, the aggregate value of provisioning ESs over the carbon store would have been greater had the value of food production been deductible. The greater net and per unit value of provisioning ESs than the peatland's carbon store demonstrates the influence of scale on the perceived and assigned economic values to different ESs (Hein *et al*, 2006). The greater value assigned to provisioning ESs, which are derived through exploitation and can be privately traded and consumed, over the more widespread long-term ESs derived from non-disruptive uses is typical of alterations to peatlands and other ecosystems. It also highlights limitations in ES valuations, where findings can seemingly emphasize the greater value of ecosystem exploitation, particularly depending on the selected ESs. For example, the case-study examined the two provisioning ESs tied to the main drivers of Alfred Bog's reduction, but only examined one component of its climate regulating ESs; biasing the value of exploitative uses versus that of the peatland's integrated supply of ESs.

6.3.7.2 Carbon store and climate regulating ESs

The carbon store's greater value than the two provisioning ESs in each of the 11 dates (Figure 6-2), despite having a lesser per unit value and cumulative value than the

provisioning ESs, is a testament to the concentrated carbon stores in peatlands. It also emphasizes Alfred Bog's continued ES supply and conservation value after two centuries of human-induced alterations. Had other ESs been included in analysis, the cumulative value of intact peatland ESs may have even surpassed that of the provisioning ESs tied to exploitation. Further, the value of the integrated supply of ESs from peatlands is arguably of greater value than the sum of its individual ESs, or the comparatively single-ES focussed production associated with a peatland's exploitation.

6.3.8 Summary of trade-offs between selected ESs

Both food and peat production led to irreparable changes in the peatland and its supply of ESs, but were distinct in their processes, techniques and overall impacts. The discussion highlights that either peat or food production can be presented as producing greater trade-offs in the peatland's carbon store, depending on whether their impacts are considered in aggregate or per unit, as well as over the entire complex or in domed sites. The unsustainability of peat extraction, combined with its concentration on deeper deposits and the smaller return in area for post-extraction uses suggests it may be a greater trade-off in the carbon store per unit area. Comparatively, the fires used in direct farmland conversion, as well as its greater aggregate areal and volumetric impacts over the entire complex indicate that farmland conversion may have led to greater trade-offs in the peatland's supply of ESs. The specific properties, processes and impacts that are considered also impact the perceived trade-offs of drivers. Thus, the way the impacts of drivers are scoped and the specific methods or proxies used in their assessment directly influences their associated trade-offs in ESs.

The peatland's remaining area and volume after 214 years also highlights the substantial cumulative alterations to Alfred Bog and losses in its ESs with the progression of disturbances over time. This underscores the incremental effects of peatland exploitation on losses in its climate regulating ESs. Although the disturbances of a single driver in any one map at Alfred Bog were relatively marginal, their cumulative impacts resulted in substantial ecosystem alterations and changes in its supply of ESs. This epitomizes broader issues of incremental disturbances to peatlands regionally, nationally and globally.

7 Chapter: Broader trends

7.1 Overview

Previous chapters focussed on the case-study at Alfred Bog. This chapter compares the case-study results with broader research trends on peatland distribution and disturbances. This not only grounds the study in a larger context, but enables both the site-specific and common factors shaping peatland exploitation in Canada to be explored. Specifically, the chapter examines: 1) Alfred Bog's pre-disturbance and present influence on peatland distribution (*i.e.* area, volume, dry-weight and carbon store) at broader administrative levels; and, 2) geographic variations in the impacts of specific drivers on peatland exploitation. They are presented successively in the results (§[7.2](#)) and discussion (§[7.3](#)). Site-specific and broader factors affecting the areal versus volumetric divergence of drivers and the ecosystem's aggregate response in domed peatlands are specifically discussed in §[7.3.3](#).

7.2 Results

7.2.1 Peatland distribution: Area, volume and carbon storage

Alfred Bog's area, volume, dry weight and carbon store are expressed as percentages of that reported at regional, provincial and national levels in Table 7-1. Alfred Bog's substantial percentage of the total peatland area and volume in the Ottawa-Brockville³⁷ region, southeastern Ontario and Ontario's southern lowlands underscores its rarity and strong influence on regional peatland distribution and supply of peatland ESs.

³⁷ Alfred Bog falls just outside the Ontario Geological Survey's Ottawa-Brockville region. Thus, as with other peatland reports it was still used to broadly infer Alfred Bog's regional influence on peatland distribution (*e.g.* Bird and Hale, 1984a; Riley, 1994), but the specific percentages are less meaningful.

Table 7-1 – Alfred Bog’s area, volume, dry-weight and carbon storage expressed as percentages of their reported distribution at broader levels.

Note: Sources marked with ¹ were cited in Tarnocai (1984, p.1) while those with ² were cited in Warner *et al* (2003, p.2).

Source	Variable	Value	Level	Study Site (%)	
				1800	2014
Tarnocai, 1984	Area	1.11×10^8 ha	National	0.010%	0.003%
Zoltai, 1980 ¹	Area	1.53×10^8 ha	National	0.007%	0.002%
Kivinen and Pakarinen, 1980 ¹	Area	1.70×10^8 ha	National	0.007%	0.002%
Tarnocai <i>et al</i> , 2000 ²	Area	1.22×10^8 ha	National	0.009%	0.003%
Gorham, 1991 ²	Area	1.19×10^8 ha	National	0.009%	0.003%
Tarnocai, 1984	Area	2.25×10^7 ha	Provincial	0.050%	0.016%
Monenco, 1981	Area	2.59×10^7 ha	Provincial	0.043%	0.014%
Warner <i>et al</i> , 2003	Area	2.61×10^7 ha	Provincial	0.043%	0.013%
Monenco, 1981, p.24	Area	2.84×10^5 ha	Regional – S Ontario Lowlands	3.9%	1.2%
Riley, 1994	Area	3.88×10^5 ha	Regional – SE Ontario	2.9%	0.9%
Bird and Hale, 1984b	Area	1.84×10^4 ha	Regional – Ottawa-Brockville	60.8%	9.0%
Tarnocai, 1984	Volume	3.00×10^{12} m ³	National	0.008%	0.005%
Tarnocai, 1984	Volume	6.77×10^{11} m ³	Provincial	0.035%	0.020%
Monenco, 1981	Volume	7.70×10^9 m ³	Regional – S. Ontario Lowlands	3.0%	1.8%
Riley, 1994	Volume	6.96×10^9 m ³	Regional – SE Ontario	3.4%	1.9%
Riley, 1994	Volume	2.44×10^9 m ³	Regional – Ottawa-Brockville	96.1%	56.5%
Tarnocai, 1984	Dry Weight	3.35×10^{11} t	National	0.006%	0.004%
Tarnocai, 1984	Dry Weight	7.71×10^{10} t	Provincial	0.027%	0.016%
Tarnocai, 2009	Carbon	1.47×10^{11} t	National	0.007%	0.004%
Tarnocai <i>et al</i> , 2000 ²	Carbon	1.56×10^{11} t	National	0.007%	0.004%
Gorham, 1991 ²	Carbon	1.52×10^{11} t	National	0.007%	0.004%
Warner <i>et al</i> , 2003	Carbon	2.51×10^{10} t	Provincial	0.043%	0.025%

Specifically, Alfred Bog's volume is unmatched by other regionally significant peatlands in southern Ontario (Bird and Hale, 1984a). However, Alfred Bog's pre-disturbance and present influence on peatland area, volume and carbon store at provincial and national levels are much smaller, with values less than or equal to 0.05% and 0.01% respectively.

7.2.2 Drivers of peatland reduction: Local to global perspectives

Figure 7-1 depicts the varied areal impacts of drivers on peatland reduction between sites and administrative levels. Their impacts are presented as a percentage of total exploited peatland area. Globally, agricultural conversion and commercial peat extraction account for 50% and 10% of disturbances by area respectively. Nationally, Keys (1992) indicates that agriculture and peat extraction account for 85% and 0.02% of disturbances since settlement respectively. The impacts of drivers in New Brunswick and Québec vary widely (Poulin *et al.*, 2004). In both provinces, peat extraction exceeds the nationally reported impacts, accounting for 94% and 3% of disturbances respectively. The impacts of agricultural conversion are also much smaller in New Brunswick (1%) and Québec (6%); highlighting regional variations in drivers.

As the examination of drivers is restricted to regional and local levels in southern Canada, the impacts of peat extraction and agricultural conversion increase, while the impacts of water reservoirs and forestry drivers decrease. This is shown in Pellerin's (2003) study of drivers on peatland reduction in the St. Lawrence Lowlands region of Québec (between Rivière-Du-Loup and L'Isle Verte). While the types and distribution of drivers in southern Canada, as well as those at global and continental levels are more representative of disturbances at Alfred Bog, disturbances still varied between sites.

Figure 7-1 – Areal impacts of anthropogenic drivers on peatland reduction: local to global assessments.

Figure 7-2 shows the areal impacts of drivers relative to remaining undisturbed peatlands. They are calculated as percentages of pre-disturbance peatland area. The

aggregate impacts of drivers are minimal compared to the remaining peatland area at provincial and national levels. Provinces with boreal and subarctic regions may have greater total peatland areas and percentages remaining undisturbed than (as seen for Québec versus New Brunswick below). National estimates suggest that 85% of peatlands are intact and provincially existing disturbances account for only roughly 5% of the existing peatlands (Rubec, 1988 cited in Joosten and Clarke, 2002; Poulin *et al*, 2004).

The impacts of anthropogenic drivers on the total distribution of peatlands are much greater in southern Canada. Approximately 70% of peatlands in southern regions of Canada have been disturbed by human activities since settlement (Keys, 1992). Pellerin (2003) reports a 62% reduction in peatland area between 1929 and 2000 at her study site in the St. Lawrence Lowlands. She cites two other studies in southern Québec that report similar losses. The first study at Small Teafeld and Large Teafeld bogs indicates they were reduced by 60% between 1934 and 1985 (Jean and Bouchard, 1987). The other study determined that 30% of the ombrotrophic bogs within a 30-km radius of Montréal were permanently altered between 1966 and 1981, largely associated with farmland conversion and horticultural peat extraction. These estimates are also reflected by the remaining percentage of peatland area at Alfred Bog (31.5%) and Burns Bog (40.4%).

Despite the broad correspondence in drivers impacts at regional levels (*i.e.* direct conversion and peat extraction in southern regions, industrial developments in northern regions), their specific impacts vary between sites. For example, Burns Bog faced greater urban development pressures and was less impacted by agricultural conversion due to its proximity to an urban centre when compared against Alfred Bog. Further, forestry initiatives only minutely impact Alfred and Burns Bogs, but have played a comparatively

greater role in disturbances in Québec. This reiterates the importance of local and regional level analyses in capturing these differences and to inform management, policy and planning decisions at these levels (Evans *et al*, 2014).

Figure 7-2 – Comparing areal impacts of drivers to undisturbed peatland area: local to global scales.

7.3 Discussion

7.3.1 Peatland distribution: Area, volume and carbon storage

Alfred Bog's disproportionate impact on regional trends in peatland area, volume and carbon storage reinforces the relevance of volumetric variations between domed peatlands. One site may have a greater influence on regional peatland distribution and the supply of certain ESs than others. Peatlands like Alfred and Mer Bleue Bogs, with greater

extents, depths and volumes than the regional averages (*e.g.* see table in “Canadian Peat Investigations 1908-1914”, 1916, p. 6), have greater influence on the regional carbon store than other nearby peatlands such as Moose Creek, Newington and Winchester Bogs. Thus, the exploitation of the former, which are boreal-like peatlands and relatively scarce in temperate regions of southern Canada, would result in greater losses in climate regulation than exploitation of the latter³⁸. A similar example at a broader scale would be the influence of the Hudson Bay Lowlands, the world’s second largest peatland complex, on the distribution of peatlands and their carbon stores at provincial and national levels (Gorham, 1991; Webster *et al*, 2015). Thus, spatial variations in the volumetric impacts of disturbances is an important consideration both within and between sites.

Moving beyond the regional level, the minimal influence of changes in Alfred Bog’s area, volume and carbon store on the provincial and national scale trends reflects the scalar mismatch between the losses in peatlands’ climate regulating ESs and the benefits derived from exploitation (Figure 2-2) (Glenk *et al*, 2014; Scholes *et al*, 2013). Its negligible influence also reflects the divergence in the spatial distribution of peatlands and past anthropogenic disturbances. Peatlands are most concentrated in boreal and subarctic regions, while disturbances have largely been confined to areas with greater populations, mostly in temperate and tropical regions (Chapman *et al*, 2003; Joosten and Clarke, 2002).

The broader level trends reinforce the cumulative effect of human-induced disturbances to peatlands, as well as the resulting release of GHGs and losses in other ESs. In isolation, the impacts of Alfred Bog’s reduction on broader level trends are negligible.

³⁸ Also applies to other ESs, such as habitat support, with Alfred Bog known to support provincially, nationally and continentally rare species, the latter only being found at a select number of sites in North America (Mosquin, 1991; OFNC, 2008).

However, the case-study exemplifies recurrent trends in incremental exploitation that have led to most peatlands in the region (~61% to 80%) (Bird and Hale, 1984b) and in southern Canada (~70%) being irreparably disturbed since settlement (Keys, 1992), with only 1 in every 150 peatlands being protected in the St. Lawrence Lowlands region (Chapman *et al*, 2003). With development pressures increasing in boreal and subarctic regions, it is imperative to avoid repeating these trends and consider the cumulative releases of GHGs from the incremental exploitation.

7.3.2 Drivers of peatland reduction: Local to global perspectives

The drivers of peatland reduction at other sites and broader levels, shown in Figure 7-1 and Figure 7-2, were quantified using areal extent. As a result, the volumetric impacts of drivers and the divergence from their extent could not be compared between the case-study and broader levels, limiting the comparison to the areal impacts of drivers between sites. Further, the specific time intervals used in establishing their impacts may have biased certain drivers, as discussed in Chapter 5 (§[5.3.1.1](#)). Many reports omitted the intervals and methods used to determine the impacts of anthropogenic drivers, restricting the ability to assess potential inaccuracies or biases.

The impacts of drivers such as agricultural conversion, forestry, peat extraction and urbanization at national, continental and global levels reflects the concentration of historical disturbances in more densely populated temperate regions (Chapman *et al*, 2003), where climatic, environmental, social and economic conditions were conducive to these drivers. This is attested by the remaining peatland area substantially outweighing ($\geq 80\%$) the impacts of disturbances at provincial and national levels, but not for sites and regions in southern Canada, where the aggregate areal extent of drivers exceeded the remaining

peatland area ($\leq 40\%$) for reported sites.

The greater impacts of agricultural conversion and peat extraction at local (Hebda *et al*, 2000) and regional (Pellerin, 2003) sites versus the greater impacts of dams at a provincial level in Québec (Poulin *et al*, 2004) in part reflects the changing suitability of different anthropogenic drivers with climatic conditions. The impacts of infrastructural, industrial or resource developments, such as water reservoir construction, is typical of disturbances in boreal regions where many alternative exploitative uses are not profitable. Further, reservoir construction is cited as the major driver of peatland disturbances in Canada, particularly in Québec, Manitoba and Alberta (Joosten and Clarke, 2002; Poulin *et al*, 2004; Webster *et al*, 2015). Comparatively, a combination of climatic, economic and environmental factors result in the concentration of commercial peat extraction in southern Canada (*e.g. socio-economic*: nearby transportation infrastructure and population centres needed for profitable distribution³⁹ due to low dry-bulk density of peat moss; *climatic*: length of operating season, efficacy of drainage and air-dried peat; *environmental*: depth of peat and peat quality) (Monenco, 1981). Thus, the distribution of these drivers (*e.g. commercial extraction and farmland conversion*) may vary both within domed peatlands (§5.3.3), as well as between sites and regions according to these broader factors.

The greater correspondence in the drivers of peatland reduction at a regional level is expected, given greater similarities in the conditions impacting their suitability. However, the variations in the impacts of drivers between sites (*e.g. Alfred Bog, Burns Bog and Rivière-Du-Loup region*) demonstrate the importance of the specific social-

³⁹ The maximum distance from markets depends on the type, use and value of extracted peat. Peat pots have the greatest distance (3000 km), followed by peat moss (2000 km) and peat fuel (<500 km) (Monenco, 1981).

ecological setting and past development pressures on the impacts and progression of drivers between sites. This suggests the specific drivers of peatland reduction and their relationships with ESs will vary between sites, regions and broader levels. Thus, capturing the specific impacts of drivers within and between sites is important in making informed decisions on land-use management and regulation at these levels, which can target the specific pressures and conditions faced at these different levels (Evans *et al*, 2014).

7.3.3 Site-specific factors on areal versus volumetric divergence and ES response

The geographic setting and site-specific historical developments can result in the following differences between domed peatland sites and at broader levels:

- 1) The presence and magnitude of disturbances, as well as their divergence;
- 2) The types and impacts of specific drivers on ecosystem alterations;
- 3) The distribution of drivers, both individually and in aggregate; and,
- 4) The relationships between drivers and ESs over time and cumulatively

The social and ecological conditions and historical interactions between humans and the environment are not fully transferable between sites. The areal versus volumetric divergence with the exploitation of domed peatlands and the impacts of drivers will vary between sites. As such, spatially explicit and geographically aware historical analyses of ESs are beneficial to assessing the relationships between drivers and ESs in domed peatlands, as well as identifying the site-specific considerations from more widely applicable findings. Some factors tied to the variations in ecosystem alterations and the impacts of drivers between sites and over time, are discussed below.

The historical events, conditions and developments of a site can be considered as path-dependent (Tomscha and Gergel, 2016). That is, small differences in the past

conditions and development trajectories can produce substantial variations in the present conditions and supply of ESs (Belyea, 2009). This is exemplified with a comparative discussion of the development trajectories at Alfred and Mer Bleue Bogs. Path-dependency underscores that the cumulative impacts of past land-use alterations are embedded in the present ecosystem conditions and supply of ESs. These past alterations shape the available land-use management decisions and constrain its potential future conditions (*e.g.* step changes in a peatland and its capacity to supply ESs with disturbances).

7.3.3.1 Progression of drivers and disturbances over time

Changes in the extent of drivers and their distribution relative to the depth profile influenced the specific variations in their volumetric impacts and, in aggregate, the peatland's volumetric losses over time. Deviations from the observed progression of drivers and disturbances at Alfred Bog would have altered both the temporal variations and cumulative changes at Alfred Bog. For example, had the progression of disturbances been reversed and moved from the domed peatland's centre outwards, the case-study's trends, both in the 11 examined dates and cumulatively, would be radically altered.

This progression, from the centre outward, is typical of commercial peat extraction (Monenco, 1981) and occurred in Alfred Bog's historical northwest dome with the government's peat fuel experiments. It also occurred at many domed peatlands in southern Ontario, such as the Moose Creek, Wainfleet and Newington bogs, where the deepest deposits were partly or completely extracted. If this trajectory was repeated in the two remaining domes, the trade-offs between commercial extraction and the carbon store, as well as the peatland's total volumetric losses would have been substantially greater.

These general disturbance progressions (*i.e.* inwards from margins versus outwards from central deposits) will yield some similarities in ES trade-offs between domed peatland sites. However, the spatial progression and cumulative distribution of drivers are, in part, unique to the specific social-ecological setting and past land-use alterations (*i.e.* path-dependent). As such, both the specific ecological impacts of drivers and response of peatland ESs will differ between sites.

Combined with the broader factors (*e.g.* techniques and regulations) altering the specific trade-offs or traits of disturbances and specific drivers over, as were discussed in earlier chapters, the specific timing of exploitation can also affect the transferability of ES dynamics between domed peatlands. Thus, in addition to broader commonalities in the effects of drivers on ES supply, context-specific factors may also critically inform spatial and temporal variations trade-offs. This may in turn help identify factors that lead to differences in present ecological conditions and ES supply of exploited peatlands that experienced similar disturbances.

7.3.3.2 The range and distribution of the depth profile

The comparison of Alfred Bog's average depth and volume to regional averages demonstrated that, the distribution of peat depths and volume vary not only within (see Chapters 4 and 5), but between domed peatlands. The geographic setting and development history influence spatial distribution and range in peat depths (Belyea, 2009). Physical confining features may influence the peatland's shape and extent, with their distribution (*e.g.* hydrological features, soils, topography) limiting the area available for the peatland's lateral expansion through paludification. This, in turn, influences the distribution of peat depths. The presence of multiple domes, like the three found at Alfred Bog (see Figure

4-1), exemplifies the site-specific distribution of depths and volume. Thus, variations in peatland structure may affect the magnitude of divergence and distribution of ESs both within other domed peatlands and between sites in broader regional analyses.

Peat depths also vary broadly between climatic regions. The greater age (*i.e.* time elapsed since accumulation was initiated) and longer growing season (*i.e.* climatic setting) means that domed peatlands in temperate regions generally have greater depths than their boreal and subarctic counterparts. For example, an average depth of 2.3 m reported for boreal and subarctic peatlands (Gorham, 1991) and 1.5 m for the Hudson Bay Lowlands, while their average depths in southern Ontario's lowlands is 2.7 m (Monenco, 1981, p. 24) and 4.5 m at Alfred Bog (Bird and Hale, 1984a). Similarly, tropical peatlands often contain greater depths than temperate peatlands. Thus, the range and distribution of peat depths, both within and between peatland sites will affect the potential for and magnitude of divergence in their areal versus volumetric responses to exploitation.

7.3.3.3 Mer Bleue and Alfred bogs: Distinct settings and development trajectories

Despite the strong ecological similarities in Alfred and Mer Bleue Bogs, both being domed peatlands with similar ranges in peat depths, the specific distribution of peat depths and the past impacts of drivers (*e.g.* changing location of drivers over time, aggregate distribution of drivers, types of drivers) varied significantly between them. The differences in the relevant factors impacting land-use management decisions highlights that the specific social-ecological settings can result in very different development trajectories and trade-offs between drivers and ESs between sites. Alfred and Mer Bleue bogs were subject to similar development pressures prior to the mid-20th century, both being impacted by

drainage, agricultural conversion, peat fuel and horticultural extraction and transportation networks (Baldwin and Mosquin, 1969).

However, Mer Bleue Bog's use in the 1940s for bombing exercises with the Royal Canadian Air Force (Baldwin and Mosquin, 1969) radically altered its development trajectory and produced a decline in subsequent development pressures⁴⁰ compared to that of Alfred Bog. Further, the expropriation of Mer Bleue Bog and adjacent farmlands by the National Capital Commission in the 1950s to incorporate into Ottawa's green belt, its recognition as a wetland of international significance in 1994 under the Ramsar convention and its establishment as a long-term monitoring and research site further contributed to the decline in development pressures, though Mer Bleue Bog's proximity to the City of Ottawa does result in certain urban development pressures that are comparatively absent at Alfred Bog, such as the municipal land-fills immediately adjacent to Mer Bleue Bog. Alfred Bog's selection as the site for provincial and national peat fuel tests in 1909 (Anrep and Nyström, 1909; Haanel, 1919), leading to the extraction of its northwest dome, also exemplifies the path-dependence in development trajectories and present ecosystem conditions between sites. Thus, the specific social-ecological setting and its historical developments can directly influence the distribution and types of drivers in ecosystem alterations. In combination, the unique distribution of peat depths and drivers between sites, indicates the relationships between drivers and ESs, as well as the cumulative areal versus volumetric losses in domed peatland's that remain partly intact, are likely to be site-specific.

⁴⁰ Undetonated ordnances from military exercises obviously reduced the suitability of subsequent exploitative uses at the affected sites in Mer Bleue Bog.

The comparison also underscores other site-specific factors and considerations, such as the influence of the jurisdictional setting on the regulations and actors influencing land-use management decisions. Mer Bleue Bog is under federal regulations due to its expropriation by the National Capital Commission, while Alfred Bog is subject to municipal zoning laws and provincial legislation. The jurisdictional and regulatory considerations, as well as the variations in past development pressures vary between Alfred and Mer Bleue Bogs, despite their ecological similarities. Since the specific drivers and their distribution differed between sites, it suggests that the relationship between drivers and peatland ESs will also vary.

8 Chapter: Data challenges in mapping 200+ years of change

8.1 Overview

This chapter examines challenges faced in the historical case-study, their influence on observed trends and methods that may be reused in future studies. Data sources dictated the spatial and temporal resolutions over which the case-study trends could be established, impacting the grain and intervals of analysis. The assumptions developed to interpret sources (§3.3.2) and address gaps in their coverage exemplify the limitations and strategies that can be used in mapping anthropogenic land-cover changes from multiple sources.

8.2 Changing data availability and interpretability

The abundance and relevance of sources increased over the course of the study period. Sources from 19th century were relatively scarce, varied in relevant spatial information, and required greater effort, as well as more assumptions, to interpret land-cover changes. This was compounded by the selective representation or discussion of landscape features in both maps and texts, conflicting observations between sources and a greater disconnect in the intended use of a source and the thesis objectives.

A greater abundance of relevant (*i.e.* peatland focussed), spatially explicit sources in the 20th century, such as the reports from the Department of Mines on peat fuel tests at Alfred Bog and historical air photos after 1927, meant that land-cover changes were more readily interpreted, at a greater spatial resolution and accuracy⁴¹ than earlier sources. The absence of peatland specific records until the late 19th century is tied to their widespread perception as unproductive wastelands to be improved through exploitation (*e.g.* Census

⁴¹ Indicated by the smaller root mean square error (RMSE) values of historic air photosets in the 20th century compared to cartographic sources in the 19th century after georeferencing.

of Agriculture's "Marsh or Wasteland" subcategory under "Unimproved Lands" from 1901 to 1941). Government records on peatlands, their uses and distribution in Canada only emerged in the late 1800s and early 1900s, driven by interests in peat fuel (*e.g.* Bureau of Mines, 1891). Thus, for other domed sites, greater efforts necessary to establish changes prior to 1900 and interpreting non-peatland focussed sources (*e.g.* PLS field notes) in establishing changes prior to 1900 will likely extends to other domed peatlands.

The effects of changing administrative boundaries, place names and landscape features on interpretation and georeferencing was more pronounced in older sources. For example, changes in the road network, township boundaries as well as lots and concessions, complicated establishing strong ground control points for older maps. The interpretability of older sources (*e.g.* air photos, maps, field notes) was also reduced by degradation and damages from physical storage and repeated use.

Georeferencing data sources in reverse chronological order could help establish GCPs for older sources, although it proved unnecessary in the case-study. Once a photoset or map was referenced, it could then be used in referencing earlier sources, reducing the timespan and increasing the common features between unreferenced data and reference sources. To avoid propagating referencing errors, only sources with minimal RMSE values after referencing should be used.

Manual delineation was the most accurate and consistent method to interpret land-cover changes over the 200-year study from the array of data sources. Mapping in reverse chronological order and reusing shapefiles between maps reduced the efforts and errors in this process. Rather than creating 11 separate land-cover maps, once the first map was created (2008), the land-cover boundaries were reused and modified accordingly to capture

changes in earlier dates. This improved the consistency of land-cover boundaries between periods, as any small positional and geometric variations in landscape features from georeferenced sources were excluded. Thus, where manual land-cover mapping is required, the benefits of reusing land-cover boundaries (*i.e.* improved spatial consistency and accuracy between maps and reduced efforts in detecting changes) should be considered.

Data sources (*i.e.* cartographic, photographic, textual) varied in the completeness of their site coverage. Gaps were particularly apparent in the 19th century, due to the scarcity of sources, smaller areal coverage and thematic focus. For example, earlier sources such as the provincial land surveyors' (PLS) field notes and maps took multiple years to complete and covered only selected concessions of the townships (*e.g.* J. Fortune's survey of Caledonia Township was conducted from 1806 to 1807 and covered concessions 1-4 and 7-11). Alfred Bog is also divided by municipal boundaries. As such, the temporal resolution between maps in the 1800s had to be compromised to maximize site coverage (*e.g.* J. Fortune's 1806 field notes had to be combined with W. Browne's 1820 map of Alfred Township to create the 1820 land-cover map). Although this issue also applied to photosets, the time between photosets and gaps in their site coverage were comparatively smaller. Other photosets from nearby years could be used to help address gaps in coverage (*e.g.* 1946-1947; 1991-1994).

Since data availability determined the time intervals between maps, the timing over which trends were established did not always align with periods of interest. This was exemplified by the mismatch between mapped periods and CSU periods (§[5.3.2](#)). This in turn affected changes that were detected and specific research objectives that were posed. For example, to extend the temporal analyses over the two centuries, the number of

examined ESs that could be interpreted from historical records and the number of periods over which they could be captured was reduced (Renard *et al*, 2015). Further, irregular intervals between periods was necessary due to the lack of long-term data records and thus, the combined interpretation of varied data sources.

As noted, the temporal intervals between maps influenced the detection and quantification of intermediary anthropogenic drivers (*e.g.* ‘Commercial Peat Extraction’ and ‘Degraded Peatland’). Ideally, both the spatial and temporal resolution of analyses reflects the minimum operational scales of examined drivers (*e.g.* ‘Farmland Conversion’ in Figure 2-2). Decadal intervals are likely sufficient in capturing most drivers, given the incremental and gradual exploitation of peatlands (*e.g.* drainage, surface clearing, levelling and successive burning or extraction).

Average interval between periods was 21 years, ranging from 6 years (2008 to 2014) to 54 years (1806-1820 to 1830-1860) and likely captured most intermediate drivers. Greater intervals in the 19th century fortunately corresponded with a time in which farmland conversion was the unrivaled driver of Alfred Bog’s reduction. For sites where intermediary drivers were not captured (*i.e.* ‘Peatland’ → ‘Farmland’), a carefully considered assumption was developed based on extensive review of historical sources to identify the most likely intermediary driver based on the period and adjacent land-uses.

Since only the aggregate changes between two maps are registered, smaller intervals and greater numbers of maps can help minimize lags between the occurrence and registration of a disturbance, as well as any potential adverse effects on the alignment of trends with known events. For example, known absences in commercial peat extraction at Alfred Bog from 1914 to 1918 (Haanel, 1919) and 1928 to 1941 (Leverin, 1944; Monenco,

1981; Warner and Buteau, 2000) were not captured by the maps in 1909, 1928 and 1947. By comparing the trends derived from maps against available sources, trends or events that were undetected in mapping were more readily identified.

8.3 Volumetric reconstruction

The limited sources available for the reconstruction of Alfred Bog's depth profile and volume required a generalized approach to its approximation (*e.g.* applying a site average for peat density and carbon content). Evaluating predicted versus reported volumes and depths for sites within Alfred Bog suggests the approach was effective in broadly estimating changes in peat volume and its carbon store. The effects of the estimated range and distribution of peat depths, as well as the distinction between 'Peat Swamp' and 'Domed' areas on the volumetric trends are discussed in §[8.3.1](#) and §[8.3.2](#) respectively. Finally, the potential to apply the case-study methods to determine the pre-disturbance volumetric distribution of other peatlands is explored in §[8.3.3](#).

8.3.1 Underestimated volume and depths in 'Domed' sites

Comparing the predicted depths and volumes against reported values highlights the predictive function underestimated the total depths and volume in Alfred Bog's remaining domed areas, while overestimating them in the smaller, exploited northwest dome. The spread of peat depth samples around the predictive function, shown in Figure 4-2, is tied to physical variations between the two independently sampled domes. The Department of Mines' (1909) samples were mostly concentrated in the smaller and shallower northwest dome, where thick roots prevented the full depth of peat from being sampled at certain sites (Anrep and Nyström, 1909, p.13; Haanel, 1926).

The majority (73%) of depth samples used to derive the predictive function were from the Department of Mines map, located in the shallower and less extensive dome. These samples had a greater influence on the predictive function and may have contributed to underestimating the maximum peat depth at Alfred Bog. The maximum predicted depth (5.8 m) matches the maximum depth recorded on the Department of Mines map in the shallower northwest (Anrep and Nyström, 1909) but not the maximum depth of 7.1 metres reported for the remaining southern dome (Bird and Hale, 1984a). The latter is supported by a high resolution DEM (LiDAR), which indicates that the peatland's surface at its maximum is 7.9 metres higher than surrounding farmland. Further, the mean peat depth derived from the predictive function in 'Domed' sites (3.1 m) was 1.4 m less than the reported mean of 4.5 m in the southern dome (Bird and Hale, 1984a). Thus, had the full range in peat depths been captured by the predictive function the divergence in areal versus volumetric trends at Alfred Bog may have been even greater.

8.3.2 Amplified divergence in the 'Entire Complex'

The distinction of 'Peat Swamp' and 'Domed' areas helped address the discrepancy (*i.e.* poor relationship) between peat depth samples and the peatland's 1800 boundaries. The strong physical basis of the Alfred Bog's spatial extent in 1800 and support of secondary sources indicates that these areas were part of the peatland complex, but not within domed areas (Bird and Hale, 1984a; Mosquin, 1991). Applying the predictive function to the 1800 boundaries would not preserve the spatial distribution observed peat depth samples in predicted depths. The rapid manual conversion of the pre-1860 area suggests that the depths must have been relatively shallow compared to domed areas. Thus, these transitional areas were considered as peat swamp or lagg areas.

The expansive area and minimal depths of ‘Peat Swamp’ sites intensified the divergence in areal versus volumetric trends both in any given period and cumulatively in the ‘Entire Complex’. Although divergence was more moderate in ‘Domed’ sites, it was not irrelevant. The results over both extents demonstrates that the volumetric impacts of drivers can deviate from their area and the importance of incorporating depth and volume variations in examining their impacts on the carbon store in peatland complexes and domed subclasses (*e.g.* raised bogs) (Gorham, 1991; Joosten and Clarke, 2002).

8.3.3 Broader applications of volumetric reconstruction

The data limitations that applied to Alfred Bog’s volumetric reconstruction are not specific to the case-study, but apply to many other domed peatlands. Using the methods applied in the case-study (*i.e.* extrapolating relation between peat depths and distance from the peatland boundaries) the pre-disturbance volumetric distribution of other domed peatlands could be estimated with relatively limited depth samples. These methods would be most valuable for many sites in southern Canada, where anthropogenic disturbances precede the earliest peat depth and peatland surveys, or acquisition of air photos.

An early repository of peatland records in Canada is the Peat Bog Investigations by the Department of Mines (1908-1914). The investigations created maps with depth samples of 74 peatlands and tabulated the total volumes, area and dry weight of peat of many others in southern Canada. Using these sources and the applied methods in the case-study could help develop a regional record of the pre-disturbance peatland distribution by both area and volume and their reduction with disturbances examined. Such a record would have diverse academic and applied uses, with the potential to be used to establish realistic baselines for ES scenarios, assess the efficacy of past resource management and land-use policies and

identify common effects of anthropogenic drivers on the supply of peatland ESs between sites.

8.4 Summary

Although the efforts involved in compiling and interpreting diverse data sources were considerable, the high spatial resolution record of Alfred Bog's changes over the past two centuries, from its pre-disturbance to present exploited state, is a novel contribution to both peatland ES studies and the regional land-use record. The applied assumptions and methods to interpret sources could be modified and extended in other historical peatland analyses. The case-study data may be reused for comparison or as a sample in other historical studies on peatland exploitation and ES changes. Further, the use of the delineated land-cover maps, as well as the digitized and georeferenced data extend well beyond the case-study. For example, the historical air photo mosaics and PLS field note transcriptions have multi-disciplinary research applications and can be reused in future studies, as could compiled records of peat production and regional farmland trends.

9 Chapter: Conclusions

The historical case-study at Alfred Bog demonstrates the importance of multidimensional and temporal analyses in examining anthropogenic impacts on ES supply within domed peatlands. The historical case-study at Alfred Bog demonstrates the importance of multidimensional and temporal analyses in examining anthropogenic impacts on ES supply within domed peatlands. A novel feature of this study was the combination of additional spatial parameters (volume and depth profile in addition to area) with an extended temporal analysis, namely over 200+ years. Historical peatland studies tend to cover 50 to 70 years, generally the length of the air photo record, and tend to be limited to areal data. This combined spatial and temporal information provided a comprehensive foundation to assess ES supply and trade-offs with disturbances at Alfred Bog, an approach that could be extended to other domed peatlands, and potentially other sub-classes and sites.

The divergence in area versus volume, in both the impacts of specific drivers and the peatland's reduction, showed that their relation varied spatially across the depth profile. This was demonstrated by their trends in each examined date and over the 200-year study. Changes in volume and the supply of associated ESs could not be inferred through areal proxies alone. Disturbances of similar extents yielded different volumetric impacts. Cumulatively, over half Alfred Bog's original volume and carbon store remained intact in less than half of its pre-disturbance area. Thus, including spatial variations in peat depths and volume enables a more thorough analysis of ES supply dynamics with disturbances in domed peatlands than examining area alone. Further, considering the variations of these parameters (depth and volume distribution) within other subclasses and sites may be

beneficial in evaluating their potential for divergence in area versus volume, as well as the suitability of applied proxies to capture ES supply changes.

In addition to the spatial considerations, Alfred Bog's incremental reduction underscores that temporal variations in divergence and the response of ESs can also be important. Although exploitation covered a larger area in the 19th century and potentially spurred greater changes in area-based ESs such as carbon sequestration, erosion control and habitat support, losses in volume-based ESs such as water and carbon storage were greater in the 20th century. Shorter intervals, as shown by the 11 examined dates, are necessary to capture these changes. Further, the shorter intervals helped identify influential factors affecting specific drivers (*e.g.* zoning, market values and techniques) and broader disturbances (*e.g.* mechanization and commercialization of exploitation or increased conservation awareness in mid and late 20th century respectively) over time. In domed peatlands, where exploitation over decades and centuries is common, such factors may fundamentally alter their relationships with ESs. The effects of disturbances on ES supply are unlikely to be static or transferable over such extensive periods.

Given the shorter operational timeframe of drivers compared to the entire duration of Alfred Bog's exploitation, shorter intervals were essential to differentiate the impacts of multiple drivers on the peatland's reduction and changes in ES supply. Consequently, establishing trends using only the pre-disturbance and present conditions not only precludes temporal analysis of changes, but can misrepresent the impacts of specific drivers (*e.g.* misclassifying and by extension underestimating 'Commercial Peat Extraction' sites that were converted to 'Farmland' as 'Direct Farmland Conversion'). Therefore, in domed peatlands that were incrementally exploited by multiple drivers, finer temporal intervals

between maps (ideally match the minimum operational timeframe of examined drivers) are necessary to distinguish their effects on ES supply.

Individual drivers were distinct in their effects on ecosystem reduction and ES supply (*i.e.* spatial distribution, magnitude of areal versus volumetric divergence, average depths and volumetric impacts per hectare), both in each examined date and cumulatively, reflecting the value of their differentiation in ES studies. The exclusive spatial distributions and specific progressions of drivers relative to the depth profile resulted in their unique areal versus volumetric divergence and effects on ES supply. The similar impacts of the two main drivers on peat volume and the carbon store compared to their differing areal extents exemplifies this point. The finer spatial grain enabled the identification of their specific properties and impacts on ESs, something that is not interpretable from their aggregate impacts alone. Further, the examination of CSUs indicated there is a potential for interactions from the concurrent operation of multiple drivers, which may also be relevant in examining ecosystem reduction and changes in ES supply over longer timeframes. Thus, a driver-specific examination can improve understanding the diverse effects of different societal pressures on peatlands and their ES supply.

The historical case-study at Alfred Bog epitomizes the cumulative effects of incremental anthropogenic exploitation in peatlands. Although the ecological impacts of individual drivers in any one date were minimal, their combined impacts led to the substantial reduction of Alfred Bog and its ES supply over the 200-year study. Further, these trends are exemplary of the effects of recurrent incremental disturbances, which has led to the irreparable exploitation of most peatlands in southern Canada. As industrial

development pressures increase in boreal regions, where the majority of pristine peatlands are located, it is critical to avoid repeating these historical trends.

The multi-dimensional analysis allows a more informed weighing of the cumulative losses in ESs and long-term effects on both environmental quality and global climate versus the immediate social and economic benefits gained through exploitation. Presenting peatlands through an ES approach emphasizes their numerous benefits to human well-being, as well as the irreversible and unbalanced trade-offs with their exploitation. In addition to the supply of direct ESs, which are often the main focus in regional studies and assessments, including the cumulative trade-offs in broader and indirect ESs, specifically the moderating climatic effects of the carbon pool and its release with disturbances in this case-study, are also necessary considerations with recurrent incremental exploitation. Multidimensional analyses, as presented in the case-study, will help to assess the integrated supply of ESs in domed peatlands and their spatially and temporally varied responses to disturbances in future peatland ESs studies.

Appendices

Appendix A - Case-Study Sources: Interpreting and Mapping Land-Cover Changes

A.1 Historical maps

#	Creator	Year	Scale	Content
1	Fortune, Joseph ¹	1807	1:47 520	Caledonia Township
2	Fortune, Joseph ¹	1816	1:63 360	Alfred and N. Plantagenet Townships
3	Browne, William ¹	1820	1:31 680	Alfred Township
4	Cattanach, Angus ¹	1829	1:31 680	Caledonia Township
5	Hamilton, Robert ¹	1856	1:15 840	Proulx clearance in Alfred Township
6	McConnell, William ¹	1858	1:31 680	Concessions 9-11, Alfred Township
7	Walling, Henry Francis ²	1862	1:63 360	Prescott and Russell Counties. Occupied lots listed.
8	H. Belden and Co.	1881	1:63 360	Township maps for Prescott County. Occupied lots listed.
9	Anrep, A. and E. Nyström ²	1909	1:316 800	Alfred Peat Bog (northern domes of complex)
10	Department of Scientific and Industrial Research (UK) (Fig. 32, between p. 70-71)	1923	1:22 500	Sketch of experimental fuel site at Alfred Bog
11	Lloyd, F.	1923	1:162 000	United Counties of Prescott and Russell's transportation network
12	Haanel, B., p.96	1926	1:22 500	Sketch of experimental fuel site at Alfred Bog
13	Fraser , p. 64-65, 67, 69, 71	1976	1:50 000	Mineral resource survey maps for townships in Prescott County
14	Bird and Hale, p.13	1984	1:63 360	Historic and present peatland boundaries (1829, 1909, 1984)
15	Bird and Hale, p. 95	1984	1:10 000	Detailed map of drainage ditches and southern dome's boundaries
16	Mosquin, T., p.5	1991	1:50 000	Historic and present peatland boundaries (1800 and 1991)

¹ Accessed from OMNR, Crown Land Surveys, Office of the Surveyor General.

² Accessed in Maps, Data and Government Information Centre (MADGIC), MacOdrum Library, Carleton University.

A.2 Historical air photos

Historical air photos used in mapping at Alfred Bog, listed by year, roll number and photo number. Sources include the original creator and the site where they were accessed. (SNC – South Nation Conservation; Ottawa U – University of Ottawa).

Note: OMNR's digital orthorectified imagery, used for the maps in 2008 and 2014, had a spatial resolution of 50 cm.

#	Year	Scale	Roll #	Photo No.	Source
1	1927	1:15000	HA149	8-18	NAPL
2	1927	1:15000	HA239	77-92	NAPL
3	1928	1:15000	A39	14-26, 76-88	NAPL
4	1928	1:15000	A40	61-75	NAPL
5	1946	1:15000	A10321	109-117	NAPL, Ottawa U
6	1946	1:15000	A10371	76-83	NAPL, SNC
7	1947	1:15000	1215	85-91, 97-110	Dep't of Planning, SNC
8	1947	1:15000	1217	45-56, 96-109	Dep't of Planning, SNC
9	1947	1:15000	1219	35-55, 84-109	Dep't of Planning, SNC
10	1947	1:15000	1221	50-60, 95-109	Dep't of Planning, SNC
11	1954	1:70000	A14526	18-20, 47-50	NAPL, Ottawa U
12	1964	1:35000	A18360	85-92, 141-147, 187-191	NAPL, Ottawa U
13	1964	1:35000	A18638	19-25	NAPL, Ottawa U
14	1969	1:15000	A30177	60-77	NAPL, Ottawa U
15	1969	1:15000	A30178	51-60, 62-63, 66-70	NAPL, Ottawa U
16	1969	1:15000	A30179	52-73	NAPL, Ottawa U
17	1978	1:5000	CAS79125	107-137	OMNR, SNC
18	1978	1:5000	CAS79126	1-32, 111-144	OMNR, SNC
19	1978	1:5000	CAS79127	01-39, 153-188	OMNR, SNC
20	1978	1:5000	CAS79128	01-30	OMNR, SNC
21	1978	1:5000	CAS79130	26-62	OMNR, SNC
22	1991	1:10000	4530	148-168	OMNR, SNC
23	1991	1:10000	4531	01-08, 66-80	OMNR, SNC
24	1991	1:10000	4532	80-97	OMNR, SNC
25	1991	1:10000	4533	16-32	OMNR, SNC
26	1991	1:10000	4534	54-60, 142-153	OMNR, SNC
27	1991	1:10000	4535	38-48	OMNR, SNC
28	1994	1:50000	A28048	11-12, 57	NAPL

A.3 Provincial Land Surveyors' field notes

Accessed through OMNR, Crown Land Surveys, Office of the Surveyor General.

#	Creator	Year	Township	Coverage
1	J. Fortune	1806	Caledonia	Concessions 1 – 4, 7 – 11
2	A. Cattanach	1828	Caledonia	Concessions 3 – 6
3	D. McDonell	1835	Boundary	Line between Alfred, Caledonia and Longueuil
4	R. Hamilton	1854	Boundary	Line between Alfred, Caledonia and Longueuil
5	W. McConnell	1858	Alfred	Concessions 9 – 11

A.4 Reports (governmental, non-governmental and private)

#	Creator(s)	Year	Content
1	Anrep and Nyström (Canadian Department of Mines [DOM])	1909	Describes site conditions and preparation for peat fuel tests (e.g. drainage, surface levelling, rail and buildings).
2	Anrep (DOM)	1910	Describes 1 st season of government peat fuel tests.
3	Anrep (DOM)	1911	Describes 2 nd operating season of peat fuel tests.
4	Anrep (DOM)	1915	Brief summary of peat fuel tests,
5	Haanel (DOM)	1919	Idle in 1918, machinery delays (p.187-192)
6	Haanel (DOM)	1920	Peat fuel tests operations in 1919. (p.142-156)
7	Haanel (DOM)	1921	Peat fuel tests operations in 1920. (p.167-170)
8	Haanel (DOM)	1922	Peat fuel tests in 1922. Detailed report on plants and machinery, as well as fire (p.1-30).
9	Department of Scientific and Industrial Research (UK)	1922	Detailed report on production methods, processes and machinery used at Alfred (Appendix 2).
10	Haanel (DOM)	1926	Detailed summary of peat fuel tests at Alfred (Chapter 7).
11	Leverin (DOM)	1944	Brief update on extraction at Alfred Bog.
12	Richardson (Ontario Department of Planning and Development)	1948	Detailed examination of landscape changes since 1800s, current land-uses and conditions. Makes recommendations to improve land management.
13	Bird and Hale	1984	Examines conditions and feasibility of commercial extraction of a property in Alfred's southern dome. Briefly discuss historical disturbances.
14	T. Mosquin	1991	Detailed survey of Alfred Bog's ecological and hydrological conditions. Also examines historical changes and pre-disturbance conditions.
15	ECO	2005	Detailed examination of legislative battles between extractors and conservationists at Alfred Bog. Discusses peatland policy and regulatory gaps.
16	F. Pope and OFNC	2008	Major actors and events in conservation.

A.5 Newspaper articles

Newspaper articles used to establish historical events and public perception surrounding Alfred Bog's exploitation. The general shift in perception from the material and commercial benefits of exploitation in the early 1900s to its conservation benefits by the late 1980s is apparent in the titles. All articles were accessed through the MacOdrum Library and ProQuest Historical Newspapers databases.

#	Author	Date	Newspaper	Title
1	Unlisted	1899, February 25 th	Globe and Mail	Peat Fuel - Recent Developments in Canada's New Industry - Bogs of Ontario - Some of the Reasons Why Peat is Expected to Replace Coal
2	Op. Ed	1920, October 23 rd	Globe and Mail	Notes and Comments Section
3	Unlisted	1920, December 29 th	Globe and Mail	Experiments with Peat
4	Unlisted	1921, July 20 th	Globe and Mail	To End Tests of Peat Fuel: Premier Announces that Final Report of Alfred Experiments Expected - Problem of Transport
5	Unlisted	1922, June 30 th	Globe and Mail	Final Peat Report Expected This Year: Royal Commission Has Nearly Completed Experimental Work
6	Op. Ed	1922, September 1 st	Globe and Mail	Notes and Comments Section
7	Mears, F.	1922, September 12 th	Globe and Mail	Peat for Fuel, Real Prospect, Says Stewart
8	Unlisted	1922, December 14 th	Globe and Mail	Peat of Province Able to Compete with Foreign Coal
9	Unlisted	1923, November 3 rd	Globe and Mail	Will Peat as Fuel Yet Heat Ontario?
10	Smith, G.E.	1927, February 9 th	Globe and Mail	Ottawa Undertakes Distribution of Peat From Alfred Bog - Government Asks \$70000 for Year's Activities in Developing Business - Compete Against Coal
11	Henry, T.	1943, August 16 th	Globe and Mail	Data Production on Peat Fuel
12	Can. Press	1988, September 24 th	Globe and Mail	Environmental Group Seeks Aid for Bog Deal
13	Editorial	1999, August 31 st	Ottawa Citizen	Toughen Protection of Wetlands
14	Unlisted	2001, June 25 th	Ottawa Citizen	Alfred Bog is Worth Saving

Appendix B - Approximating Peat Production and Carbon Storage ESs

B.1 Peat production

The losses in peat volume considered in the case-study were drainage, surface levelling and a thin residual peat layer left at the completion of extraction. The proxies used to account for each of these losses, as well as the conversion to a weight measurement at 30% moisture, are described below.

1) Drainage:

Drains are installed both within and surrounding extraction sites. Perimeter ditches are connected to smaller field ditches spaced every 20 to 30 metres within. Using literature values and the configuration maps, averages of 20.8 m³ ha⁻¹ and 500 m³ ha⁻¹ were used to estimate the peat volume removed by perimeter and field ditches respectively (Monenco, 1981, p.47-49). They were multiplied by the area of 'Commercial Peat Extraction' in each date and their sum was subtracted from the volume under commercial production to quantify volumetric losses with drainage.

For perimeter ditches, Monenco (1981) indicates commercial extraction of a 20 km² bog necessitates roughly 19 km of perimeter ditches, with widths ranging from 1.5 to 2 metres and depths between 1 and 1.5 metres (p.127). Thus, the average volume (m³) removed for installing perimeter ditches per hectare (20.8 m³ ha⁻¹) was calculated as follows:

$$\begin{aligned} V &= l \times w \times h \\ &= 19000 \times 1.75 \times 1.25 \\ &= 41562.5 \text{ m}^3 \end{aligned}$$

$$\begin{aligned} \bar{x} \text{ m}^3 \text{ ha}^{-1} \text{ impact} &= V/A \\ &= 41562.5/2000 \\ &= \mathbf{20.8 \text{ m}^3 \text{ ha}^{-1}} \end{aligned}$$

For field ditches, Monenco (1981, p.49) suggests one hectare of peatland necessitates 500 metres of field ditches for extraction, with widths and depths of one metre. Thus, the peat loss associated with their installation is 500 m³ ha⁻¹. Sampling ($n=105$) the area of extraction fields and the length of their ditches at Alfred Bog using configurational land-cover maps and air photos corroborated this value, returning an average of 501 m³ ha⁻¹.

Year	<i>N</i>	$\bar{x}$ Volume (m ³)	$\bar{x}$ Area (ha)	$\bar{x}$ m ³ ha ⁻¹
1947	30	717	2.08	385
1964	15	1129	2.87	430
1991	15	864	1.78	569
2008	30	916	1.68	579
2014	15	1057	1.89	581

2) Clearing vegetation and surface levelling:

Surface levelling removes between 0.05 to 0.2 m of the uppermost peat layer (Monenco, 1981, p.127). With each point covering 100 m² and an average of 0.125 m removed in

levelling, a volumetric loss of 12.5 m³ was applied. Thus, the point count of 'Commercial Peat Extraction' was multiplied by 12.5 and subtracted from the volume under commercial production in each date.

3) Residual peat layer (post-extraction):

Commercial operations leave a layer of peat *in-situ* to avoid contaminating extraction machinery and peat products. Residual depths range between 0.3 and 1.0 m (Monenco, 1981, p.133). A value of 0.5 m or 50 m³ was used at Alfred Bog, since the underlying mineral soils were visible at many post-extraction sites in field visits, air photos and reports, suggesting extraction was only limited by undulations in the peat-substrate interface. This value was then multiplied by the point count of commercial peat extraction and subtracted from the volume under extraction.

4) Determining peat bulk density at 30% moisture

The final conversion determines the weight of peat (at 30% moisture) yielded from one cubic metre (m³) after air-drying, with commercial peat often containing 20% to 50% moisture (Monenco, 1981; Tarnocai, 1984). Using Values from the Final Report of the Joint Peat Fuel Committee at Alfred Bog determined that one cubic metre of peat would weigh 0.17 tonnes at 30% moisture (Haanel, 1926, p.127). This conversion was applied to the peat volume remaining after pre- and post-extraction losses to determine the weight of peat produced in each date.

The report specifically indicates that 187 ft³ of extracted are needed to produce 1 short ton of peat (Haanel, 1926, p.127).

$$187 \text{ ft}^3 = 1 \text{ short ton (30\% moisture)}$$

Unit Conversions	$1 \text{ ft}^3 = 0.028 \text{ m}^3$	$1 \text{ short ton} = 0.907 \text{ tonnes}$
	$187 \text{ ft}^3 = x \text{ m}^3$	
	$= 187 \times 0.028$	
	$= 5.295 \text{ m}^3$	

Weight (t) of peat at 30% moisture for 1 m³ of extracted peat:

$1 \text{ m}^3 = x \text{ tonnes}$	$5.295 \text{ m}^3 = 0.907 \text{ tonnes}$
$x/0.907 = 1/5.295$	
$x = 1/5.295 \times 0.907$	
$x = 0.171 \text{ tonnes}$	

B.2 Carbon storage

To determine the carbon stored in peat at Alfred Bog and its changes with exploitation, the dry bulk density and average (organic) carbon content were calculated from the proxies outlined below.

1) Peat's dry bulk density:

Monenco's (1981, p.17) average dry bulk density of peat for different humification rankings on the von Post scale was converted to ($\text{t}^{-1} \text{m}^3$) and multiplied by the corresponding percentage of Alfred Bog's peat profile occupied by that rank, as reported in Bird and Hale (1984a, p.22-23). The sum of these output values, after being divided by 100 was the weighted bulk density (**$0.09 \text{ t}^{-1} \text{m}^3$**), which was applied to determine the dry weight of peat and carbon stored remaining at Alfred in the 11 dates.

Dry Bulk Density for Humified Peat Layers (Monenco, 1981, p.17)			Site Depths of Humified Layers (Bird and Hale, 1984, p.22-23)		Weighted
Von Post Rank	kg m^3	t m^3	m	%	
H1	45	0.045	0.2	3.4	0.15
H2	60	0.060	0.2	3.4	0.20
H3	75	0.075	0.2	3.4	0.26
H4	90	0.090	4.0	81.6	7.35
H5	105	0.105	0.2	4.1	0.43
H6	120	0.120	0.2	4.1	0.49

2) Carbon content

The carbon density or percentage of the peat that is carbon at Alfred Bog was determined by averaging the reported carbon composition of Bird and Hale's (1984, p.62) peat samples ($n=25$). The resulting average (51.4%) was largely consistent with those reported at regional, provincial, national and global levels (Joosten and Clarke, 2002; Monenco, 1981; Tarnocai, 1984).

Appendix C - Sources for Broader Level Trends

C.1 Peatland distribution: Area, volume and carbon store

Sources that reported peatland area, volume and stored carbon at various administrative levels within Canada (¹Cited in Tarnocai, 1984, p.1; ²Cited in Warner *et al*, 2003, p.2). The source, administrative level, variable and reported values are listed.

Source	Variable	Value	Level
Tarnocai, 1984, p.7	Area	1.11×10^8 ha	National
Zoltai, 1980 ¹	Area	1.53×10^8 ha	National
Kivinen and Pakarinen, 1980 ¹	Area	1.70×10^8 ha	National
Tarnocai <i>et al</i> , 2000 ²	Area	1.22×10^8 ha	National
Gorham, 1991 ²	Area	1.19×10^8 ha	National
Tarnocai, 1984, p. 7	Area	2.25×10^7 ha	Provincial
Monenco, 1981, p.24	Area	2.59×10^7 ha	Provincial
Warner <i>et al</i> , 2003, p.2	Area	2.61×10^7 ha	Provincial
Monenco, 1981, p.24	Area	2.84×10^5 ha	Regional – S Ontario Lowlands
Riley, 1994, p.3	Area	3.88×10^5 ha	Regional – SE Ontario
Bird and Hale, 1984b, p.51	Area	1.84×10^4 ha	Regional – Ottawa-Brockville
Tarnocai, 1984, p.6	Volume	3.00×10^{12} m ³	National
Tarnocai, 1984, p.6	Volume	6.77×10^{11} m ³	Provincial
Monenco, 1981, p.24	Volume	7.70×10^9 m ³	Regional – S Ontario Lowlands
Riley, 1994, p.5	Volume	6.96×10^9 m ³	Regional – SE Ontario
Riley, 1994, p.39	Volume	2.44×10^9 m ³	Regional – Ottawa-Brockville
Tarnocai, 1984, p.7	Dry Weight	3.35×10^{11} t	National
Tarnocai, 1984, p.7	Dry Weight	7.71×10^{10} t	Provincial
Tarnocai, 2009, p.459	Carbon	1.47×10^{11} t	National
Tarnocai <i>et al</i> , 2000 ²	Carbon	1.56×10^{11} t	National
Gorham, 1991 ²	Carbon	1.52×10^{11} t	National
Warner <i>et al</i> , 2003, p.2	Carbon	2.51×10^{10} t	Provincial

C.2 Drivers of peatland reduction

Sources used to derive the areal impacts of anthropogenic drivers on past peatland disturbances, both in other peatlands and at broader levels, as depicted in Figure 7-1 and Figure 7-2. The examined timespan, drivers and spatial extent are listed for each source, as well as their reporting units.

#	Source	Timespan	Drivers	Units	Level
1	Joosten and Clarke, 2002, p.33	Pre-disturbance - Publication	Agriculture, Forestry, Peat Extraction, Urbanization, Inundation, and Other	Area and Percent	Global (non-tropical)
2	Hebda <i>et al</i> , 2000, p. 144	Pre-disturbance - Publication	Abandoned Railway Line ¹ , Cultivation, Fire ¹ , Forestry, Land-Clearing, Land-Fill ¹ , Peat Extraction, Roads ¹ , and Drainage	Area and Percent	Burns Bog, BC
3	Keys, 1991, p.14	Pre-disturbance - Publication	Reservoir Flooding, Forestry, Urban Expansion, Peat Harvesting, Ports and Harbours ¹ , Agricultural Impacts	Percent	National (Canada)
4	Poulin <i>et al</i> , 2004, p.334	Pre-disturbance - Publication	Total Peatland Area, Total Peatland Losses, Hydroelectric Production, Agriculture, Peat Extraction, and Protected Peatland	Area	Provincial (QB, NB)
5	Pellerin, 2003, p.19	1929-2000	Peat Extraction (Horticulture), Forestry, Agriculture, Power lines ¹ , Land-Fill ¹ , Urbanization, Drainage, and Roads ¹	Area and Percent	Regional – Part of St. Lawrence Lowlands in Québec
6	Joosten and Clarke, 2002, p.207	Pre-disturbance - Publication	Pristine, Agriculture, Urban and Hydro ¹ , Forestry, and Peat Extraction	Percent	Canada

¹ Classified as 'Other' to compile and compare drivers.

C.3 Censuses of Agriculture: Farmland and food production trends

Census of Agriculture records and variables used to examine food production at Alfred Bog. Censuses were accessed at Carleton's MacOdrum Library and through online archives ([archive.org](#), [CHASS](#) and [ODESI](#)). Digitized data was used where available (e.g. Beyond 2020 or .csv files). The specific records used in inferring the changing value of farmland per hectare (Table 3-2) at Alfred Bog are listed in the table on p.158.

Year(s)	Creator	Variables	Level
1851-1861	Board of Registration and Statistics	Number of Farms, Area of Farms (Total and Improved), Cash Value of Farm in Dollars and of Farm Implements.	Municipal, Country
1871-1966	Dominion Bureau of Statistics	Number of Farms, Area of Farms (Occupied Lands, Improved Lands), Farm Values (Total Value, Value of Land and Buildings, Value of Machinery and Equipment)	Municipal, Country
1971-2011	Statistics Canada	Number of Farms, Area of Farms (Total, Improved), Value (Farm Capital, Land and Buildings, Machinery and Equipment)	Municipal, Country

Year(s)	Table	Variables	Level
1861 (p.60-61)	11	“Occupiers of Lands” – Total, “Lands in Acres” - Amount Held, “Values” - Cash Value of Farm in Dollars, Cash Value of Implements	Municipal - County
1911 , p.82-83	2	“Number of Occupiers of Land” - Total, “Acres of Land” - Total Occupied Land, Improved	Municipal - County
1911 p.362-363	9	Land Owned, Rent of Lands and Buildings, and Farm Implements and Total Grain Value	County
1921 , p.116	79	“Farm Values” – Lands, Buildings, Implements and Machinery	County
1921 , p.238-239	81	“Number of Occupiers of Farms” - Total, “Area of Occupied Farms” - Total Occupied Land, Total Improved	Municipal - County
1931 , p. 32	22	“Farm Values” – Total, Land, Building, Implements and Machinery	County
1931 , p.126-127	37	“Occupiers of Land” – Total, “Condition of Occupied Land” -Total Occupied Lands, Total Improved Lands	Municipal - County
1951 , p.29.16 – 29.18	29	“Farm Operators” – Total, “Area of Occupied Farm Land” – Total, “Condition of occupied farm land” - Total Improved Lands	Municipal - County
1951 , p.30.17-30.18	30	“Farm Values” – Total, Land and Buildings, Implements and Machinery, “Size of Farm” – All Occupied Farms	Municipal - County
1961 , p.28.17	28	“Operators” – Total, “Area of All Farmland” - Total	Municipal - County
1991	1	Total Area of Farms	Municipal - County
1991	2	Total Value of Land and Buildings, Total Farm Machinery and Equipment, Total Farm Capital, Total Number of Farms	Municipal - County
2001	3	Total Farm Area	County
2001	4	Total Farm Capital, Value of Land and Buildings, Value of Farm Machinery and Equipment	County
2011	004-0203	Total Farm Area, Farms Reporting	County
2011	004-0234	Total Farm capital, Land and Buildings, Farm Machinery and Equipment	County

Note: Census of Agriculture data after 1971 was largely accessed through ODESI, under Farm Data and Farm Operator Data.

¹ Operating arrangements, Land Use and Land Management Practices, 1991

² Farm Machinery and Personal Computers, Farm Capital, 1991

³ Land use, greenhouses, land managements, 2001

⁴ Capital, expenses, sales, product type, labour, 2001

C.4 Mining reports: Peat production trends

Sources were used to compile an annual time-series on the provincial and national peat production trends, specifically the weight (prior to 1976 - in short tons, metric tons thereafter) and value of extracted peat. The year of publication, years reported, as well as administrative level at which trends were recorded are reported in the table below.

Creator	Year	Years Reported	Level
Dominion Bureau of Statistics (p.56, 60, 90-91)	1957	1900-1956	Canada and Ontario
Ontario Department of Mines (p. 6)	1963	1956-1960	Ontario
Ontario Department of Mines (p. 5)	1968	1961-1965	Ontario
Ontario Department of Mines and Northern Affairs (p.20-21)	1971	1964-1969	Ontario
Statistics Canada	Undated	1941-1975	Canada
Statistics Canada ¹	1977	1960-1977	Canada and Ontario
Statistics Canada ¹	1978	1975-1976	Canada
Monenco Ontario Ltd (p.115)	1981	1976-1980	Ontario
OMAFRA (p.4)	1986	1978-1985	Canada and Ontario
Keys, 1992 (p.10)	1990	1986-1990	Canada
Energy, Mines and Resources Canada (p.8) ²	1993	1990-1992	Canada
Natural Resources Canada_(p.5) ²	1995	1993-1995	Canada
Natural Resources Canada_(p.7) ²	1997	1996-1997	Canada
Natural Resources Canada_(p.4) ²	2001	1998-2001	Canada
Natural Resources Canada_(p.4) ²	2003	2001-2003	Canada
Mining Association of Canada (p.62)	2008	2005-2007	Canada
Mining Association of Canada (p.105)	2011	2007-2010	Canada
Mining Association of Canada (p.98)	2015	2008-2014	Canada

¹ Physical sources accessed in MADGIC, MacOdrum Library, Carleton University.

² Data was compiled from Statistical Reports in the Canadian Minerals Yearbooks series, available through an archived NRCan website.

Appendix D - Configurational Land-Cover Maps (1800-2014)

Alfred Bog - 1800

Alfred Bog - 1806-1820

Land-Cover Classification

Peatland	Forest
Cleared Lands	Roads
Farmland	Structures
Peat Extraction	Water

Composition

A horizontal scale bar with alternating black and white segments. Above the bar are numerical markers at 0, 0.5, 1, 2, 3, and 4. The word "Kilometers" is written at the right end of the bar.

Alfred Bog - 1830-1860

0 0.5 1 2 3 4 Kilometers

Alfred Bog - 1880

Alfred Bog - 1909

N

Alfred Bog - 1928

Alfred Bog - 1947

N

0 0.5 1 2 3 4 Kilometers

Alfred Bog - 1964

0 0.5 1 2 3 4 Kilometers

Alfred Bog - 1991

0 0.5 1 2 3 4 Kilometers

Alfred Bog - 2008

N

0 0.5 1 2 3 4 Kilometers

Land-Cover Classification

Peatland	Forest
Cleared Lands	Roads
Farmland	Structures
Peat Extraction	Water
Other	

Composition

Alfred Bog - 2014

0 0.5 1 2 3 4 Kilometers

Land-Cover Classification

Peatland		Forest
Cleared Lands		Roads
Farmland		Structures
Peat Extraction		Water
Other		

Composition

Appendix E - Case-Study Results

E.1 Alfred Bog's areal and volumetric reduction

The remaining peatland and reduction rates for area and volume in the 11 dates, as depicted in Figure 4-3 and Figure 4-4, are shown for the 'Entire Complex' (Top) and 'Domed' sites (Bottom). They are expressed in their units and as percentages to facilitate their comparison.

Note: With the exception of volumetric impacts per unit area, these values include the delayed volumetric impacts of Peat Extraction after 1909.

Year	Area (ha)				Volume (m ³)				
	Remaining		Reduction Rate		Remaining		Reduction Rate		m ³ ha ⁻¹
	ha	%	ha ⁻¹ yr ⁻¹	% yr ⁻¹	m ³	%	m ³ yr ⁻¹	% yr ⁻¹	
1800	1.11×10^4	100.0	0	0.00	2.34×10^8	100.0	0.00×10^0	0.00	0
1820	1.02×10^4	92.1	44	0.40	2.31×10^8	98.9	1.32×10^5	0.06	3.00×10^3
1860	7.32×10^3	65.9	73	0.65	2.23×10^8	95.1	2.22×10^5	0.09	3.05×10^3
1880	6.95×10^3	62.5	19	0.17	2.17×10^8	92.7	2.84×10^5	0.12	1.52×10^4
1909	6.23×10^3	56.1	25	0.22	2.02×10^8	86.2	5.22×10^5	0.22	2.10×10^4
1928	5.55×10^3	50.0	36	0.32	1.88×10^8	80.2	7.40×10^5	0.32	2.31×10^4
1947	4.86×10^3	43.7	36	0.33	1.78×10^8	76.2	4.92×10^5	0.21	2.35×10^4
1964	4.22×10^3	38.0	37	0.34	1.63×10^8	69.5	9.23×10^5	0.39	3.00×10^4
1991	3.96×10^3	35.7	10	0.09	1.51×10^8	64.7	4.19×10^5	0.18	2.52×10^4
2008	3.64×10^3	32.7	19	0.17	1.42×10^8	60.6	5.52×10^5	0.24	2.81×10^4
2014	3.50×10^3	31.5	23	0.20	1.38×10^8	58.9	6.72×10^5	0.29	2.49×10^4
2030	3.50×10^3	31.5	0	0.00	1.32×10^8	56.2	3.94×10^5	0.17	N/A

Year	ha	%	ha ⁻¹ yr ⁻¹	% yr ⁻¹	m ³	%	m ³ yr ⁻¹	% yr ⁻¹	m ³ ha ⁻¹
1860	7.26×10^3	100.0	0	0.00	2.22×10^8	100.0	0.00×10^0	0.00	0
1880	6.89×10^3	94.8	19	0.26	2.17×10^8	97.4	2.84×10^5	0.13	1.76×10^4
1909	6.18×10^3	85.1	24	0.34	2.02×10^8	90.7	5.16×10^5	0.23	2.10×10^4
1928	5.50×10^3	75.8	36	0.49	1.88×10^8	84.4	7.40×10^5	0.33	2.31×10^4
1947	4.84×10^3	66.6	35	0.48	1.78×10^8	80.2	4.92×10^5	0.22	2.35×10^4
1964	4.21×10^3	58.0	37	0.51	1.63×10^8	73.1	9.23×10^5	0.41	3.00×10^4
1991	3.96×10^3	54.5	9	0.13	1.51×10^8	68.0	4.19×10^5	0.19	2.51×10^4
2008	3.64×10^3	50.0	19	0.26	1.42×10^8	63.8	5.52×10^5	0.25	2.81×10^4
2014	3.50×10^3	48.2	23	0.31	1.38×10^8	62.0	6.72×10^5	0.30	2.49×10^4
2030	3.50×10^3	48.2	0	0.00	1.32×10^8	59.2	3.94×10^5	0.18	N/A

E.2 Changes in landscape composition

The changing area, both in hectares (top) and as a percentage of the study site (bottom), occupied by different land-cover classes in the 11 maps. Changes in landscape composition are graphed in Figure 5-2 and Figure 5-3.

Class	Years										
	1800	1820	1860	1880	1909	1928	1947	1964	1991	2008	2014
Peatland	11110	10208	7257	6864	6164	5481	4814	4195	3954	3654	3499
Cleared Lands	0	841	2103	553	321	598	421	160	114	101	104
Farmland	0	13	1605	3513	4394	4567	4824	5325	5590	5842	5888
Peat Extraction	0	0	0	0	2	172	767	959	612	556	553
Forest	0	22	73	99	117	151	129	308	625	650	680
Other	0	26	118	121	143	147	154	166	200	294	354
Water	99	99	32	32	26	38	41	37	56	61	67
Roads	0	0	19	28	42	47	51	50	51	51	51
Structures	NA	NA	NA	NA	NA	8	8	9	8	9	9

Class	Years										
	1800	1820	1860	1880	1909	1928	1947	1964	1991	2008	2014
Peatland	99.1	91.1	64.7	61.2	55.0	48.9	42.9	37.4	35.3	32.5	31.3
Cleared Lands	0.0	7.5	18.8	4.9	2.9	5.3	3.8	1.4	1.0	0.9	0.9
Farmland	0.0	0.1	14.3	31.3	39.2	40.7	43.0	47.5	49.9	52.1	52.5
Peat Extraction	0.0	0.0	0.0	0.0	0.0	1.5	6.8	8.6	5.5	5.0	4.9
Forest	0.0	0.2	0.6	0.9	1.0	1.4	1.1	2.7	5.6	5.8	6.1
Other	0.0	0.2	1.1	1.1	1.3	1.3	1.4	1.5	1.8	2.6	3.2
Water	0.9	0.9	0.3	0.3	0.2	0.3	0.4	0.3	0.5	0.5	0.6
Roads	0.0	0.0	0.2	0.2	0.4	0.4	0.5	0.4	0.5	0.5	0.5
Structures	NA	NA	NA	NA	NA	0.1	0.1	0.1	0.1	0.1	0.1

E.3 Areal impacts of drivers (ha⁻¹)

Impacts are shown as a percentage of the pre-disturbance area in brackets (Top - EC, Bottom - DS). Impact rates were derived from these values, but are not included due to space limitations. These results are graphed in Figure 5-5 and Figure 5-6.

Drivers	Years										Total
	1820	1860	1880	1909	1928	1947	1964	1991	2008	2014	
Direct Conversion	855 (7.7)	2796 (25.2)	357 (3.2)	686 (6.2)	463 (4.2)	109 (1.0)	153 (1.4)	70 (0.6)	20 (0.2)	N/A	5510 (49.6)
Peat Extraction	N/A	N/A	N/A	2 (0.0)	164 (1.5)	574 (5.2)	318 (2.9)	169 (1.5)	272 (2.4)	93 (0.8)	1592 (14.3)
Degraded Peatland	9 (0.1)	17 (0.2)	3 (0.0)	8 (0.1)	31 (0.3)	1 (0.0)	157 (1.4)	15 (0.1)	31 (0.3)	39 (0.4)	311 (2.8)
Other	16 (0.1)	78 (0.7)	4 (0.0)	10 (0.1)	5 (0.0)	3 (0.0)	4 (0.0)	6 (0.1)	3 (0.0)	4 (0.0)	132 (1.2)
Drainage	N/A	2 (0.0)	0 (0.0)	3 (0.0)	10 (0.1)	2 (0.0)	N/A	1 (0.0)	1 (0.0)	N/A	19 (0.2)
Transportation	N/A	17 (0.2)	9 (0.1)	12 (0.1)	5 (0.0)	3 (0.0)	1 (0.0)	0 (0.0)	N/A	N/A	47 (0.4)
Total	879 (7.9)	2910 (26.2)	372 (3.4)	720 (6.5)	680 (6.1)	692 (6.2)	633 (5.7)	262 (2.4)	327 (2.9)	136 (1.2)	7611 (68.5)

Drivers	Years									Total
	1860	1880	1909	1928	1947	1964	1991	2008	2014	
Direct Conversion	4 (0.1)	356 (4.9)	681 (9.4)	463 (6.4)	83 (1.1)	148 (2.0)	64 (0.9)	19 (0.3)	N/A	1819 (25.0)
Peat Extraction	N/A	N/A	2 (0.0)	164 (2.3)	574 (7.9)	318 (4.4)	169 (2.3)	272 (3.7)	94 (1.3)	1592 (21.9)
Degraded Peatland	N/A	3 (0.0)	8 (0.1)	31 (0.4)	1 (0.0)	157 (2.2)	15 (0.2)	31 (0.4)	39 (0.5)	285 (3.9)
Other	3 (0.0)	3 (0.0)	10 (0.1)	5 (0.1)	3 (0.0)	4 (0.1)	3 (0.0)	0 (0.0)	3 (0.0)	36 (0.5)
Drainage	0 (0.0)	N/A	3 (0.0)	4 (0.1)	2 (0.0)	N/A	1 (0.0)	1 (0.0)	N/A	12 (0.2)
Transportation	2 (0.0)	2 (0.0)	4 (0.1)	10 (0.1)	2 (0.0)	1 (0.0)	0 (0.0)	N/A	N/A	22 (0.3)
Total	10 (0.1)	365 (5.0)	708 (9.7)	678 (9.3)	665 (9.2)	628 (8.6)	253 (3.5)	323 (4.4)	136 (1.9)	3765 (51.8)

E.4 Volumetric impacts of drivers (m³)

Volumetric impacts of specific drivers, also expressed as percentages of the pre-disturbance total. Along with the areal impacts shown above, these results are graphed in Figure 5-5 and Figure 5-6. For convenience this table includes the volume of ‘Commercial Peat Extraction’ sites not yet exhausted by 2014 in its 2014 impacts.

Entire Complex

Drivers	Years										Total
	1820	1860	1880	1909	1928	1947	1964	1991	2008	2014	
Direct	2.56× 10 ⁶	8.43× 10 ⁶	5.55× 10 ⁶	1.47× 10 ⁷	1.07× 10 ⁷	2.29× 10 ⁶	3.84× 10 ⁶	1.96× 10 ⁶	3.74× 10 ⁵	N/A	5.03× 10 ⁷
Conversion	(1.1)	(3.6)	(2.4)	(6.2)	(4.6)	(1.0)	(1.6)	(0.8)	(0.2)		(21.5)
Peat	N/A	N/A	N/A	1.50× 10 ⁴	2.27× 10 ⁶	6.90× 10 ⁶	5.72× 10 ⁶	8.86× 10 ⁶	8.12× 10 ⁶	9.40× 10 ⁶	4.13× 10 ⁷
Extraction				(0.0)	(1.0)	(2.9)	(2.4)	(3.8)	(3.5)	(4.0)	(17.6)
Degraded	2.58× 10 ⁴	5.24× 10 ⁴	3.10× 10 ⁴	1.72× 10 ⁵	5.37× 10 ⁵	1.33× 10 ⁴	5.96× 10 ⁶	4.16× 10 ⁵	8.37× 10 ⁵	8.76× 10 ⁵	8.92× 10 ⁶
Peatland	(0.0)	(0.0)	(0.0)	(0.1)	(0.2)	(0.0)	(2.5)	(0.2)	(0.4)	(0.4)	(3.8)
Other	4.8 × 10 ⁴	2.84× 10 ⁵	2.30× 10 ⁴	1.94× 10 ⁵	9.76× 10 ⁴	3.21× 10 ⁴	1.31× 10 ⁵	5.59× 10 ⁴	1.54× 10 ⁴	6.10× 10 ⁴	9.43× 10 ⁵
	(0.0)	(0.1)	(0.0)	(0.1)	(0.0)	(0.0)	(0.1)	(0.0)	(0.0)	(0.0)	(0.4)
Drainage	N/A	3.22× 10 ²	4.20× 10 ²	7.12× 10 ⁴	3.58× 10 ⁵	7.40× 10 ⁴	N/A	2.13× 10 ⁴	3.46× 10 ⁴	N/A	5.60× 10 ⁵
		(0.0)	(0.0)	(0.0)	(0.2)	(0.0)		(0.0)	(0.0)		(0.2)
Transport.	N/A	1.07× 10 ⁵	6.64× 10 ⁴	1.08× 10 ⁵	9.16× 10 ⁴	3.98× 10 ⁴	3.44× 10 ⁴	1.91× 10 ³	N/A	N/A	4.49× 10 ⁵
		(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)			(0.2)
Total	2.64× 10 ⁶	8.87× 10 ⁶	5.68× 10 ⁶	1.51× 10 ⁷	1.41× 10 ⁷	9.35× 10 ⁶	1.57× 10 ⁷	1.13× 10 ⁷	9.39× 10 ⁶	1.03× 10 ⁷	1.02× 10 ⁸
	(1.1)	(3.8)	(2.4)	(6.5)	(6.0)	(4.0)	(6.7)	(4.8)	(4.0)	(4.4)	(43.8)

Domed sites

Drivers	Years									Total
	1860	1880	1909	1928	1947	1964	1991	2008	2014	
Direct	6.19× 10 ⁴	5.45× 10 ⁶	1.46× 10 ⁷	1.07× 10 ⁷	2.21× 10 ⁶	3.82× 10 ⁶	1.94× 10 ⁶	3.69× 10 ⁵	N/A	3.91× 10 ⁷
Conversion	(0.0)	(2.4)	(6.6)	(4.8)	(1.0)	(1.7)	(0.9)	(0.2)		(17.6)
Peat	N/A	N/A	1.50× 10 ⁴	2.27× 10 ⁶	6.90× 10 ⁶	5.72× 10 ⁶	8.86× 10 ⁶	8.12× 10 ⁶	9.40× 10 ⁶	4.13× 10 ⁷
Extraction			(0.0)	(1.0)	(3.1)	(2.6)	(4.0)	(3.7)	(4.2)	(18.6)
Degraded	N/A	3.06× 10 ⁴	1.72× 10 ⁵	5.37× 10 ⁵	1.33× 10 ⁴	5.96× 10 ⁶	4.16× 10 ⁵	8.37× 10 ⁵	8.76× 10 ⁵	8.85× 10 ⁶
Peatland		(0.0)	(0.0)	(0.0)	(0.0)	(2.7)	(0.2)	(0.4)	(0.4)	(3.7)
Other	6.10× 10 ⁴	2.10× 10 ⁴	1.94× 10 ⁵	9.76× 10 ⁴	3.21× 10 ⁴	1.30× 10 ⁵	4.64× 10 ⁴	1.00× 10 ⁴	6.03× 10 ⁴	6.52× 10 ⁵
	(0.0)	(0.0)	(0.1)	(0.0)	(0.0)	(0.1)	(0.0)	(0.0)	(0.0)	(0.3)
Drainage	3.22× 10 ²	N/A	7.05× 10 ⁴	3.58× 10 ⁵	7.38× 10 ⁴	N/A	2.13× 10 ⁴	3.46× 10 ⁴	N/A	5.58× 10 ⁵
	(0.0)		(0.0)	(0.2)	(0.0)		(0.0)	(0.0)		(0.2)
Transportation	5.65× 10 ⁴	4.57× 10 ⁴	8.38× 10 ⁴	8.95× 10 ⁴	3.65× 10 ⁴	3.42× 10 ⁴	1.91× 10 ³	N/A	N/A	3.48× 10 ⁵
	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)			(0.2)
Total	1.80× 10 ⁶	5.54× 10 ⁶	1.51× 10 ⁷	1.40× 10 ⁷	9.27× 10 ⁶	1.57× 10 ⁷	1.13× 10 ⁷	9.38× 10 ⁶	1.03× 10 ⁷	9.08× 10 ⁷
	(0.1)	(2.5)	(6.7)	(6.1)	(4.2)	(7.0)	(5.1)	(4.2)	(4.6)	(40.5)

E.5 Volumetric impacts per unit area (m³ ha⁻¹)

The average volumetric impacts per hectare of drivers in the ‘Entire Complex’ (Top) and ‘Domed’ sites (Bottom).

Note: $\bar{x}_A$ represents the average of all drivers in each date, while $\bar{x}_C$ captures their averages over the 200-year study period. The lagged volumetric response to ‘Commercial Peat Extraction’ disturbances removed to calculate its volumetric impact per hectare.

Drivers	Years										$\bar{x}_C$
	1820	1860	1880	1909	1928	1947	1964	1991	2008	2014	
Direct Conversion	3.00×10^3	3.01×10^3	1.56×10^4	2.13×10^4	2.31×10^4	2.10×10^4	2.51×10^4	2.80×10^4	1.83×10^4	N/A	9.13×10^3
Peat Extraction	N/A	N/A	N/A	7.95×10^3	2.38×10^4	2.40×10^4	2.84×10^4	2.45×10^4	2.92×10^4	2.63×10^4	2.59×10^4
Degraded Peatland	3.01×10^3	3.00×10^3	1.10×10^4	2.23×10^4	1.71×10^4	1.98×10^4	3.81×10^4	2.70×10^4	2.67×10^4	2.25×10^4	2.88×10^4
Other	3.11×10^3	3.66×10^3	6.31×10^3	1.99×10^4	1.82×10^4	9.20×10^3	2.94×10^4	8.62×10^3	6.05×10^3	1.71×10^4	3.18×10^4
Drainage	N/A	1.65×10^2	2.47×10^3	2.78×10^4	3.51×10^4	4.13×10^4	N/A	2.20×10^4	3.85×10^4	N/A	3.18×10^4
Transportation	N/A	6.26×10^3	7.22×10^3	9.20×10^3	1.86×10^4	1.33×10^4	3.07×10^4	1.59×10^4	N/A	N/A	1.06×10^4
$\bar{x}_A$	3.00×10^3	3.05×10^3	1.52×10^4	2.10×10^4	2.31×10^4	2.35×10^4	3.00×10^4	2.52×10^4	2.81×10^4	2.49×10^4	1.35×10^4

Drivers	Years										$\bar{x}_C$
	1820	1860	1880	1909	1928	1947	1964	1991	2008	2014	
Direct Conversion	N/A	1.46×10^4	1.53×10^4	2.14×10^4	2.31×10^4	2.66×10^4	2.58×10^4	3.02×10^4	1.97×10^4	N/A	2.15×10^4
Peat Extraction	N/A	N/A	N/A	7.95×10^3	2.39×10^4	2.40×10^4	2.84×10^4	2.45×10^4	2.92×10^4	2.61×10^4	2.59×10^4
Degraded Peatland	N/A	N/A	1.08×10^4	2.23×10^4	1.71×10^4	1.98×10^4	3.81×10^4	2.70×10^4	2.67×10^4	2.25×10^4	3.11×10^4
Other	N/A	2.33×10^4	6.19×10^3	1.99×10^4	1.82×10^4	9.20×10^3	3.21×10^4	1.40×10^4	2.64×10^4	1.80×10^4	1.83×10^4
Drainage	N/A	9.46×10^2	N/A	2.07×10^4	8.54×10^4	4.24×10^4	N/A	2.20×10^4	4.17×10^4	N/A	4.85×10^4
Transportation	N/A	2.43×10^4	2.05×10^4	2.18×10^4	8.78×10^3	1.85×10^4	3.20×10^4	1.59×10^4	N/A	N/A	1.60×10^4
$\bar{x}_A$	N/A	1.89×10^4	1.52×10^4	2.13×10^4	2.31×10^4	2.43×10^4	3.03×10^4	2.60×10^4	2.84×10^4	2.49×10^4	2.41×10^4

E.6 Average depths of disturbances

The average depth of drivers in the ‘Entire Complex’ (Top) and ‘Domed’ sites (Bottom).

Note: $\bar{x}_A$ represents the average depths of all drivers in each date, while $\bar{x}_C$ represents their average depths over the 200-year study period.

The date in which maximum depths occur are bolded.

Drivers	Years										$\bar{x}_C$
	1820	1860	1880	1909	1928	1947	1964	1991	2008	2014	
Direct Conversion	0.3	0.3	1.6	2.1	2.3	2.1	2.5	2.8	1.8	N/A	0.9
Peat Extraction	N/A	N/A	N/A	0.8	2.4	2.4	2.8	2.5	2.9	2.6	2.6
Degraded Peatland	0.3	0.3	1.1	2.2	1.7	2.0	3.8	2.7	2.7	2.2	2.9
Other	0.3	0.4	0.6	1.9	1.8	0.9	3.0	0.9	0.7	1.7	0.7
Drainage	N/A	0.3	0.3	1.9	3.3	3.9	N/A	2.5	3.5	3.5	2.7
Transportation	N/A	0.6	0.7	0.9	1.9	1.3	3.1	1.5	N/A	N/A	0.9
$\bar{x}_A$	0.3	0.3	1.5	2.1	2.3	2.3	3.0	2.5	2.8	2.5	1.3

Drivers	Years										$\bar{x}_C$
	1820	1860	1880	1909	1928	1947	1964	1991	2008	2014	
Direct Conversion	N/A	1.5	1.7	2.1	2.3	2.7	2.6	3.0	2.0	N/A	2.2
Peat Extraction	N/A	N/A	N/A	0.8	2.4	2.4	2.8	2.5	2.9	2.6	2.6
Degraded Peatland	N/A	N/A	1.1	2.2	1.7	2.0	3.8	2.7	2.7	2.2	3.1
Other	N/A	2.3	0.8	2.0	1.8	0.9	3.3	1.4	2.6	1.8	1.9
Drainage	N/A	0.1	N/A	2.0	3.3	4.0	N/A	2.5	3.5	3.5	3.1
Transportation	N/A	2.4	2.0	2.2	2.1	2.0	3.3	1.5	N/A	N/A	2.2
$\bar{x}_A$	N/A	1.9	1.7	2.1	2.3	2.4	3.0	2.6	2.8	2.6	2.4

E.7 Magnitude of areal versus volumetric divergence (Δ_{A-V})

The areal versus volumetric divergence of individual drivers and the peatland's aggregate response in the 'Entire Complex' (Top) and 'Domed' sites (Bottom), determined by subtracting the volumetric percentages from those of area.

Drivers	Years										$\bar{x}_C$
	1820	1860	1880	1909	1928	1947	1964	1991	2008	2014	
Direct Conversion	6.6	21.6	0.8	-0.1	-0.4	0.0	-0.3	-0.2	0.0	0.0	28.1
Peat Extraction	0.0	0.0	0.0	0.0	0.5	2.2	0.4	-2.3	-1.0	-0.5	-3.3
Degraded Peatland	0.1	0.7	-0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.8
Other	0.0	0.0	0.0	0.0	0.1	-0.1	0.0	0.0	0.0	0.0	-0.1
Drainage	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Peatland*	-6.8	-29.2	-30.1	-30.1	-30.2	-32.5	-31.5	-29.0	-27.9	-24.7	-24.7

Drivers	Years									$\bar{x}_C$
	1860	1880	1909	1928	1947	1964	1991	2008	2014	
Direct Conversion	0.0	2.5	2.8	1.6	0.2	0.3	0.0	0.1	0.0	7.5
Peat Extraction	0.0	0.0	0.0	1.2	4.8	1.8	-1.7	0.1	-0.1	3.4
Degraded Peatland	0.0	0.0	0.1	0.4	0.0	-0.5	0.0	0.1	0.1	0.3
Other	0.0	0.0	0.1	0.1	0.0	0.0	0.0	-0.1	0.0	0.2
Drainage	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	-0.1
Transportation	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Peatland*	-0.1	-2.6	-5.6	-8.6	-13.6	-15.2	-13.5	-13.8	-13.8	-11.0

*Peatland trends show cumulative differences in area versus volume remaining over the 11 dates, while the trends of individual drivers show the divergence in each map (*i.e.* not cumulative).

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