Mapping Cumulative Threats and its Application to Canada

by

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Abstract

Methods for cumulative threat mapping, such as the human footprint, have been rapidly developing to inform the management of biodiversity and ecosystem services. Here, I perform the first comprehensive literature review establishing what methods are used, what threats are mapped and where, and if threats or impacts are mapped statically or dynamically in time. From knowledge gained in the review, I compiled geospatial datasets in a geographic information system to map the first Canadian human footprint. Subsequently, I answer where the most intact and heavily threatened areas are, what the most prevalent threats in Canada are and assess the accuracy of the data through a technical validation. This thesis contributes to conservation science by highlighting where regional studies are lacking, which threats are not being captured, providing examples of how studies have managed dynamic timescales and mapped through to impacts, and provides key information for future conservation in Canada.

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List of Acronyms

CBD: Convention on Biological Diversity

WWF: World Wildlife Fund

IUCN: International Union for the Conservation of Nature

SD: Standard Deviation

P-S-I: Pressures - State - Impact

CMP: Conservation Measures Partnership

COSEWIC: Committee on the Status of Endangered Wildlife in Canada

VIIRS: Visible Infrared Imaging Radiometer Suite

NOAA: National Oceanic and Atmospheric Administration

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1. INTRODUCTION

1.1 Context

The world is currently experiencing its sixth mass extinction of species (Butchart et al. 2010; Barnosky et al. 2011). This rapid loss of biodiversity is caused by habitat loss, overexploitation and the introduction of non-native species, where humans are ultimately the agents of this change. Global consensus that the loss of species must be addressed, led to the creation of the Convention on Biological Diversity (CBD) in 1992 (Convention on Biological Diversity 2020). This is the first and largest global agreement with a unified conservation goal to maintain ecosystems, species and genes for the long term.

As part of the CBD Strategic Plan for Biodiversity, the signatories agreed to 20 international targets for maintaining biodiversity and ecosystem services (i.e., Aichi Biodiversity Targets). Target 11 from the Strategic Plan for Biodiversity is to conserve 17% of terrestrial and inland waters, particularly areas of importance to biodiversity and ecosystem services that are integrated in the broader landscapes (Convention on Biological Diversity 2020). Now, the zero draft of the post-2020 global biodiversity framework includes a target of protecting "sites of particular importance for biodiversity through protected areas and other effective area-based conservation measures, by 2030 covering at least [60%] of such sites and at least [30%] of land and sea areas". To implement Target 11, and the more ambitious post-2020 framework, countries need to examine the current anthropogenic use of their lands, to support the evaluation of areas for conservation and management (Working Group on the Post-2020 Global Biodiversity Framework 2020). With 196 countries as signatories to the Aichi Targets, there is a need for the expansion of knowledge on what anthropogenic threats are present on the many landscapes where land conservation is being targeted.

1.2 Conservation and Managing Threats to Biodiversity

Conservation biology is a relatively young and developing field (Soulé 1985). However, the importance of conserving species from extinction is not a new idea. For example, Alfred Russel Wallace in 1863 made a call to scientists to become stewards for species diversity and to act responsibly for species diversity (Meine 2010). Systematic conservation planning provides a structured approach to prioritize areas and resources for protected areas that support the goals and values of the given project (Margules & Pressey 2000). A crucial step in systematic conservation planning is the need for the better understanding of patterns and the spread of threats to biodiversity (Margules & Pressey 2000). However, there remains a gap in our understanding of the nature and location of threats and how they interact across space, making their understanding important for harnessing systematic conservation planning to achieve conservation goals (Margules & Pressey 2000; Carwardine et al. 2019).

Measuring threats to biodiversity can help us to better assess conservation potential and risks (Theobald 2003). Mapping threats can aid in the identification of priority areas for conservation, highlighting where biodiversity is at risk with a transparent and replicable method (Tulloch et al. 2015). Such threat maps already exist for global forest loss (Hansen et al. 2013), agricultural expansion and associated water usage (Pfister et al. 2011) and urbanization effects on bird and plant diversity (Aronson et al. 2014). Single threat assessments do offer valuable information. However, understanding the temporal and spatial patterns of more than one threat can help us understand the intensity of human pressure and how threats are interacting across space, which will help focus conservation resources where they are most needed (Margules & Pressey 2000).

Single threat assessments fail to capture the multiple threats affecting biodiversity that can accumulate at a single location or across a landscape (Whitehead et al. 2016). Small threats when acting alone may not have a large impact, but when there are many of these small threats acting together, they could have a significant effect on biodiversity. As such, single threat assessments can lead to "death by a thousand cuts" (Whitehead et al. 2016). For example, often habitats experience sections being removed, therefore fragmenting the overall functioning habitat size (Laurance 2010). Habitat loss is a single threat that often interacts with other threats which can lead to a number of impacts on biodiversity (Burgman et al. 2007). Therefore, better understanding of the full extent of interacting threats can aid in mitigating loss of biodiversity and ecosystem services.

Cumulative threat mapping allows for the combination of more than one anthropogenic threat, quantifying the extent and intensity at multiple spatial and temporal scales (Tapia-Armijos et al. 2017). For example, cumulative threat mapping has been used to evaluate the effectiveness of protected areas over time for South Ecuador (Tapia-Armijos et al. 2017) and globally (Geldmann et al. 2014). The steps for producing a cumulative threat map include identifying core anthropogenic threats, obtaining spatial data to represent these threats, assigning scores to individual threats, then overlaying the layers together to create a cumulative threat map, sometimes referred to as a human footprint map (Watson & Venter 2019). Many different studies have used these methods to develop human footprint maps in different areas of the world (González-Abraham et al. 2015; Lin et al. 2016; Mann & Wright 2018). However, there is yet to be a comprehensive review identifying which threats are the main focus, the geographic locations or main practices of these studies.

The first global human footprint map found that 83% of the globe's terrestrial land was directly influenced by humans, which was previously unknown (Sanderson et al. 2002). The first product comparing the global human footprint from two different years has shown a 9% increase in the human footprint and highlights that pressures are increasing in places with high biodiversity (Venter et al. 2016a). Since the production of these global products, as data have become more available, studies have applied the human footprint to assess global loss of wilderness areas (Watson et al. 2016), prediction of extinction risk for mammal species (Di Marco et al. 2018) and changes in animal movement and behaviour (Tucker et al. 2018; Kühl et al. 2019), to give a few examples of applicability. With growing publications in the field, there have been reviews highlighting assumptions and challenges (Halpern & Fujita 2013), case studies of cumulative threat assessments (Foley et al. 2017) and a synopsis of history and capabilities of human footprint studies (Watson & Venter 2019). However, there has yet to be a synthesis of cumulative threat mapping locations, kind of threats mapped or main approaches which are important to understanding cumulative threats as drivers of biodiversity decline.

1.3 Canadian Context

Although global cumulative threat maps exist, Canada is not accurately represented (Venter et al. 2016a, 2016b) and has yet to have a product created for the country using national data. Canada is often considered as being full of wilderness (Henderson 1992). However, it is not immune to the global biodiversity crisis. The Living Planet Report Canada found that there has been an average decline of 59% in wildlife populations that have previously been assessed as "at-risk" by the Committee on the status of Endangered Wildlife in Canada (COSEWIC) from 1970 – 2016 (WWF Canada 2020). As of April of 2019, COSEWIC found that there were 799 species "at-risk" in Canada, 356 of which are classified as endangered (Government of Canada, Environment and Climate Change 2019).

The Aichi Targets from the CBD were adopted by Canada and reworked into the 2020

Biodiversity Goals and Targets for Canada. Target 1 of the goals and targets address Aichi target 11; to protect 17% of terrestrial and inland water (MacKinnon et al. 2015). As of December 2019, 12.1% of Canada's land and freshwater has been conserved (Indigenous Circle of Experts et al. n.d.). However, Canada has been criticized as the country seeks to meet numerical targets, without having the understanding of threats and quality of the protected areas for biodiversity and ecosystem services (Lemieux et al. 2019).

In 2019, the government of Canada committed to even stronger conservation targets including 25% of terrestrial and marine lands by 2025 and 30% by 2030 (Liberal Party of Canada 2019). As Canada has set these new targets to protect biodiversity and ecosystem services, it is important to understand the variety of threats occurring across the country. Canada is host to some of the world's largest freshwater reservoirs and sources, as well as intact swaths of the boreal forests (Shiklomanov & Rodda 2004; Laurance 2010; Coristine et al. 2019). As such, protecting biodiversity and ecosystem services within Canada will have global benefits, like carbon storage and climate regulation (Watson et al. 2016; Coristine et al. 2019).

The topic of cumulative threats has become more popular in the literature (Halpern & Fujita 2013). In Canada, there have been efforts to measure single threats (Lee & Cheng 2014) and multiple threats (Clarke Murray et al. 2015b; Shackelford et al. 2017). However, most of the studies have a more localized focus, assessing threats at a project level (Ban & Alder 2008; Sterling et al. 2014; Mann & Wright 2018) yet, no uniform product exists at the Canadian scale. Although the global human footprint (Venter et al. 2016a) has shown different types of threats at the global scale, it is still too coarse a resolution to understand anthropogenic threats nationally (Sanderson et al. 2002). Using local datasets, and including threats from the natural resource industry, to make a country-level assessment would provide greater clarity on where and what type of threats exist. In addition to providing a clearer understanding of the patterns and spread of anthropogenic threats to biodiversity and ecosystem services, a Canadian human footprint would present itself as a useful tool for government and non-government organizations to focus their conservation investments.

1.4 Thesis aim

In this thesis, I address two knowledge gaps to better understand the practice behind cumulative threat mapping and develop the first human footprint map for Canada. First, I review the growing field of cumulative threat mapping by assessing what is being published, how and where we are mapping anthropogenic threats. Second, I apply the information obtained from the comprehensive review to the Canadian context and use spatial analysis to address the patterns of anthropogenic threats within Canada.

I divided my thesis into four chapters including an Introduction (Chapter 1) and Concluding Remarks (Chapter 4). In Chapter 2 (A Review of Mapping Cumulative Threats, the Trends, the Gaps and the Future) I use a comprehensive literature review to question:

1. Which ecological realms (terrestrial, marine, freshwater) are studied most?
2. What are the different types of threats and which ones are most often mapped?
3. What are the geographical scales of the studies?
4. Are temporal dynamics taken into account and how?
5. Are threats or impacts most often mapped?

In chapter 3 (Canada's Human Footprint Reveals Large Wild Areas Juxtaposed Against Areas under Immense Anthropogenic Threat), I applied the knowledge obtained in chapter 2 to undertake spatial analyses to identify the patterns of anthropogenic threats across

Canada. Here, I address the following questions:

1. What areas are free of cumulative threats?
2. What areas of Canada are the most heavily threatened?
3. What are the most prevalent threats in Canada?

Chapter 4 is where I discuss the main findings and contributions of my research from chapter 2 and 3. I share emergent conclusions from the overall thesis and look at the implications of the findings, limitations and recommend future research directions.

2. A REVIEW OF MAPPING CUMULATIVE THREATS, THE TRENDS, THE GAPS AND THE FUTURE

Abstract: The loss of biodiversity is often caused by multiple interacting threats. To monitor and manage biodiversity declines, a variety of approaches have been developed to simultaneously map multiple threats and their cumulative impacts across space. Here, I provide the first standardized review of these approaches. Through a comprehensive literature review, I identified 65 peer-reviewed studies that reported spatial cumulative threat analyses in terrestrial (n = 30), marine (n = 26), freshwater (n = 7) and mixed realms (n = 2), recording where, how many and what kind of threats were studied. My results show that on average each study reported 8.6 (Standard Deviation (SD) = 7.6) threats, with freshwater studies including the greatest number (14.3, SD = 18.6) and terrestrial studies the least (6.3, SD = 2.4). Pollution was the most commonly mapped threat for the marine (n = 75) and freshwater (n = 65) realms and agriculture was the most mapped threat for the terrestrial realm (n = 39). Of the cumulative threat studies reviewed, few represented the impacts of mapped threats (n = 4). My results show a bias in the spatial distribution of studies to favour upper-middle and high-income countries (with Gross National Income per capita of $4,063 to 12,475 and >$12,475, US dollars, respectively), with no regional studies carried out in any of the world's 31 low-income countries, as classified by the World Bank. The majority of the world (88%) has had no regional or national cumulative threat mapping products. Future efforts to map cumulative threats can maximize their utility for conservation planning by focusing on areas that have yet to be mapped and developing and implementing methods to more directly map the impacts to ecological systems and processes, not just the simple footprint of the threat.

2.1 Introduction

The alteration of natural systems is driving rapid ecosystem change and biodiversity declines (Pimm et al. 2014; Watson et al. 2016). The rate at which human enterprise is altering natural systems is accelerating, especially in areas that house important concentrations of biodiversity (Steffen et al. 2015a; Maxwell et al. 2016). Globally, 75% of the terrestrial planet is under measurable human threat (Venter et al. 2016a) and these threats affect Earth's resiliency to adapt to change (Steffen et al. 2015a). Therefore, understanding where threats are overlapping and interacting will help in developing strategies to aid in preventing and mitigating threats to biodiversity.

Threats to biodiversity are actions taken by humans that have the potential to harm natural systems (Venter et al. 2016a). The term "threat" can be used interchangeably with "pressure" and "stressor". However, it is important to note that these terms differ from "impacts". An impact is a consequence from the threat exerted on the system, such as population decline or altered disturbance regime (Verones et al. 2017). Impacts on biodiversity can accumulate spatially as the extent of human threats expand. Impacts can also accumulate, temporally as a result from intensifying threats on a system over time (Whitehead et al. 2016). These impacts can originate from a single source, multiple sources or can act cumulatively across threat types. The potential for a number of human threats to act cumulatively can result in additive, synergistic or nonlinear impacts (Halpern & Fujita 2013). Such cumulative threats and their impacts are difficult to predict, yet their interactions could have profound consequences for the natural environment (Watson & Venter 2019). Therefore, understanding cumulative threats and their impacts represent some of the greatest challenges to maintaining biodiversity and ecosystem services (Burgman et al. 2007).

While the threats to biodiversity are numerous and vary spatially and temporally, efforts to map them typically only consider a single threat. Such single threat maps can represent forest loss (Hansen et al. 2013), urban expansion (Seto et al. 2012) and the exploration and development of fossil fuels (Butt et al. 2013). Although useful, single threat maps fail to capture the full scope of cumulative effects, including interactions and synergies that may occur when considering threats from multiple types of activities. To circumvent this limitation, cumulative threat maps are becoming more prevalent (Watson & Venter 2019). Cumulative threat maps, as opposed to single threat maps are used as a means to quantify the extent and intensity of multiple anthropogenic threats across space and time (Tapia-Armijos et al. 2017). By incorporating greater than one threat, the resulting maps provide a more complete understanding of the interacting threats to biodiversity and ecosystem services (Halpern et al. 2008b). Cumulative threat maps are recognized as a crucial first step for developing informed conservation plans and directing development to areas that will cause the least amount of harm to biodiversity and ecosystem services (Crain et al. 2009; Venter et al. 2016a).

Cumulative threat maps have been produced across terrestrial (Sanderson et al. 2002), marine (Halpern et al. 2008a) and freshwater realms (Vörösmarty et al. 2010; Sterling et al. 2014) and from global (Rodríguez-Rodríguez & Bomhard 2012) to regional scales (Woolmer et al. 2008). Threats have been mapped, with data from a single time period, (Orsi et al. 2013) and dynamically over time (Walker et al. 1986; Roth et al. 2016). Despite rapid growth in the number of studies and associated methodologies to map cumulative threats, there has yet to be a comprehensive review of those works. Understanding the kind of information, threats being used and methods to map cumulative threats are crucial for advancing conservation efforts.

There has been important work to identify some of the lessons learned through cumulative threat mapping. For example, Halpern and Fujita (2013) compiled the assumptions, challenges and future directions in cumulative threat analyses from their experiences in the field. Foley et al. (2017) performed a comparative analysis of cumulative effects assessments and how they were practiced by four jurisdictions considered as leaders in environmental law: California, USA; British Columbia, Canada; Queensland, Australia; and New Zealand. The study found that science and practice are not aligned in addition to there being varied definitions for project baselines and scales showing the opportunity to advance and align the field in science, policy, management and practice (Foley et al. 2017). More recently, Watson and Venter (2019) created a synopsis of mapping the terrestrial human footprint providing a history and capabilities of the product. These studies are important because they present the applicability of cumulative threat maps for conservation science and highlight opportunities for future work. However, none of these studies provided a synthesis of cumulative threat mapping internationally and across biogeographic realms. Given the importance of understanding cumulative threats as drivers of biodiversity decline, I provide the first formal review for the field. Understanding how to develop and use cumulative threat maps could help conservation practitioners and resource managers to address threats to biodiversity.

In this study, I reviewed and summarized the scope and methods used to conduct spatial cumulative threat analyses, as reported in the peer-reviewed literature. I identified the realms investigated (i.e. terrestrial, marine or freshwater), the type and number of threats mapped and the geographic location of each study. I also assessed whether studies mapped Pressures, State and/or Impacts (P-S-I). These three elements are typical of cumulative threat analyses and provide insight on the methods used to translate threats into impacts on natural systems. Lastly, I identified whether a study mapped cumulative threats with a dynamic or a static approach.

Results informed a critical review of the methods for threats mapping as well as the geographic and thematic scope of cumulative threat analyses conducted globally.

2.2 Methods

Literature Review

I reviewed the literature to identify studies that mapped cumulative threats. These studies used a variety of terms to describe their objectives and methods, which made a systematic literature review with a discrete set of search terms intractable. Instead, I reviewed the literature focusing on titles and abstracts, to identify published studies of relevance to my research objectives. For inclusion, a study must have been a peer-reviewed journal article, have a spatially explicit analysis, map at least two threats and lastly combine threats to develop a cumulative threat map. I focused the literature review on peer-reviewed articles only as these articles have been vetted by the scientific community, confirming the soundness of methods and acceptable confidence in the study results. Studies focussed on terrestrial, marine or freshwater realms and were identified accordingly. I excluded studies that did not develop primary data, such as reviews and perspective pieces.

The initial searches, performed through Thomson Reuters ISI Web of Science database and Google Scholar, included studies with any combination of the following keywords: *multiple, cumulative, threat, pressure, impact, stress, hazard, effect, map*, freshwater, river, lake, riparian, watershed or footprint* (n = >30,000). Further refinement through advance searches and different keyword combinations reduced the number of studies to n = 1,379 which was sorted by relevance. The reference sections of all included studies were reviewed for additional studies that met my inclusion criteria. I also evaluated studies listed by the Web of Science as citing Sanderson et al. (2002) (n = 1,149), Halpern et al. (2008) (n = 3,038) and Vörösmarty et al. (2010) (n = 2,673). These are the three most frequently cited studies focused on cumulative threat analysis for each of the terrestrial, marine and freshwater realms, respectively. As the search progressed, I noted repeated citations of previously identified studies. This suggested that I identified most studies that met my search criteria. Some studies were added on an ad hoc basis after the initial search if they fit the definition. As papers continue to be published, the cut-off date for inclusion in this review was October 2017. I identified 65 papers for further review.

Data Collation and Analysis

I collected the following information from each relevant study: realm (terrestrial, marine, freshwater), the number and type of threats mapped, scale (regional, national, global), geographic location, whether the data were temporally static or dynamic and whether the analysis addressed pressure, state and/or impact. I reclassified each threat according to the 12 category Unified Classification of Direct Threats developed by the International Union for the Conservation of Nature (IUCN) and the Conservation Measures Partnership (CMP) (IUCN-CMP) (hereafter referred to as the threat classification scheme). This classification scheme provided a consistent organizational structure for the wide range of threats identified in the literature (Salafsky et al. 2008). To avoid double counting, threats were only identified as unique if they fit into a different subcategory of the threat classification scheme.

Using ArcGIS 10.5.1, I either received a shapefile from the study authors or digitized the spatial area for each identified study. For all digitized areas, I recorded biome, country and realm. Less than 10 studies mapped threats for the freshwater environment, thus I did not perform a biome analysis for that realm. I quantified the number of studies of each terrestrial and marine biome and used all digitized non-global studies to identify the concentration of studies occurring around the globe.

I used the income classes of each country in 2015 from the World Bank to determine if there were differences in the number of studies across levels of national development (World Bank 2014). Income class was determined by the World Bank Analytical Classifications where income classes were determined by Gross National Income per capita in US dollars. In 2015 the classifications were: <=1,025 for low income, 1,026 to 4,035 for lower middle income, 4,036 to 12,475 for upper middle income and >12,475 for high income (World Bank 2014). I used Marine Exclusive Economic Zones so that all realms of study could be included, however excluding global studies. To classify income class, I used the digitized study areas that I joined to the World Bank data to apply a unique identifier and summarized the data. As data were collected at the scale of country, studies within the same national boundary received the same income class, if any shapefile crossed country boundaries it was included in all areas. With the resulting information, the number of countries studied across levels of national development was determined.

2.3 Results

Threats Considered

I identified candidate peer-reviewed studies of which 65 reported cumulative threat analyses. Of these studies, 30 covered cumulative threats or impacts in the terrestrial realm, 26 the marine realm, seven the freshwater realm and two covered mixed realms (Appendix 6.1). All studies mapped at least three threats, surpassing the minimum threshold of two threats for inclusion in my study. Freshwater studies mapped the highest average number of threats at 14.3 (SD = 18.6), followed by the marine realm with 9.6 (SD = 4.0) then the terrestrial realm with 6.3 (SD = 2.4) (Fig. 2.1).

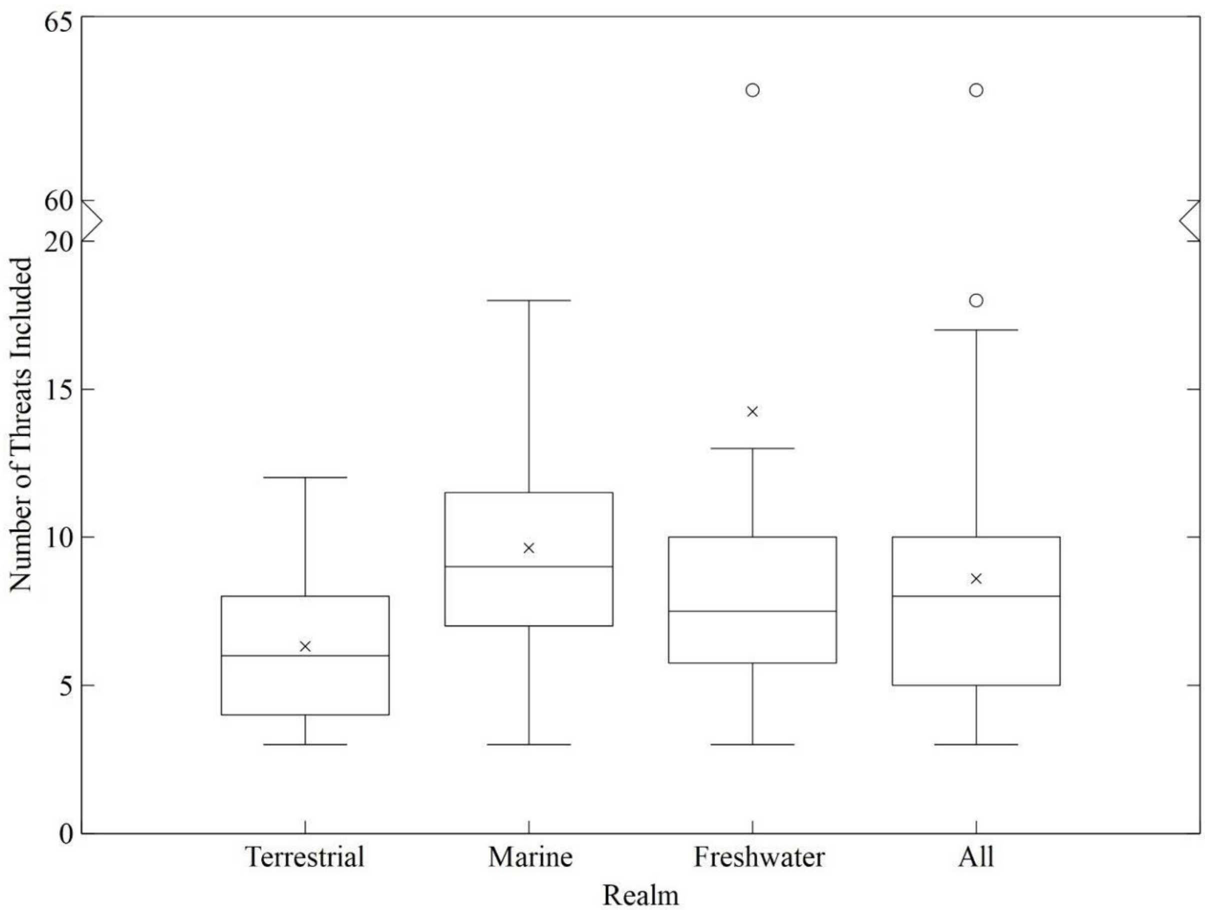

Figure 2.1: Box plot of the number of threats mapped in each study separated by realms, terrestrial (n = 32), marine (n = 27), freshwater (n = 8) and studies from all realms combined (n = 65). Boxes represent the interquartile range around the median. Outliers shown by open circles, the mean by an 'x' and the whiskers represent the 10th to the 90th percentile. Note that Y axis is not to scale above 20 to allow for the display of outliers.

The most commonly mapped threat categories were pollution (n = 158, number is greater than the number of studies included, as individual studies can map multiple forms of each threat), linear features (n = 77) and built environments (n = 69). The marine (n = 75) and freshwater (n = 65) realms reported pollution more frequently than the terrestrial realm (n = 18). With built environments, the marine realm accounted for 22 of the mapped threats for structures such as ports, marinas, lodges and lighthouses. Biological resource use dominated the marine realm, a threat that included fishing pressure (n = 20) (Appendix 6.2). For the terrestrial realm, agriculture (n = 39), linear features (n = 38), and built environments (n = 37) were the most commonly mapped threats. Invasive species and geologic events were the least reported threat categories, totalling 20 and zero mapped threats across all realms, respectively (Appendix 6.2; Fig. 2.2).

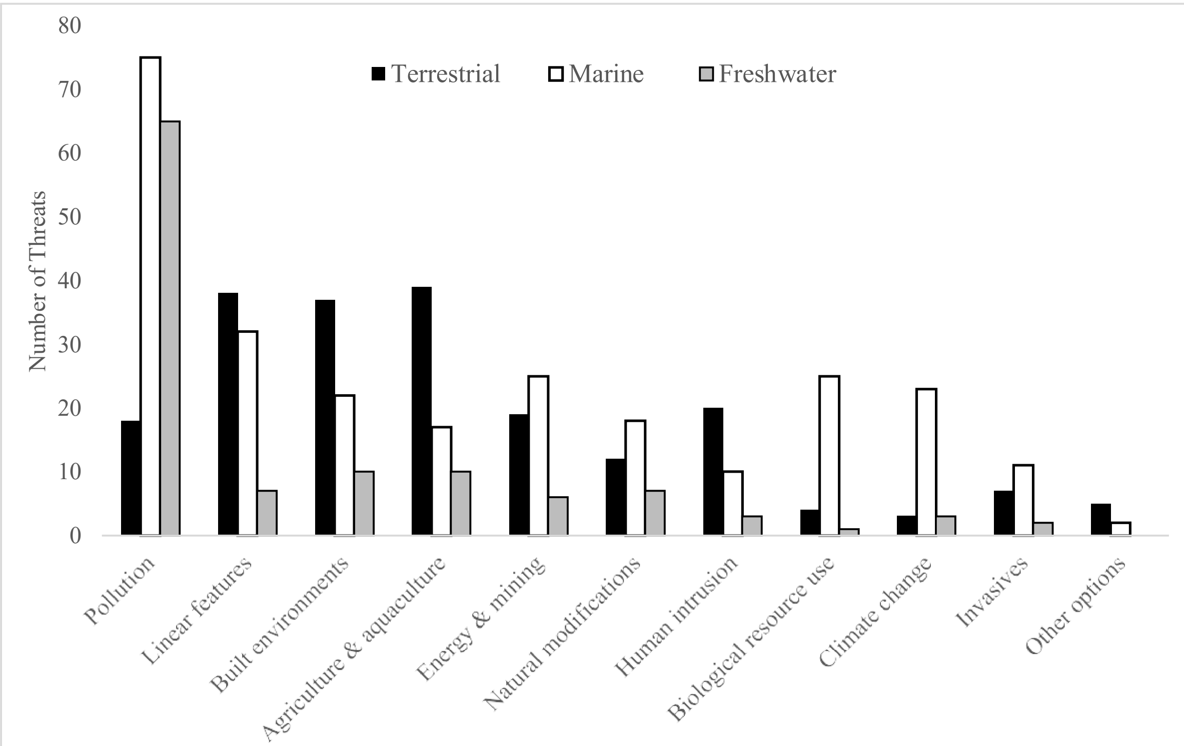

Figure 2.2: Total number of threats for each of the 11 threat categories stratified by realm (terrestrial, marine and freshwater). Threats were reported in 65 studies and categories were identified through a comprehensive literature review.

Geographic Distribution of Studies

Fifty-four of the 65 studies reported mapped threats at either a national or sub-national scale, whereas only 11 mapped cumulative threats at a global (n = 9) or continental (n = 2) scale (Appendix 6.1). However, when all 54 national and sub-national studies were combined, their area only covered 12% of the terrestrial world, and no studies took place on the continent of Africa (Antarctica was excluded from all global-scale studies). This means that 88% of the planet's terrestrial area is only mapped by global scale cumulative threat studies (Fig. 2.3). The distribution of effort for mapping cumulative threats also showed strong geographic bias. On land, 18 of the 26 studies (not including global) were set in the Americas, nine of which were concentrated in the United States. Only a few studies mapped threats in other regions, such as two that focused on Australia (Pert et al. 2012; Whitehead et al. 2016) and one that partially covered the "three parallel rivers" region in China (Lin et al. 2016). In marine areas, studies were largely located near coasts, especially along the North American Pacific coast, European coasts and in the Mediterranean Sea. However, one study covered the waters surrounding Hawaii (Selkoe et al. 2009), one focused on the north-eastern coast of Australia (Grech et al. 2011) and another represented the Chinese coast (Marcotte et al. 2015).

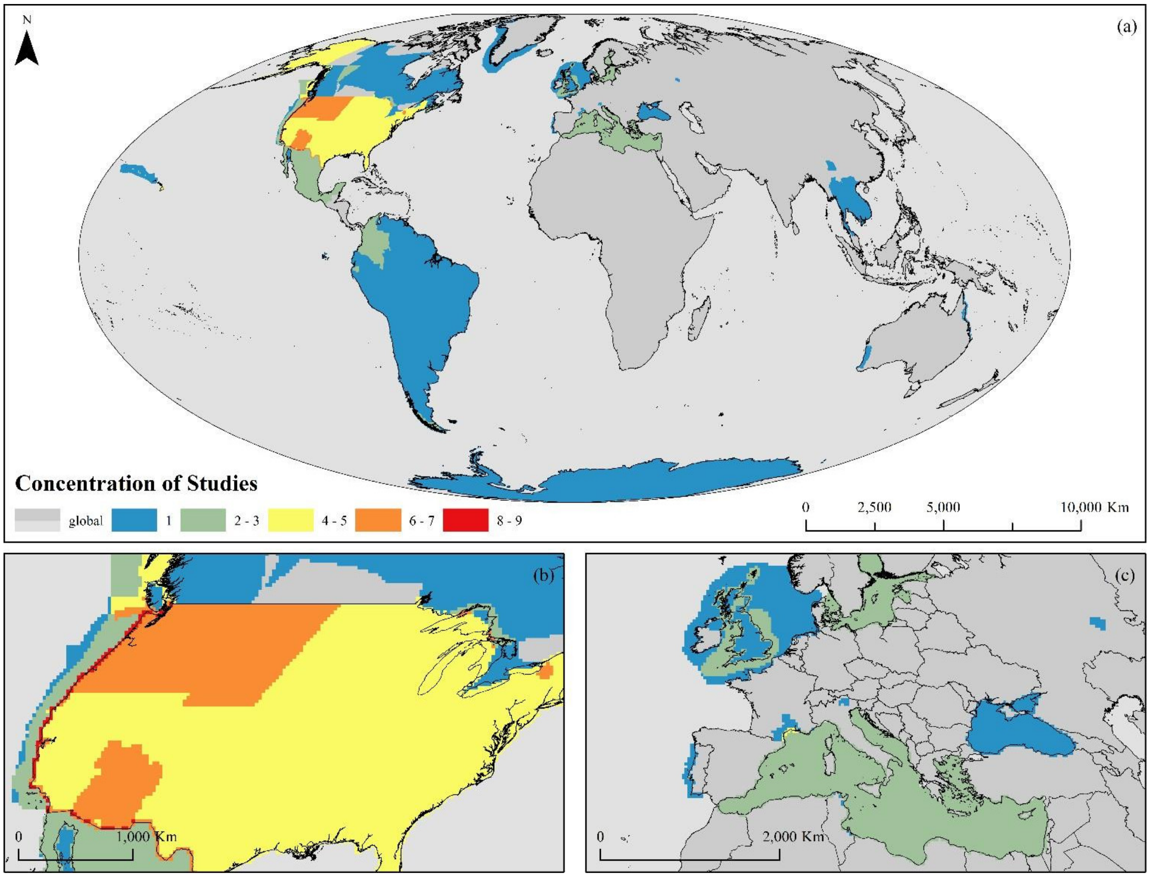

Figure 2.3: Concentration and geographic extent of cumulative threat mapping studies. Areas in grey have been studied at the global scale, darker for the land masses and lighter for water. A. Global concentration of cumulative threat maps from the review of 65 peer-reviewed studies. B. Close up of Western United States. C. Close up of Mediterranean Sea and surrounding areas. Projection in World Mollweide.

Cumulative threat studies were more evenly distributed across terrestrial biomes, with at least one study for each of the world's 14 vegetated biomes (16 including rock and ice and inland waters/lakes). The most studied biomes were the temperate conifer forests (n = 15), temperate broadleaf and mixed forests (n = 13) and the deserts and xeric shrublands (n = 12). The least studied was the montane grasslands and shrublands biome (n = 3) (Appendix 6.3). Cumulative threat mapping of the 12 marine biomes was less complete, as only six were represented in the literature reviewed. A total of 11 and 10 studies focused on the Temperate Northern Atlantic and Temperate Northern Pacific biomes, respectively. The Central Indo-Pacific (n = 2) and

Arctic, Temperate Australasia and Eastern Indo-Pacific biomes were poorly studied (n = 1) (Appendix 6.4).

Cumulative threat studies were biased to countries with a greater economic status, with 39% of upper middle income and 34% of high income countries studied. This compared to only 17% of lower middle income countries being included in a non-global study, and zero non-global studies covering any of the world's 31 low income countries (Appendix 6.5; Table 2.1).

Table 2.1: Distribution of studies performed in each of the National Development levels defined by the World Bank

Income Level	Number of Countries Studied	Number in each Class	Proportion of Countries studied
High	27	79	0.34
Upper middle	22	56	0.39
Lower middle	9	52	0.17
Low	0	31	0.00

Temporal Dynamics

Fifty-eight of the studies were static, leaving seven studies that assessed the change in cumulative threats over time (Appendix 6.1). Timescales ranged from five to 26 years, which spanned from 1982 to 2008 (Halpern et al. 2015; Tapia-Armijos et al. 2017 respectively). Marcotte et al. (2015) forecasted future potential cumulative threats resulting from a proposed construction project. This differed from the other six that only mapped changes from the past to the present (Marcotte et al. 2015).

Pressure-State-Impact Framework

The Pressure-State-Impact framework (P-S-I) allows for the assessment of management measures, progress towards conservation efforts and highlights the connections between the pressures and impacts (Martins et al. 2012; Watson & Venter 2019). As stated earlier, the terms threat and pressure can be used interchangeably; the term pressure is used in this section to align with the P-S-I framework terminology. The state of a system can be assessed by applying a variety of metrics. The state often refers to the combination or singular status of the socio-economic or natural systems, aiming to address temporal changes in the system (Martins et al. 2012). An impact represents the consequence of the changes caused by the threat (Johnson 2011). In order to determine specific impacts to a study area, the pressure and state must have already been evaluated.

Of the 65 papers included, 55 mapped cumulative pressures exclusively (Appendix 6.1). Of the 10 studies that reported the state of the study area or ecosystem, seven used measures of the health, distribution or richness of indicator or threatened species to determine the state (Leu et al. 2008; Coll et al. 2012; Maxwell et al. 2013; Poudyal et al. 2016; Whitehead et al. 2016; Correa Ayram et al. 2017; Verones et al. 2017). Only four studies reported pressures through to impacts (Appendix 6.1). In these studies, impacts were measured directly as biodiversity loss, species abundance change or range changes of species (Leu et al. 2008; Whitehead et al. 2016; Wang & Zhonglin Xu 2016). The human footprint measuring resource use identified the impacts of emissions, water use, land occupation, eutrophication and terrestrial acidification, from the included pressures by using a lifecycle assessment tool of the resource use (Verones et al. 2017).

2.4 Discussion

To my knowledge, this is the first review of studies that assessed spatial and temporal dynamics of cumulative threats. I identified 65 cumulative threat studies that spanned all 14 terrestrial biomes and all three ecological realms. I found that studies were more evenly distributed throughout the different terrestrial biomes than the marine biomes. However, there was not an even distribution of studies across the threat categories, and many regions of the world were understudied. Most studies have captured a snapshot in time of cumulative threats and have not represented the impacts of mapped threats. My comprehensive literature review offers insight in the efforts to map cumulative threats and highlights the gaps for future research.

I expected to see a strong terrestrial bias for mapping threats. This result would be consistent with the general ecosystem bias found throughout the conservation sciences (Di Marco et al. 2017). However, my review revealed that the number of marine based studies (n = 26) were nearly equal to those focused on terrestrial systems (n = 30). A potential reason for the lack of bias is that cumulative threat mapping is a new area of research, having a proliferation of studies published in the last 10-15 years (Halpern & Fujita 2013), that is unburdened by the legacy of traditional conservation science. Also, there may simply be a recent emphasis on the assessment and conservation of marine ecosystems. Di Marco et al. (2017), for example, reported that the proportion of conservation science studies addressing aquatic systems has grown by 50% in the last 20 years. However, they still found that 81% of the reviewed studies focused on the terrestrial realm. Although I found many studies focused on the marine realm, freshwater systems were underrepresented by cumulative threat studies.

My results support the idea that the creation of laws and policies for the protection of geographic areas or biomes has encouraged the production of cumulative threat maps. I discovered a concentration of studies focused on the Mediterranean Sea, other European coastal waters and the Pacific coast of North America. In these areas, the European Union has created the Marine Strategy Framework Directive with the goal of achieving good environmental status of European marine waters by 2020 and to form better protection of the marine environment (European Parliament 2008; European Commission, Environment 2020).

Nine of the 11 studies covering the marine realm in European waters cited that framework. California, USA, had a similar act to protect the marine system: the Marine Life Protection Act (Mach et al. 2017). There were four studies performed in the California area, half of which specifically mention that act (Halpern et al. 2009; Mach et al. 2017).

The terrestrial human footprint is changing most rapidly in areas of lower middle income and low-income classes (Venter et al. 2016a). My review found no studies focused on countries of low income class and only nine countries were studied in the lower middle class. The lack of studies performed in the areas where the human footprint is growing most rapidly shows that there is a need to redirect the focus of future cumulative threat mapping projects (Venter et al. 2016a). In countries that have a low development index and high population growth there have been correlations with high deforestation rates. Many of these countries contain biodiversity hotspots, so understanding the dynamic nature of threats in these areas is essential (Jha & Bawa 2006; Allan et al. 2019). Woolmer et al. (2008) demonstrated that when compared to global-scale products, regional threats mapping improved conservation-based land use planning. Understanding the threats at a regional level will therefore provide more constructive conservation opportunities for countries experiencing the highest growth in the human footprint.

Over 8000 species were included in Maxwell et al.'s (2016) analysis of threats to the IUCN Red List of Threatened Species. Biological resource use was the threat that affected the greatest number of species. Within that category, the majority of the species were threatened by unsustainable logging practices. In contrast, I found that biological resource use ranked only eighth for prevalence in threats mapping. Furthermore, the biological resource use threat was focused almost exclusively on the marine realm, not logging as reported by Maxwell et al.

(2016). Invasive species affect nearly 24% of the species assessed by Maxwell et al. (2016), yet it remained the least mapped category excluding the other options. Maxwell et al. (2016) listed climate change as the seventh ranked threat to species-level biodiversity, but they reported that the significance of this threat will likely increase in the future. For the marine realm, Halpern et al. (2015) showed that over 60% of the ocean experienced increases in human impacts, most of which were driven by climate change. I also recognize the need for climate data, that can be included in cumulative threat maps, as we see from my review that climate change and severe weather threats were the least mapped categories.

Threats are intrinsically related to the impacts they cause. Identifying the links between threats and impacts is important for understanding the mechanisms that result in the loss of biodiversity and change in ecosystem services (Margules & Pressey 2000; Martins et al. 2012). I found that few studies (n = 4) represented the relationship between mapped threats and the resulting impacts. However, it is often difficult to determine the impacts of threats that may have a lag time before the impacts can be detected (Johnson 2011). The P-S-I framework allows research to build on previous work in the same study area, with the potential to use a pressure map from a different project and translate it to impacts on biodiversity or ecosystem services, which will provide more valuable information for conservation (Walsh et al. 2011; Martins et al. 2012).

My findings may not represent an exhaustive accounting of the studies focused on cumulative threat mapping. First, the literature search did not include studies in languages other than English, which could have biased my results against non-English speaking countries and biomes found in those countries. However, most peer-reviewed journals are produced in English. Second, my search criteria only allowed for the inclusion of peer-reviewed articles, excluding grey literature such as reports and theses. There is a number of countries that have cumulative effects practices in place, such as Laos and South Africa, that have reports on cumulative threats, but those results are not represented in the peer-reviewed literature (Retief et al. 2008; Dusik & Xie 2009). However, searching and including the grey literature for the world in all realms for a field that does not have standardized terminology was simply intractable. Lastly, the lack of an inclusive definition or keywords that describe the field of cumulative threat mapping could have led me to overlook some studies. Proper use of nomenclature in cumulative threat mapping is necessary to streamline searches and clarify what is really being mapped. Often when weighting threats, studies name the results of the calculation “cumulative impacts” when the map still shows cumulative threats and not impacts. The proper use of terminology will better facilitate future meta-analyses and provide a more consistent understanding of cumulative threat mapping.

The maps produced by the studies I reviewed provide crucial baseline information for conservation planners, allowing them to assess changes in threats over time and the successes and failures of conservation efforts. Consideration of the interrelationship between pressures or threats, the state of the system and the resulting impacts (i.e., P-S-I framework) provides greater guidance to conservation planners as the chain of impacts can be assessed and mitigated. As the field of cumulative threat mapping moves forward, priority should be given to map the 88% of the planet that has no regional analyses. This should include efforts to increase the understanding of threats to freshwater systems and those that occur across Africa, which has yet to host a single peer-reviewed study. Better understanding of how cumulative threats interact with the state of natural systems to create ecological impacts, such as the loss of biodiversity or ecosystem services, remains an almost unexplored research frontier. I believe that cumulative threat maps provide a unique means of documenting and understanding human interactions with the natural world, but much work remains to fully understand and map these interactions.

3. CANADA'S HUMAN FOOTPRINT REVEALS LARGE WILD AREAS JUXTAPOSED AGAINST AREAS UNDER IMMENSE ANTHROPOGENIC THREAT

Abstract: As Canada undergoes a biodiversity crisis, efforts to set aside some of the country's terrestrial land from anthropogenic threats are underway. Here, I use spatial analyses to produce the first Canadian human footprint map to identify intact wildlands and ecosystems under threat. I improve upon available global data by providing a finer resolution and analysis of additional threats that are prevalent in Canada. My results show strong spatial variation in threats across the country, with 82% of Canada considered wild, when incorporating 12 specific anthropogenic threats. However, the data from across Canada are do not include data on climate change, invasive species, overexploitation. The Great Lakes Plains and Prairies National Ecological Areas have over 75% and 56% of their areas with a high human footprint, respectively. In stark contrast, the Arctic and Northern Mountains have less than 0.02% and 0.2% under high human footprint. I found several improvements between the results of the Canadian human footprint and the global human footprint, with the most significant advancements derived from using national datasets or more recent remotely sensed data for roads, crop land and nighttime lights. I was able to run a technical validation on my data which resulted in the Cohen Kappa statistic of 0.911, signifying an 'almost perfect' agreement between the human footprint and the validation data set. The National Ecological Areas with little wild left, highlight challenges that may arise when planning for ecologically representative protected areas to mitigate threats to biodiversity and ecosystem services.

3.1 Introduction

Global threats to biodiversity are increasing as humans continue to alter terrestrial ecosystems (Steffen et al. 2015b; Venter et al. 2016a), and the conversion and degradation of habitats from a number of anthropogenic threats are leading to biodiversity declines (Newbold et al. 2015; Maxwell et al. 2016). Threats to biodiversity are actions taken by humans that have the potential to harm natural systems (Venter et al. 2016a), and their occurrences are increasing at an accelerating rate (Primack 1993; McNeill & Engelke 2014). Threats on a landscape interact with each other in a complex manner and vary in their spatial and temporal scales making their understanding essential for conservation planning (Primack 1993; Geldmann et al. 2014; Tapia-Armijos et al. 2017). Identifying the patterns of change in these threats provides the basis for the mitigation of environmental damage (Halpern et al. 2015; Venter et al. 2016a).

When threats are analysed, especially those from resource development projects, the focus is typically on the project in isolation of other development projects (Johnson 2016). By incorporating more than one threat, the resulting product provides a more complete understanding of the interacting threats to biodiversity, with the potential to assess how ecosystem services are affected (Halpern et al. 2008b). Cumulative threat mapping allows for the combination of more than one threat on a spatial and temporal scale showing the full extent and intensity of anthropogenic threats (Tapia-Armijos et al. 2017). Cumulative threat maps, or human footprint maps, combine threats into a single product which can be used for making conservation plans that yield the greatest benefits and directing development to areas that will cause the least amount of harm (Crain et al. 2009; Venter et al. 2016a).

As a signatory of the Convention on Biodiversity and its Aichi Biodiversity Targets, Canada's Target 1 is to protect 17% of terrestrial and 10% of marine areas (MacKinnon et al. 2015).

With this ambitious conservation target there is a need to better understand the distribution of threats to natural systems across Canada. Mapping out the threats to biodiversity nation-wide will help determine what ecosystems are most wild or intact and which areas are heavily threatened. Wilderness is defined as large landscapes that are biologically and ecologically intact and mostly free of human disturbances. This definition does not exclude people such as Indigenous peoples and their stewardship practices, but it does exclude large-scale land conversion, activity and development (Watson et al. 2016; Waller & Reo 2018). Mapping the human footprint will serve as an important step in selecting which areas to protect, restore and sustainably manage.

Canada's natural systems have a number of threats to biodiversity. Woo-Durand et al. (2020) analysed threats to 820 species identified as "at-risk" in Canada by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). They found that the number of threats affecting each species has increased significantly from an average of 2.5 to an average of 3.5 threats between 1999 and 2018, showing the need to map threats in Canada cumulatively and not in isolation (Venter et al. 2006; Woo-Durand et al. 2020). Nevertheless, no cumulative threat map covers the entirety of Canada. At present, Canada has cumulative threat maps for parts of the coastal waters (Ban & Alder 2008; Ban et al. 2010; Clarke Murray et al. 2015b, 2015a) and two studies covering freshwater (Robb 2014; Sterling et al. 2014). For terrestrial studies, the greatest coverage spans the largest ecological area of Canada, the Boreal/Taiga (Pasher et al. 2013). Other terrestrial maps cover sections of western Canada (Shackelford et al. 2017; Mann & Wright 2018), part of eastern Canada and the United States (Woolmer et al. 2008) and the whole of Canada to display the number of pollution threat categories present (McCune et al. 2019). In addition to human footprint maps, a binary human access map exists showing the presence and absence of access into nature across Canada (Lee & Cheng 2014). However, solely displaying access does not allow for the accurate representation of the differences between large metropolitan cities and smaller resources centric towns (Lee & Cheng 2014). Compiling means of access in addition to human settlement and land use in Canada would allow for a more accurate depiction of anthropogenic threats in Canada. The global human footprint map displays Canada as mostly wild (Venter et al. 2016a, 2016b), however this includes only a subset of threats relevant to the country. Therefore, until a national human footprint is produced, incorporating other relevant threats, there will continue to be a gap in our understanding for the Canadian human footprint.

Here, I used geospatial techniques to develop a threat map for Canada that represents nationally-specific threats that are not incorporated in coarse-scale global maps. Using a higher spatial resolution of 300 metres, I produced the first national terrestrial human footprint of Canada. Visually and quantitatively comparing the global and national products I was able to identify improvements and address where errors in representation may have occurred. I am able to confirm the soundness of the national product by means of technical validation comparing the Canadian human footprint to high-resolution satellite imagery. As the maintenance of biodiversity and ecosystem services depends on the comprehensive understanding of the full set of overlapping threats (Sala et al. 2000), the results of this project will be important for the future of natural resource management and conservation planning in Canada.

3.2 Methods

Overview

To produce the Canadian human footprint, I adopted the methods originally developed by

Sanderson et al. (2002) and later refined by Venter et al. (2016a, 2016b). The threats I mapped for Canada were: (1) the extent of built environments; (2) crop land; (3) pasture land; (4) human population density; (5) nighttime lights; (6) railways; (7) roads; (8) navigable waterways; (9) dams and associated reservoirs; (10) mining activity; (11) oil and gas; and (12) forestry. Each anthropogenic threat was placed on a 0-10 scale to allow for comparison across threats. Scoring methods were selected from pre-existing peer-reviewed articles following Venter et al. (2016a, 2016b) and Woolmer et al. (2008) methods and one threat layer following methods used in Jarvis et al. (2010). After scoring, all non-compatible land uses were analysed and adjusted to avoid spatial overlap. Non-compatible land uses included built environments, crop land, mining and pasture land. I eliminated any pixels from the given layers that overlapped with built environments, then did the same operation for crop land and mining. The order of priority, to adjust for spatial overlap, reflected how high up on the 0-10 scale the individual layers placed. To produce the final product of the terrestrial human footprint map of Canada, all the weighted layers were summed together. Individual threats may overlap spatially and are therefore not mutually exclusive. Thus, each cell could range in value from 0-55 for any given grid cell, representing the observed maximum. The map was generated at a spatial resolution of 300 metres, yielding around 1,000,000 pixels. ArcGIS 10.5.1 and the Lambert Conformal Conic projection were used for all spatial analyses. Specific details on each of the threat layers are provided in the following sections.

Built environments

Built environments are lands that are constructed for human activity and include buildings, paved surfaces, and urban areas. Land transformation from built environments leads to habitat loss and fragmentation, changes in nutrient and hydrological flows, reduction of viable habitats for species and decreased temperature regulation and carbon sequestration (Tratalos et al. 2007; Haase 2009).

I acquired data from the 2016 annual crop inventory (Government of Canada; Agriculture and Agri-Food Canada; Science and Technology Branch 2016), which provides a 30 metre spatial resolution of land-use type and applied the subset of the 'urban/developed' lands for the layer. The data does not include the Yukon, Northwest and Nunavut territories, and therefore I captured the anthropogenic threats for the northern territories through other layers such as: population density, nighttime lights and roads. The data are a combination of satellite imagery: Landsat-8, Sentinel-2 and Gaofen-1 for optical imagery with RADARSAT-2 radar imagery, generating an accuracy of at least 85% (Government of Canada; Agriculture and Agri-Food Canada; Science and Technology Branch 2016). Built environments were assigned a score of 10 (Venter et al. 2016a, 2016b).

Population density

Human population density is linked to biodiversity loss (Cincotta & Engelman 2000). Presence of high human populations has led to over-hunting, deforestation and introduced species (Prebble & Wilmshurst 2009). Though Canada generally has a low population density, averaging four people per square kilometre, there have been significant increases in introduced species, over-exploitation and pollution from 1999-2018 (Government of Canada; Statistics Canada 2017a; Woo-Durand et al. 2020).

Human population density was mapped using the 2016 Canadian Census Data which provides more detailed information than the Gridded Population of the World dataset (Venter et al. 2016b; Government of Canada; Statistics Canada 2017a). The vector layer used was the Census Dissemination Blocks, the smallest unit with an associated population, available through the Geo Suite 2016, a Statistics Canada tool I used for data retrieval (Government of Canada; Statistics Canada 2016). Following Venter et al. (2016a, 2016b), I calculated population density for each block; any block that had more than 1,000 people per square kilometre I assigned a threat score of 10. For more sparsely populated areas, I logarithmically scaled the threat score as follows:

$$\text{Threat Score} = 3.333 * \log(\text{Population density} + 1)$$

Nighttime lights

Nighttime lights captures the sparser electric infrastructure found in rural, suburban and working areas that have an associated threat on natural environments (Venter et al. 2016a, 2016b). The Visible Infrared Imaging Radiometer Suite (VIIRS), mounted on the Sumo National Polar Partnership satellite, provides the means to collect and map low light sources such as nighttime lights (Elvidge et al. 2013).

I used an annual composite from 2016 generated by the National Oceanic and Atmospheric Administration (NOAA) to assess nighttime lights. The spatial resolution of the data is 589 metres (15 arc-second geographic grids). For areas above 67N, that were not included in the annual composite, I randomly selected a single date of imagery to fill the northern section and compared it to other dates to make sure it was not an outlier (NOAA 2019). I then rescaled the data on a 0-10 scale using an equal quintile approach (Venter et al. 2016b, 2016a).

Crop and pasture land

Agriculture is recognised as one of the most important threats to biodiversity globally (Ricketts & Imhoff 2003). For the Canadian human footprint, I used the 2016 annual crop inventory which includes pasture, agricultural land, cereals, pulses, oil seeds, vegetables, fruits and other crops (Government of Canada; Agriculture and Agri-Food Canada; Science and Technology Branch 2016). Satellite imagery from optical (Landsat-8, Sentinel-2 and Geifen-1) and radar (RADARSAT-2) was used to obtain a spatial resolution of 30 metres. There was also ground-truth information provided by several organizations. The provincial accuracy for crop class had a minimum of 86.27% and a maximum accuracy of 94.51% (Government of Canada; Agriculture and Agri-Food Canada; Science and Technology Branch 2016). I assigned crops a threat score of seven (Venter et al. 2016b, 2016a).

Pasture lands are areas that are grazed by domesticated livestock. Pastures are often associated with fences, soil compaction, intensive browsing, invasive species and altered fire regimes (Kauffman & Krueger 1984). Using the annual crop inventory (30 metre spatial resolution) (Government of Canada; Agriculture and Agri-Food Canada; Science and Technology Branch 2016), I assigned pastures a threat score of four (Venter et al. 2016b, 2016a).

Roads and railways

Roads are linear features that directly convert and fragment habitats. Roads can alter the immediate physical and chemical environments, provide access for human recreation into wilderness areas, allow for the spread of invasive species and be a sink for populations through vehicle collisions and mortality from construction (Trombulak & Frissell 2000).

I used the publicly available 2016 National Road Network vector layer produced by Statistics Canada (Government of Canada; Statistics Canada 2017b). The data are divided into different categories of use: Trans-Canada highway, national highway system, major highway, secondary highways, major streets and all other streets. I adapted the weights developed by Woolmer et al. (2008) assessing roads as an access point to wilderness (Table 3.1).

Table 3.1: Road Threat Scoring, separated by the different road types to allow for differential scoring. The distances represent the scores associated with each of the buffers.

	0-300m	300-600m	600-900m	900-3000m
Road Type				
Trans-Canada Highway	10	8	6	4
National Highway and Major Highways	8	6	4	2
Secondary Highways, Major streets and all other streets	6	4	2	0

Railways provide a direct threat to the ecosystems that host them, however, in terms of access they differ from roads. For roads and railways, direct threats exist as a result of the actual footprint such as physical removal of viable habitat or reduction in the quality of it, indirect threats may present themselves in the form of altering ecological functions, edge effect, reducing connectivity or other human disturbances made possible by the direct threat (Burton et al. 2014). However, discontinued rail lines provide an indirect threat as they can be used as a means of dispersal of humans and their activities into landscapes. Conversely, operational rails only allow for human access from individual rail stations. I used the publicly available National Railway Network vector layer (Government of Canada; Natural Resources Canada 2016) and adapted the methods from Woolmer et al. (2008) (Table 3.2).

Table 3.2: Rail Threat Scoring, separated by operational and discontinued. The distances represent the scores associated with each of the buffers.

	0-300m	300-600m	600-900m
Rail Type			
Operational	6	4	0
Discontinued	6	4	1

Navigable waterways

Navigable waterways like roads and rails act as means of access to wilderness areas. Canada's waterways have a long history of human use as they have enabled travel from sea to sea (Brine 1995). Once the people's 'highway', settlements were formed along the waterways to allow movement and access. Used by First Nations in pre-colonial times, the knowledge was shared when the first European explorers arrived. These waterways were later instrumental in the fur trade (O'Donnell 1989; Brine 1995).

I used the dataset generated for navigable coasts for 2009 from the global human footprint with a 1 km^2 spatial resolution (Venter et al. 2016b). The layer included the Great Lakes, as they can act like inland seas and was generated using distance to settlements, stream depth and hydrological data (Venter et al. 2016b). I found the centreline of the waterway then weighted them to follow the other access-based layers (Table 3.3).

Table 3.3: Navigable Waterway Threat Scoring. The distances represent the scores associated with each of the buffers.

	0-300m	300-600m	600-900m
Navigable Waterways	6	4	2

Dams and reservoirs

Dams directly change hydrology of the areas and they modify the environment, often producing human-made flooded reservoirs (Woolmer et al. 2008). The vector dataset was obtained from 'Large Dams and Reservoirs of Canada' (Global Forest Watch Canada 2010). I mapped the dam itself just as I would a built environment, scoring it as 10 (Woolmer et al. 2008; Venter et al. 2016b, 2016a). I scored dams and associated reservoirs in the same manner as navigable waterways given that they can provide additional access to areas by watercraft (Table 3.3).

Mining

Mining often alters topography, watercourses and removes topsoil as a form of land conversion. Mining can be a point source for air and water pollution (Woolmer et al. 2008). I used the mines and minerals dataset, updated in 2015, to obtain all active mines in Canada. The data were discrete points in vector format (Government of Canada; Natural Resources Canada 2017). I placed the mineral groups in their designated categories: open large, open small, underground large and underground small (WWF Canada 2003). For the minerals that were not previously classified by Woolmer et al. (2008) I consulted with an expert to determine if the mineral group would be mined underground or in an open pit (McGill 2018). Once confirmed to be open or underground, I placed them all in the small category, for open pit and underground mining, as a way to make sure I did not over-estimate the threat. The scoring from Woolmer et al. (2008) was used for mines (Table 3.4).

Table 3.4: Mines Threat Scoring, separated by the designated mining categories. The distances represent the scores associated with each of the buffers.

	0-600m	600-1500m	1500-2400m	2400-5100m	5100-10000m
Mine Type					
Open pit (large)	8	8	4	2	1
Open pit (small)	8	4	2	2	0
Underground (large)	6	6	4	2	1
Underground (small)	6	4	2	2	0

Oil and gas

Oil and gas production has a number of associated threats to nature such as wildlife mortality, habitat fragmentation and loss, noise and light pollution, introduction of invasive species and sedimentation of waterways (Brittingham et al. 2014; Jones et al. 2015). The mines and minerals dataset, updated in 2015, was used as it lists active oil and gas fields. The data were discrete points in vector format (Government of Canada; Natural Resources Canada 2017). The direct threats from oil and gas have been found to be highly localized, therefore, I adapted my scoring method using a 10 to 0 scale to score the linear circular decay out to five kilometres away from the site centre (Jarvis et al. 2010).

Forestry

Forestry operations alter the forest structure by changing stand dynamics and age (Freedman et al. 1994). Clear cut forestry can remove habitat for species dependent on old trees, deadwood and tree cavities and, by altering paths of travel and allowing for deep snow to form. Forestry operations could also introduce species and allow for more access for recreation including hunting through the creation of forestry roads (Freedman et al. 1994).

The forest-harvest data were obtained from a 25-year annual forest disturbance characterization project for Canada that has a 30-metre spatial resolution (White et al. 2017). The timescale of the harvest recorded was from 1985-2015. I separated fresh clear cuts and areas that have reached their free-to-grow state, as they offer different habitat qualities (Bergeron et al. 2011). I selected 12 years as it is a common value for free-to-grow, so anything from 0-12 years would be considered newly regenerating forest (Smith 1983; Lieffers et al. 2002). I adapted the scoring from Woolmer et al. (2008) with early regeneration scored as four and older regeneration as two (Woolmer et al. 2008).

Technical Validation

Following the methods used by Venter et al. (2016a, 2016b), a single person used high resolution satellite imagery to visually identify human threats within 5,000, 1-km^2 randomly located sample plots. Using World Imagery, available through ArcGIS, the 5,000 plots had a median resolution of 0.5 metres and a median acquisition year of 2014 (ArcGIS n.d.).

I used Venter et al. (2016a, 2016b) methods to develop a standardized key to visually interpret the threats. For the eight threats that both my Canadian human footprint and the global human footprint had in common I mimicked their scoring, but for the new threats included in my study I simply followed their standards for linear or polygons features (Appendix 6.6). Interpretations were marked if they were 'certain' or 'uncertain'; in my case 254 plots were 'uncertain' and therefore discarded, leaving 4,746 validation plots. Generally, plots were classified as 'uncertain' for two main reasons: due to inadequate resolution of the imagery (15 metres) so it was not clear if there were any threats present on the land, or because of cloud cover obscuring some or all of the image. The plots that were retained for the visual scoring were all 'certain' and I therefore consider the in-situ threats for the plot as true. The mean human footprint score for the 1-km^2 plots were determined in ArcGIS, then both the visual and human footprint scores were normalized on a 0-1 scale.

The root mean squared error (Chai & Draxler 2014) and the Cohen kappa statistic of agreement (Pontius & Millones 2011) were used to quantify the level of agreement between the Canadian footprint map and the validation dataset. The root mean squared error measures the differences between the values calculated in the human footprint and the visual scores from the validation. As the error is squared, outliers are emphasized with this statistical calculation. The Cohen kappa statistic of agreement expresses the agreement between the human footprint scores and the visual interpretation scores considering the potential that agreement or disagreement may occur by chance. Following previous analyses (Venter et al. 2016b, 2016a), visual plots that were within 20% of the human footprint plots scores were considered a match for the Cohen kappa statistic.

3.3 Results

1. The Canadian human footprint

Canada has an area-weighted average human footprint score of 1.48, and the maximum observable score for the country is 55 out of a theoretical 68. The threats across Canada display strong spatial patterns, showing higher values in Southern Canada where the majority of the country's population lives (Fig. 3.1). With the 12 threats included, I found that 82% of Canada's land areas had a human footprint score of less than 1, and therefore were considered wild (Allan et al. 2017). In this context, wild is defined as large landscapes that are biologically and ecologically intact and mostly free of the 12 human disturbances I mapped. To conceptualize this definition of wild, cells that had a population density of one or more per square kilometre obtained a threat score of one or above and were therefore not wild. However, threats like seismic lines, recreation trails or other threats that were not incorporated in the Canadian human footprint may still be present in wild areas. Many of the non-wild areas outside of cities appear as linear features which are from roads and navigable waterways connecting the different population centres to each other and industry. The intact state is defined as areas where the human footprint score is between one and four. The upper limit was determined based on the assignment of a score of four for pasture land, which would often have fences fragmenting the intactness (Venter et al. 2016a). Canada was found to have 5% of the country in the intact state. The moderate human footprint areas had scores between four and 10 and covered 7% of the country. The areas of high human footprint, with a value of 10 or higher, cover 6% of Canada and highlight areas with a number of overlapping threats to biodiversity (Fig. 3.1).

I used the National Ecological Areas defined by COSEWIC as a means of comparing the different regions (COSEWIC 2018). The condition of Canada's National Ecological Areas differ significantly, with 84% of the Boreal ecological area, which covers the largest extent of Canada, still being wild. The Great Lakes Plains, the smallest ecological area, has 76% in the high human footprint category, being the largest percentage in the high category compared to all other ecological areas. The Prairies follow the Great Lakes Plains as the second largest values in the high human footprint category with 57%. The Great Lakes Plains has the smallest percentage in the wild category with a value of 0.6% followed by the Prairies with 8%. Conversely, the Arctic, which is the second largest ecological area, is over 99% wild.

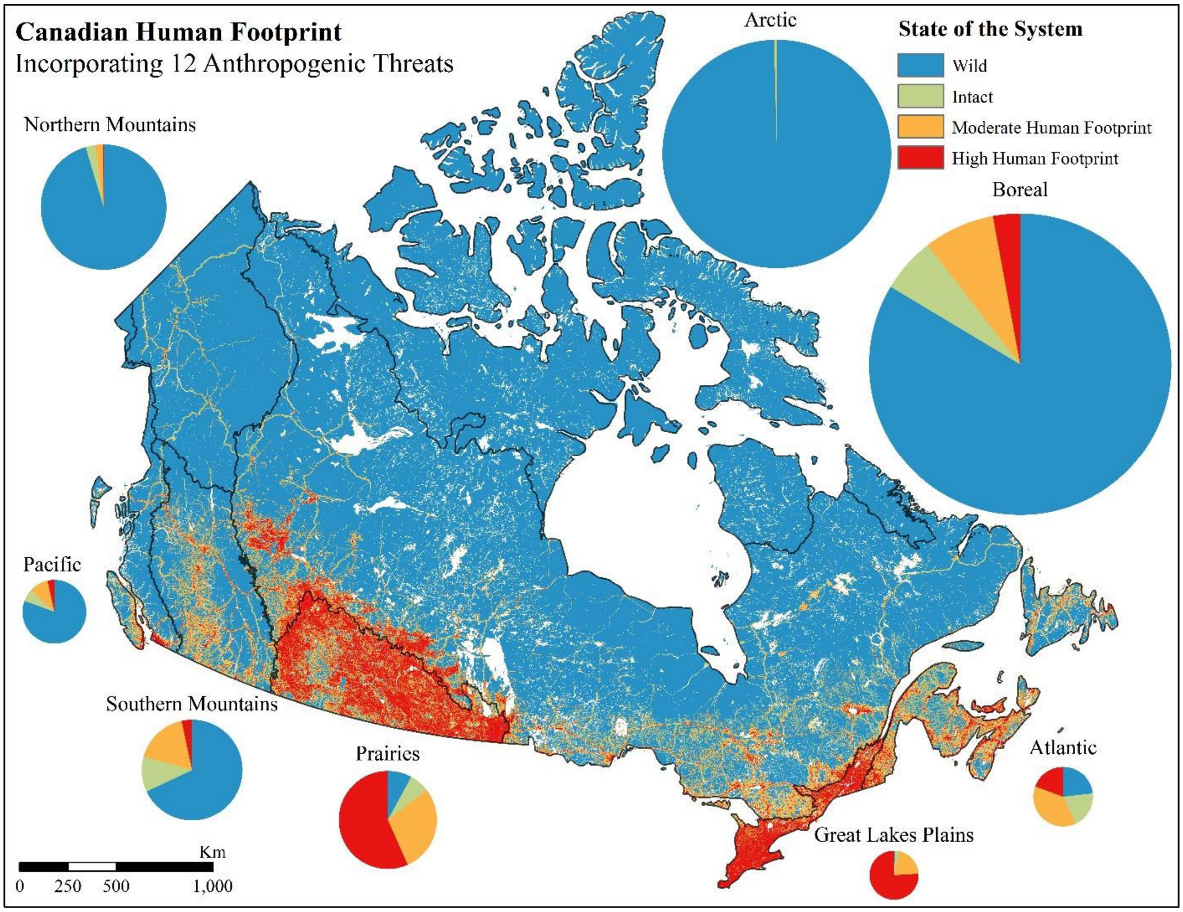

Figure 3.1: Human footprint map of Canada showing the state of the system for COSEWIC National Ecological Areas. Pie chart sizes represent the approximate proportions each ecological area covers of Canada. The footprint represents 12 anthropogenic threats: built environments, population density, nighttime lights, crop land, pasture land, roads, railways, navigable waterways, dams and associated reservoirs, mines, forestry and oil and gas.

The threat layer that contributes the most towards the mean human footprint of Canada is roads with a mean human footprint score of 0.72 (Fig. 3.2) and covering over 1,000,000 km^2. Crop land is the second most prevalent threat with a mean human footprint score of 0.27, then the only other threat above 0.10 was population density with a value of 0.20. In terms of extent, population density covers just under one third of Canada with over 3,200,000 km^2. While nighttime lights cover over 200,000 km^2 of Canada, it has a relatively small mean human footprint of 0.01.

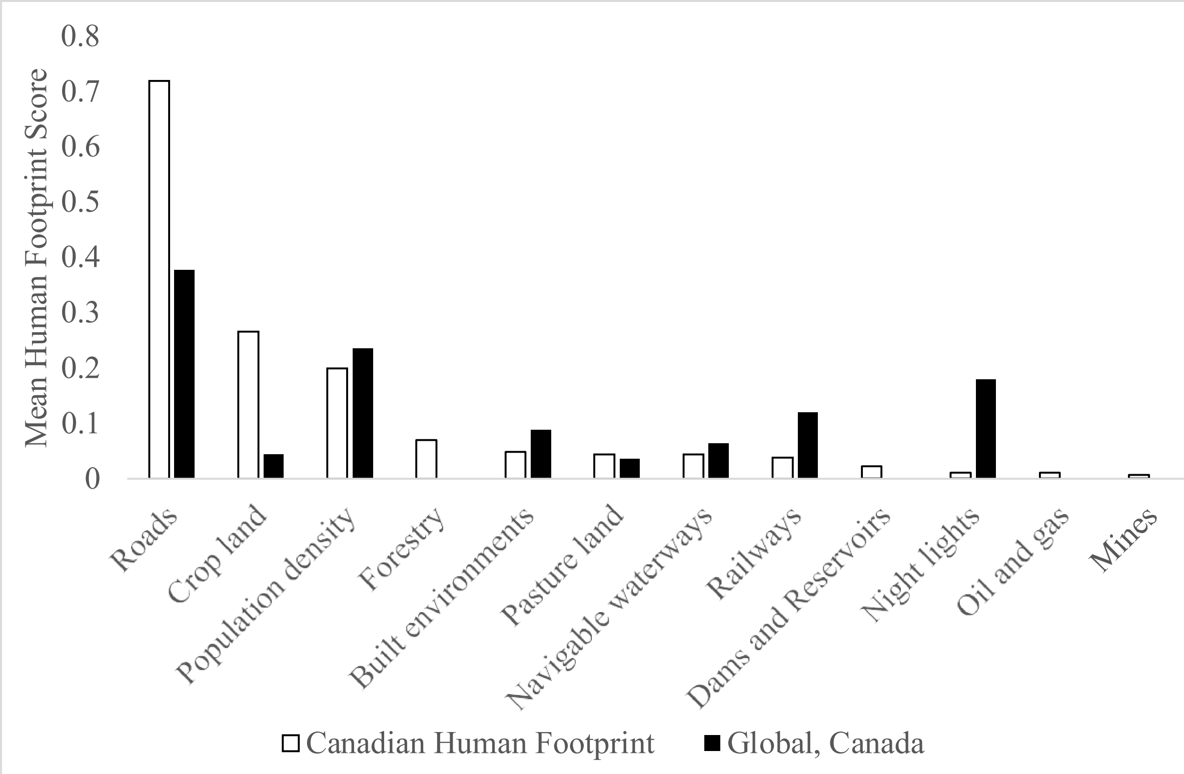

Figure 3.2: Mean human footprint scores for each of the threats included in the Canadian human footprint and the Global Human Footprint. 'Canadian human footprint' (white) are from the results produced in this project, the 'Global, Canada' (black) is from the global human footprint product clipped to Canada for comparison.

2. The Canadian Product versus the Global product

Visually comparing the global human footprint (Venter et al. 2016a) to the national product at a broad scale shows similarities in the spatial patterns of anthropogenic threats (Appendix 6.7). Closer examination shows a number of variations in the details. In agricultural areas, such as the prairies ecological region, the Canadian human footprint shows a higher concentration of threats than the global one (Fig. 3.3 A, B, C). For urban areas, the Canadian human footprint captures the distinction between areas such as parks, urban areas and industrial areas showing a lower human footprint score than the global one (Fig. 3.3 D, E, F). In natural resource intensive areas, higher scores for the Canadian human footprint are present compared to the global product that missed these features across Canada. For example, in the boreal ecological area, forestry harvest and infrastructure from oil and gas could be included with the Canadian human footprint (Fig. 3.3 G, H, I).

When mapping nationally explicit data the greatest improvements to the global datasets were found with the National Roads Network and the Annual Crop Inventory. The global human footprint scores roads within Canada as 50% less of a threat than the Canadian human footprint. The Annual Crop Inventory that was used for mapping crop land for Canada captured over 285,000 km^2 more than the global product (Fig. 3.2).

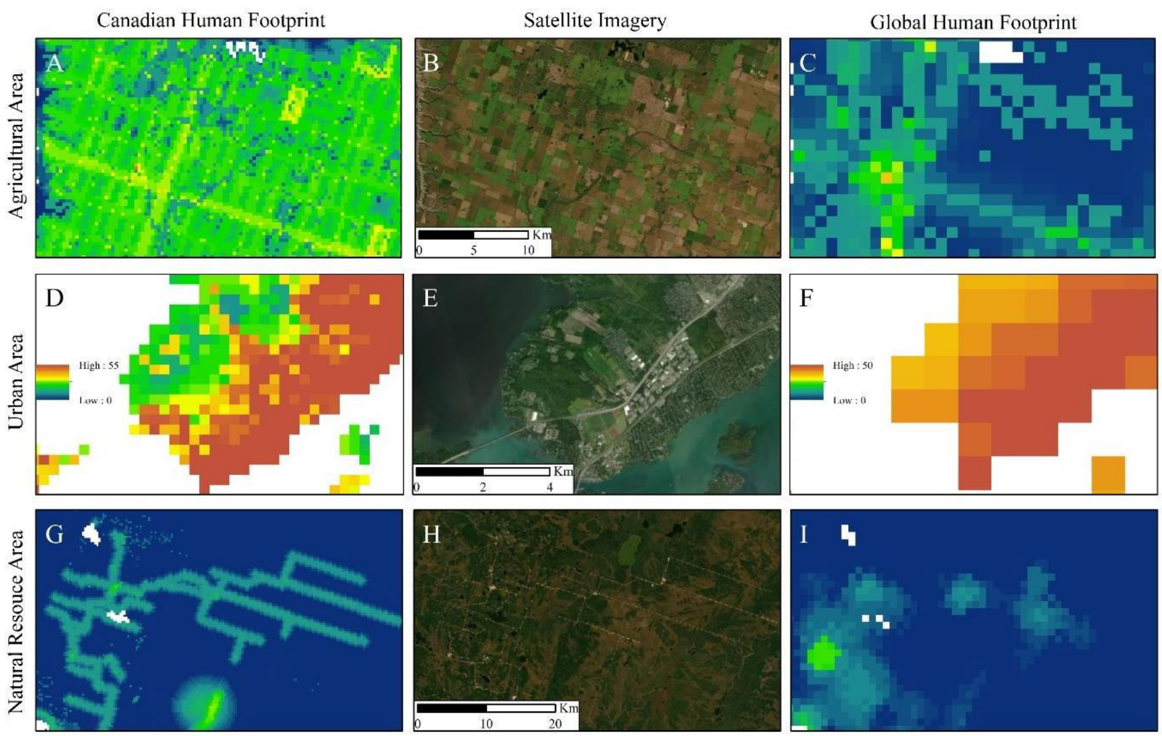

Figure 3.3: Visual comparison between the Canadian human footprint (first column) the high resolution satellite imagery (second column) and the Global human footprint (third column). The first row, Agricultural Area (A, B, C), is located in the prairies ecological area. The second row, Urban Area (D, E, F), shows the western part of the island of Montreal which is located in the Great Lakes Plains ecological area. The third row, Natural Resource Area (G, H, I), located in the Boreal ecological area, looks at a natural resource intensive area where forestry cutblocks and oil and gas infrastructure are present. The legend for column one is found in pane D and for column three in pane F. The scale bar for each row is found in the second column. The source for first column is from this project, second column is from the high resolution imagery basemap option in ArcGIS and the third column from Venter et al. (2016).

3. Validation results

My validation shows a strong agreement between the Canadian human footprint measure of threats and the threats scored using visual interpretation of high-resolution images. The root mean squared error for 4,746 validation 1 km^2 plots was 0.07 on a normalized 0–1 scale (Chai & Draxler 2014). The Cohen Kappa statistic was 0.911, signifying 'almost perfect' agreement between the human footprint and the validation data set (Landis & Koch 1977; Pontius & Millones 2011). For the 4,746 validation plots, the human footprint scored 40 of these 20% higher than the visual score (false positive) and 113 20% lower (false negative). The remaining 4,593 plots (96.8%) were within 20% agreement. While the results from the validation display almost perfect agreement, it appears from the higher false-negative rate that the Canadian human footprint may be susceptible to some small level of false negatives, where threats are actually present in locations where the human footprint maps them as absent. The maps should therefore be considered as slightly conservative estimates of anthropogenic threats on the environment (Fig. 3.4). If applying a more rigorous threshold for agreement, within 15% of one another, the Cohen Kappa statistic is found to be of substantial strength with 0.772. By applying a less rigorous threshold of 25% the Cohen Kappa statistic increases to 0.952 (almost perfect strength) (Appendix 6.8).

I did a comparison between the validation results obtained for the Canadian human footprint and those of the global human footprint clipped to Canada to demonstrate that the Canadian product is a better representation of what is on the ground. The global human footprint obtained a root mean squared error of 0.10 on a normalized 0–1 scale for the same validation plots (Chai & Draxler 2014). For the Cohen Kappa statistic, the value obtained was 0.762 using 20% agreement, which is considered substantial agreement between the human footprint and the validation data set, demonstrating lower agreement than the Canadian product (Landis & Koch 1977; Pontius & Millones 2011).

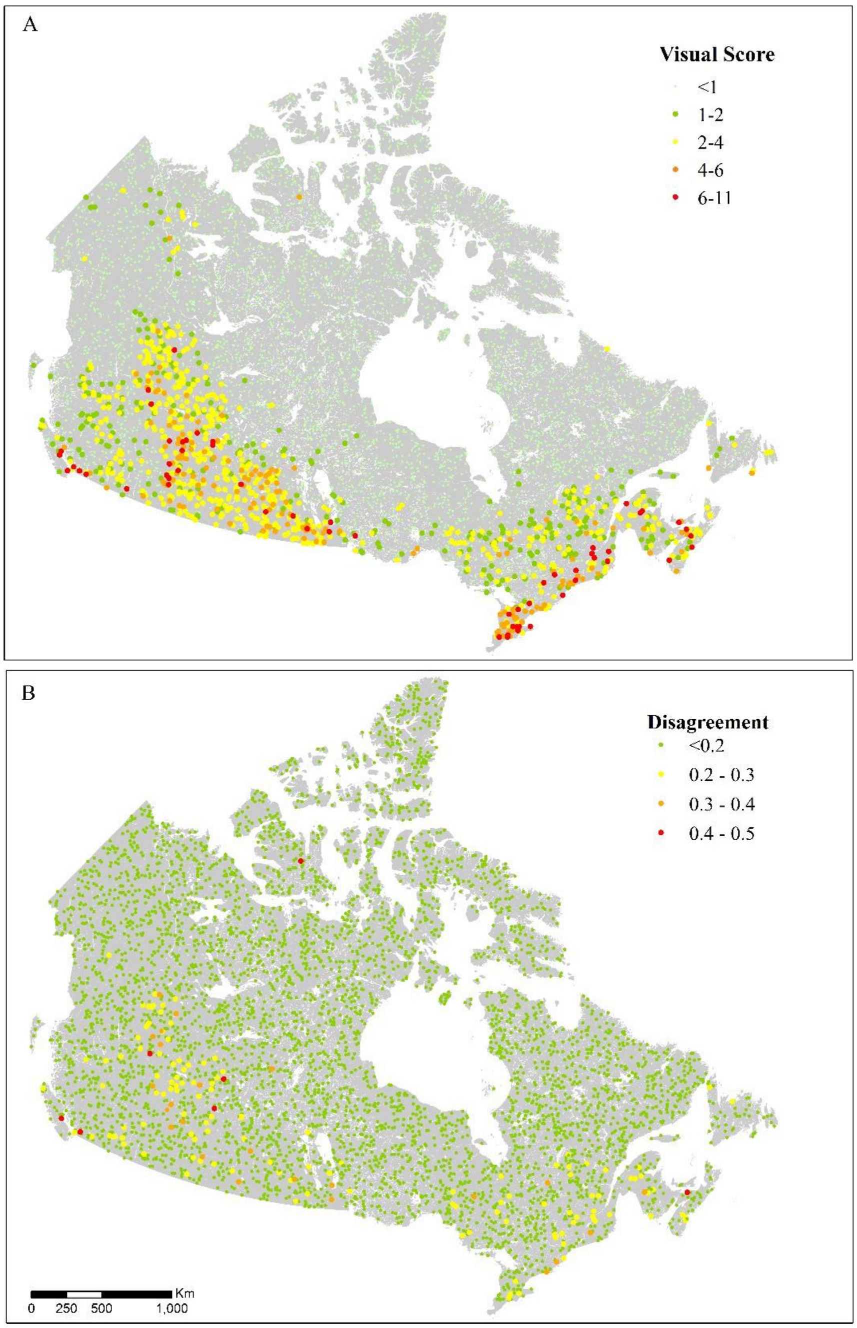

Figure 3.4: Results from the 4,746 x 1km^2 validation plots interpreted and scored following Appendix 6.6. (A) the visual interpretation score assigned and location for plots, and (B) the disagreement between the Canadian human footprint score and the visual interpreted score for validation normalized on a 0-1 scale.

3.4 Discussion

This is the first national attempt to produce a continuous measure of human threats to biodiversity and ecosystem services across Canada, which I term the Canadian human footprint. While I find that the large majority of Canada is still considered wild (82%), by my definition, the ecosystems in the country are still exposed to numerous threats. Overall, the individual threat that had the highest mean human footprint value, out of the 12 anthropogenic threats I observed, was roads. My dataset improves upon the global product by increasing the number of relevant threats measured and by rescaling to a finer resolution through the use of national datasets. Understanding where there are overlapping threats on the natural system provides more insight for preventing and mitigating threats to biodiversity than an access map of Canada that acts as a binary presence or absence of access.

Wilderness in Canada

Wilderness areas worldwide are experiencing increasing threats from human land use, therefore the need to protect wild areas to help conserve biodiversity and ecosystem services is becoming more apparent. Furthermore, the importance of large-scale and intact ecosystems is increasing as these wild areas become rarer (Watson et al. 2016). Using the 12 anthropogenic threats, of the eight National Ecological Areas in Canada, five of them have over 50% of their area in a wild state; the Arctic has over 99%, the Northern Mountains has over 95% and the Boreal follows with over 83%. This demonstrates promising numbers for the three largest ecological areas in Canada, however, the Boreal was found to be experiencing significant forest loss and degradation from natural resource exploration, industrial forestry, rapid climate change and anthropogenic fires (Watson et al. 2016). Although faced with criticism, the Canadian Boreal Forest Conservation Framework provides an outline on how to protect at least

50% of the forest through a network of connected protected areas, to prevent excessive degradation, which is crucial to protect wild areas of Canada (Nishnawbe Aski Nation n.d.; Boreal Leadership Council 2003).

Canada has little wilderness left in three of the eight ecological areas (Great Lakes Plains, Prairies and Atlantic). My human footprint shows where species are experiencing the most anthropogenic threats and would likely have the least intact natural ecosystem function. However, it is known that certain species can thrive in large cities and built environments (Sanderson et al. 2002). As mentioned above, Canada Target 1 cites the importance of the 17% of terrestrial land to be ecologically representative (Convention on Biological Diversity 2020). With the Atlantic, Prairies and Great Lakes Plains areas containing less than 45%, 15% and 5% of wild or intact lands respectively, it is unclear how Canada will develop protected areas that represent the ecosystems in those regions.

Threats to Biodiversity

One of the most prevalent threats to wilderness and biodiversity are roads. The existence and expansion of roads cause direct and indirect threats to ecosystems, such as fragmenting habitats and by providing a means of access into wild areas (Sanderson et al. 2002; Lee & Cheng 2014b). For conservation efforts, roads are one of the important threats to address (van der Marel et al. 2020), especially in Canada where roads are the most prevalent threat.

Conservation planning recognises the need to understand the patterns of threats and how they interact with each other to help achieve future conservation targets (Margules & Pressey 2000). COSEWIC identified that species classified as “at-risk” in Canada are most commonly affected by the threat of habitat loss, affecting over 80% of species included (Venter et al. 2006; Woo-Durand et al. 2020). I mapped nine threats that directly contributed to habitat loss for the

Canadian human footprint to help address the threat that most commonly affects Canadian biodiversity “at-risk”. A global analysis of over 8,000 threatened or near-threatened species found the threats with the largest impact on biodiversity were overexploitation, followed by agricultural activities then urban development (Maxwell et al. 2016). With my product the incorporations of the above threats occur with the inclusion of crop land, forestry, built environments and pasture land layers, all of which fall within the top six mean human footprint scores for Canada. With Canada’s “at-risk” species facing more than one threat (Woo-Durand et al. 2020), the utility of the Canadian human footprint, which includes the threats that are most affecting biodiversity (Maxwell et al. 2016), is an important tool for conservation planning and the mitigation of such threats.

Data comparison: Global vs. Canadian

While the overall intensity, or the mean human footprint score, remained low, I found several differences when comparing global and national human footprints. The most significant difference in the mean human footprint score was found in nighttime lights. Nighttime lights for Canada had a mean human footprint score 18 times less than in the global human footprint. The reduction in score from the global to the national product is the result of using more recent and higher resolution imagery that addresses saturation and spillage observed with the global product (Elvidge et al. 2013).

Producing the human footprint for Canada also allowed me to include datasets that were nationally relevant and offered more information and detail than many of the global ones. The largest increase in mean human footprint score comes from crop land which has a mean human footprint score over six times higher than that in the global product. The improved accuracy for mapping crop land could be part of the reason we see higher footprint values in the Prairies when compared to the global product, as the Prairies are a large agricultural centre for the country. Furthermore, the Canadian dataset for roads allowed for the inclusion of minor roads which the global dataset could not include (Venter et al. 2016b). The Canadian data led to a near doubling of the mean human footprint score for roads when compared to Canada's score with the global data. There is still room for improvement however, since when I compared the national roads with some provincial road data we see that the national data still does not capture all the dynamic resources roads and some of the smaller roads, showing that I have underestimated the presence of roads in Canada.

The global human footprint and the Canadian human footprint show the same overall patterns of threats. However, I found more disagreements in the validation in areas where there were more threats overlapping. By developing a finer resolution national product with Canadian data we can measure the improvements from global human footprints and confirm the soundness of my human footprint with the almost perfect validation score. This demonstrates the importance of national studies for conservation of biodiversity and ecosystem services (Woolmer et al. 2008).

Future Efforts

This is the first national product for the Canadian human footprint and I recognize the potential for improvements. Firstly, there were some threats that could not be included in the national product due to the lack of data. Certain threats, such as seismic lines or outdoor recreation like trails, appeared in approximately 1% of the validation plots but were not mapped as there was no national dataset for oil and gas exploration and recreation. A comprehensive recreation and tourism system is still needed, but we know that recreation is often found near roads built for resource extraction as they can provide means of access into nature (Mullins & Wright 2016).

These should be a priority for future improvements to my work. There were also threats affecting terrestrial endangered species in Canada, such as extreme weather and introduced species, that I was unable to incorporate in the human footprint (Venter et al. 2006; Woo-Durand et al. 2020). My product only included terrestrial anthropogenic threats, so it is important to note that threats to the aquatic ecosystems were not included. Secondly, there were four datasets (built environments, crop land, pasture land and nighttime lights) that did not cover the whole extent of the country, as they excluded certain northern areas. Despite lower population density in the north, natural resource exploration in the region has increased, bringing with it more temporary workers and work camps (Ensign et al. 2014). Thirdly, the datasets for mining and oil and gas only provided point features. When performing spatial analysis, only having a point feature and not the complete polygon boundary or linear feature of the threat will not display the complete area. I account for this limitation with the scoring system using a series of buffers, decreasing the score further away from the centralized point. However, I still may have underestimated the threats associated with those point features. Lastly, my product is not immune to the limitations of the field such as mixed pixel problems that arise when resampling to the resolution of the project, assumption of linear responses and consistent ecosystem responses to threats (Halpern & Fujita 2013).

My Canadian human footprint map provides a baseline for the country's threats which can allow for future comparisons to be made to measure changes in threats over time as more national biodiversity protection policies and initiatives are implemented. My cumulative threat map provides the first step towards being able to translate mapped threats to the impacts of those threats for biodiversity and ecosystem services. I demonstrate that Canada does contain large wild areas which is in line with Watson et al. (2016) who identified North America as one of the areas in the world with the most remaining wilderness. Therefore, understanding how ecosystem services are impacted from cumulative threats on the landscape is crucial for future prevention and mitigation of biodiversity loss and degradation of ecosystem services in a country where large wilderness areas still remain.

4. CONCLUSION

My thesis was structured to better understand the practice behind cumulative threat mapping and develop the first human footprint map for Canada. Here, I reiterate the main findings from chapter 2 and 3 and discuss the significance for conservation science. I also explore the overall conclusions from the thesis as a whole. The limitations that arose from the research are shared before adding my thoughts on future avenues to explore that could build upon my contributions to science.

In chapter 2, I conducted a global comprehensive review of the 65 peer-reviewed papers to highlight the trends in methodology for mapping cumulative threats as a means to consolidate current knowledge on the subject. I found that studies were present in each of the Earth's realms (terrestrial, marine and freshwater). I also investigated whether the 12 identified threat categories, in the threat classification scheme, were mapped. I found that of the 12 threat categories identified, some threats were accounted for more than others. For example, there were many cases of pollution being mapped while very few measured climate change. I asked what the geographic scope of studies were, while the different terrestrial biomes were well represented in the literature, the marine and freshwater biomes were not. The marine realm had an uneven geographical representation of its 12 biomes, with two biomes representing the majority of the studies. Furthermore, there were so few studies in the freshwater realm (n = 7) that I was not able to perform a similar review of cumulative threat mapping. I also found that 88% of the world's terrestrial land lacks regional analyses of cumulative threats, with fewer studies in countries of low or lower middle income compared to the upper middle and high income classes. I identified if studies mapped threats that were temporally static or dynamic, and if they were presenting information on pressure, state, or impact of the threats. I found that the majority of studies mapped a single snapshot of cumulative threats as opposed to through time and most mapped only pressure and not the impacts of the threats studied.

By producing the first, to my knowledge, comprehensive review of what threats are being mapped, where and how studies are mapping threats or impacts, I provided insight and highlighted areas for future research. The review provides examples of studies that mapped cumulative threats in the freshwater realm, temporally, or how studies have mapped cumulative impacts from pressures to inform future users what techniques have been applied in the past. Through this review I found that there were no human footprint analyses established for the whole of Canada. I also noted that the global human footprint performed worst for Canada in their technical validation of global terrestrial land, highlighting the need for future studies. The threat of logging is affecting many threatened species (Maxwell et al. 2016), yet it was not being included in cumulative threat maps. I therefore made a point of finding a forestry dataset for Canada to incorporate clear cut logging in the threats I mapped. By using the information from the literature review I was able to look at the methods other studies have used to establish their threat weights for the 12 different layers I included in the Canadian human footprint.

The Canadian human footprint, chapter 3, provides the first national continuous measure of anthropogenic threats to biodiversity and ecosystem services. With use of spatial analysis, I produced a 300-metre resolution map incorporating 12 human threats. I found that around 82% of Canada is classified as wild. Whereas, more occurrences of cumulative threats are in the southern part of Canada, as I expected. The National Ecological Area with the least amount of wild was the Great Lakes Plains, with under 1% and also had the most intense high human footprint at 75%. Notably, the Atlantic National Ecological Area had the most even distribution of wild, intact, moderate and high human footprint values.

Roads were found to be the most pervasive threat in Canada, used to connect communities to one another and to industry. I used higher resolution and Canada specific datasets to improve upon a previous global-scale footprint maps (Venter et al. 2016a). By including additional threats relevant to Canada from the natural resource industry and rescaling to a finer resolution it has resulted in a more accurate representation of the nation. I used the methods from Venter et al. (2016a, 2016b) to demonstrate the accuracy with use of technical validation, comparing plots from the human footprint map with high resolution satellite imagery plots recording root mean squared error and Cohen Kappa Statistics.

A large part of my analysis was the visual scoring of satellite imagery and statistical comparison to the human footprint scores. I found that areas with a greater mean human footprint score had a higher chance of disagreement with the visual scoring. Taking into account that a large percentage of the country does not have the presence of human threats, a random sampling design for the validation process could have biases, so future consideration into stratified sample plots should be assessed (Olofsson et al. 2013, 2014). However, it is only recently that any human footprint map has used a form of validation, so I am able to have stronger confidence in my product as it has undergone a form of validation with high resolution satellite imagery (Venter et al. 2016a, 2016b).

Producing the baseline for anthropogenic threats in Canada provides insight for preventing and mitigating threats to biodiversity and ecosystem services. By rescaling the human footprint, I have provided a tool for Canada that is spatially relevant with a resolution that can be applied to the whole of Canada or a smaller planning unit (Sanderson et al. 2002; Woolmer et al. 2008).

My results highlight future challenges that may arise when planning ecologically representative protected areas in Canada (MacKinnon et al. 2015), as the Great Lakes Plains and Prairies National Ecological Areas have little wild areas remaining. As Canada continues to plan for greater conservation efforts (Liberal Party of Canada 2019), utilizing the Canadian human footprint as a means for understanding the spatial extent of anthropogenic threats and assessing future patterns will be important (Margules & Pressey 2000). The human footprint could also be used as a tool for planning and monitoring conservation efforts (Haines et al. 2008). My Canadian human footprint product is already in demand for connectivity, conservation and planning tools and applications, demonstrating how my work is helping to fill the knowledge gap that previously existed.

After reviewing cumulative threat literature and producing a human footprint map, there are a few emerging themes. I noted through the comprehensive literature review that cumulative threat mapping studies are not always including the threats that are most relevant to biodiversity. Considering the threats that affect biodiversity most globally (Maxwell et al. 2016) and within Canada (Woo-Durand et al. 2020), I sought to develop a human footprint map incorporating threats with the most up to date layers. Although I did address parts of the three 'big killers' for global biodiversity - Over-exploitation with logging, Agricultural Activity and Urban Development (Maxwell et al. 2016), I was unable to include introduced species that affect 46% of Canada's "at-risk" species and many aspects of habitat loss and overexploitation (Woo-Durand et al. 2020). Even though habitat loss from seismic lines and recreation trails could be seen with high resolution imagery in my validation plots, there were no national spatial datasets that could be applied. Many of the factors contributing to land use change are complex in the way they interact and many of the driving forces of threats to ecosystems cannot be mapped spatially (Lambin et al. 2003). I have found that overall data deficiencies in quality, access and availability are frequently a limiting factor when using spatial data. There are often calls for more and better data, so this conclusion is not new (Morrison 1995). However, it is clear that in the relatively short timeframe that cumulative threat studies have been taking place, the advancements in data quality and availability (e.g. through means of open access, better satellite imagery and data repositories) have led to innovative uses for conservation science and practice (Watson & Venter 2019; Riggio et al. 2020). Overall, cumulative threat mapping is a powerful tool with a number of applications which can aid to mitigate anthropogenic threats on the environment.

There are many opportunities for continued research from my thesis. From the literature review in chapter 2, it would be interesting to complete another comprehensive review in a few years to observe if we are seeing the same patterns and methods of mapping cumulative threats. As I highlighted, there is a lack of regional studies covering areas of low income and lower middle income class countries. By completing another review, we could better identify the trends in the field. A different area to include in future reviews is how the human footprint is being used as a tool for planning and monitoring conservation efforts. As data availability improves, an updated review could gather information on whether cumulative threat maps are moving towards incorporating threats driving biodiversity trends and if there are additional temporal analyses as more yearly data emerges.

For chapter 3, mapping the Canadian human footprint, the potential for temporal analyses would provide a unique opportunity to track patterns of Canada's wild areas and areas under highest human threat. Temporal analyses for cumulative threats in Canada for 2020, 2025 and 2030, could address whether the increase in protected areas promised (Liberal Party of Canada

2019) is leading to a reduction in cumulative threats across the country. By applying the techniques and scoring used in my Canadian human footprint, we could address if plans to conserve more terrestrial lands in Canada are leading to a reduction in anthropogenic threats in the most human dominated National Ecological Areas. As Canada still has around 82% of terrestrial land in a wild state, conserving 30% terrestrial lands by 2030 should be feasible, however the extent of wild areas is not evenly distributed across all National Ecological Areas.

In this thesis, I develop the first human footprint map for Canada by using the knowledge obtained from my review of cumulative threat mapping. Understanding where threats overlap is the first step towards consolidating conservation action for protection and restoration. By providing open access to the data, future research can build on my product and continue to advance conservation science and planning for the wellbeing of all Canada.

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6. APPENDICES

Appendix 6.1

List of the 65 studies included in the review and the number of Threats mapped, Scale, Realm, whether a study mapped Pressures, State or Impacts, and Timescale.

Study	Number of Threats Mapped	Scale: Global (G), Continental (C), National (N) or Regional (R)	Realm: Terrestrial (T), Marine (M) or Freshwater (F)	Pressure (P)-State (S)-Impact (I)	Static (S) or Dynamic (D) Timescale
(Andersen et al. 2017)	5	R	M	P	S
(Aplet et al. 2000)	10	N	T	P	S
(Ban & Alder 2008)	39	R	M	P	S
(Ban et al. 2010)	38	R	M	P	S
(Batista et al. 2014)	19	R	M	P	S
(Bellard et al. 2015)	8	N	T	P	S
(Carver et al. 2002)	4	N	T	P	S
(Carver et al. 2012)	10	R	T	P	S
(Clarke Murray et al. 2015a)	46	R	M	P	S
(Clarke Murray et al. 2015b)	12	R	M	P	S
(Coll et al. 2012)	19	R	M	P-S	S
(Correa Ayram et al. 2017)	8	R	T	P-S	S
(Danz et al. 2007)	75	R	F	P-S	S
(Etter et al. 2011)	10	N	T	P	S
(Geldmann et al. 2014)	3	G	T	P	D
(González-Abraham et al. 2015)	5	N	T	P	S
(Goodsir et al. 2015)	5	R	M	P	S
(Grech et al. 2011)	9	R	M	P	S
(Halpern et al. 2008a)	17	G	M	P	S
(Halpern et al. 2009)	25	R	M	P	S

(Halpern et al. 2015)	19	G	M	P	D
(Henriques et al. 2014)	16	R	M	P	S
(Holon et al. 2015)	10	R	M	P	S
(Inostroza et al. 2016)	13	R	T	P	S
(Jarvis et al. 2010)	7	C	T	P	S
(Kano et al. 2016)	3	R	F	P	S
(Kelly et al. 2014)	11	R	M	P	S
(Kline et al. 2013)	4	R	T	P	S
(Korpinen et al. 2012)	14	R	M	P	S
(Korpinen et al. 2013)	15	R	M	P	S
(Lasram et al. 2016)	9	R	M	P	S
(Leu et al. 2008)	12	R	T & F	P-S-I	S
(Lin et al. 2016)	5	R	T	P	S
(Mach et al. 2017)	19	R	M	P	S
(Marcotte et al. 2015)	5	R	M	P	D
(Mattson & Angermeier 2007)	12	R	F	P	S
(Maxwell et al. 2013)	24	R	M	P-S	S
(Micheli et al. 2013)	23	R	M	P	S
(Morzaria-Luna et al. 2014)	25	R	T & M	P	S
(Orsi et al. 2013)	7	R	T	P	S
(Pasher et al. 2013)	15	R	T	P	S
(Paukert et al. 2011)	11	R	F	P	S
(Pert et al. 2012)	7	R	T	P	S
(Pertierra et al. 2017)	9	C	T	P	S
(Poudyal et al. 2016)	3	N	T	P-S	S
(Rodríguez-Rodríguez & Bomhard 2012)	4	G	T	P	S
(Roth et al. 2016)	7	N	T	P	D

(Sanderson et al. 2002)	9	G	T	P	S
(Selkoe et al. 2009)	14	R	M	P	S
(Shackelford et al. 2017)	5	R	T	P	S
(Shen et al. 2016)	3	R	M	P	S
(Stelzenmüller et al. 2010)	9	N	M	P	S
(Sterling et al. 2014)	13	R	F	P	S
(Tallis et al. 2008)	5	R	M	P	S
(Tapia-Armijos et al. 2017)	7	R	T	P	D
(Theobald 2013)	14	N	T	P	S
(Venter et al. 2016a)	8	G	T	P	D
(Verones et al. 2017)	12	G	T	P-S-I	S
(Vimal et al. 2012)	4	R	T	P-S	S
(Vörösmarty et al. 2010)	23	G	F	P	S
(Walker et al. 1986)	16	R	T	P	D
(Wang & Zhonglin Xu 2016)	9	G	T	P-S-I	S
(Whitehead et al. 2016)	6	R	T	P-S-I	S
(Woolmer et al. 2008)	10	R	T	P	S
(Yermolaev & Usmanov 2014)	6	R	F	P	S

Appendix 6.2

Re-classification of pressures into the unified threat classification scheme

For all cumulative threat papers I identified all their listed threats and reclassified them into the threat classification scheme to create a way to assess which threats are being mapped. The table below has separated the threats into the different categories by realm.

Threat Categorization	
Residential & Commercial Development	
Terrestrial Realm	urban, industrial, rural residential, infrastructure, residential density, tourism and recreation areas, settlement, built environments, nighttime lights, dwelling density, built-up centers, population settlements, stable lights, urban centers, villages, developed land, human settlements, artificial building, huts, urban areas, population centers, human artifacts (built up lands), urbanization, fragmentation for housing and infrastructure, residential, development, construction (induced thermokarst), gravel pads, cities, towns, remote sites, facilities, campgrounds, rest stops
Marine Realm	beaches, industrial infrastructure, marinas, pulp and paper, towns (human settlements), fishing and other lodges, ports, harbors, industry, boat launches, moorage, docks, piers, built up areas, lighthouses, urban areas, urbanization, beach access, human settlements, industrial tenures, recreational fishing lodges, sailing competition areas, urban and port development, coastal infrastructure, pile driving works, inland socioeconomic activities
Freshwater Realm	developed land, residential, commercial/industrial, urban/recreational grasses, facilities that physically disturb the landscape, urban areas, industrial areas, manufacturing sites, settlement area %, portion of streams bounded by human land use, portion of watershed with human land use, portion of watershed with erodible soils and human land use, urban landcover
Agriculture & Aquaculture	
Terrestrial Realm	Crop land, pulp and paper plantation, agriculture, pasture land, land transformation to crop land, aquaculture areas, marine aquaculture, cultivated grasslands, forestry plantations, perennial crops, heterogenous agriculture, conversion to agriculture, grazing pressure, arable and horticultural lands, fragmentation for agriculture, irrigation agriculture, rain-fed agriculture, introduced grasslands, agricultural intensification, agricultural land area, vegetal cover
Marine Realm	aquaculture activities, finfish aquaculture, shellfish aquaculture, agriculture, fish farming
Freshwater Realm	amount of cultivated crop land, row crops, orchards/vineyards, amount of grazing land, pasture/hay, amount of non-cultivated crop land, soil loss, aquaculture pressure, crop land, livestock density, pastures, cultivated area %, agriculture landcover, agriculture

Energy Production & Mining	
Terrestrial Realm	basic raw materials, mining, oil and gas wells and infrastructure, wind turbines, seismic exploration line, electrical power infrastructure, oil/gas exploration blocks, mineral deposits, hydro-electric infrastructure, excavations of river gravels or other gravel sources, biomass burning, oil rigs
Marine Realm	presence of oil rigs, thermal plants, benthic structures, onshore mining, terrestrial mining, Coastal Power Plants, power plants, marine renewables (tidal and wave licensed sites), selective extraction of non-living resources, the extraction of hydrocarbons, renewable energy, Coastal nuclear power plants, wind farms
Freshwater Realm	mine density, mine processing plant density, quarries/strip mines/gravel pits, mining sites, fragmentation of forest for oil industry, acid rock drainage risk, oil-gas wells
Transportation & Service Corridors	
Terrestrial Realm	road type, highway traffic, utility powerlines, towers, pipeline, railway, road, airstrip, navigable waterways, utility corridors, main roads, secondary roads, paths, maritime routes, projected roads, fragmentation from roads, cable car stations, accessibility, tracks, bridges, electrical power infrastructure, road density, fragmentation due to transportation infrastructure, road infrastructures, gravel roads, pipeline construction roads, peat roads, winter roads, vehicle tracks (deeply rutted or with thermokarst), vehicle tracks (not deeply rutted), major highways, visitor landing site, shipping, terrestrial access, aerodromes, federal and state highways, interstate highways
Marine Realm	maritime traffic due to shipping and other transport, dredging disturbance and work, shipping lane, cruise ship routes, anchorage, ferry route, commercial shipping, roads, ship strike risks, forestry roads, pipelines, forest service roads, paved roads, recreational boat routes, anchoring areas, boat damage(commercial and recreational), coastal infrastructure (cables and pipelines), ship wrecks, telecommunications, sand extraction
Freshwater Realm	road density, transportation, railroad density, bridges, length of road within 30m of streams, road length on erodible soils, stream road crossing, stream crossings
Biological Resource Use	
Terrestrial Realm	cutblock, forestry, plantation trees
Marine Realm	bottom trawling , artisanal fisheries, non-habitat destructive purse seines, multi-gear local vessels, multi-gear coastal vessels, pelagic low-bycatch fishing, pelagic high-bycatch fishing, demersal habitat-modifying fishing, demersal non-habitat-modifying low-bycatch fishing, demersal non-habitat-modifying high-bycatch fishing, demersal destructive, demersal non-destructive high bycatch, demersal non-destructive low bycatch, demersal fisheries high

	bycatch, demersal fisheries low bycatch, dive, traps, recreational fishing, logging, bottom fishing, forestry cutblocks, log booms, sport fishing, hook and line, vessel, fishing with angling from shoreline, spearfishing, fishing with angling from boat, netting, commercial fisheries (finfish, shellfish), selective extraction of species, industrial fishing, abrasion from fishing, demersal trawling fishery, bottom longline, surface longline, gillnet, trammel net
Freshwater Realm	fishing pressure
Human Intrusion & Disturbance	
Terrestrial Realm	population density, coastlines, rivers, touristic zones, coast, population stress, hiking trails, ski trails, rural population density, stations' area of influence, visitor sites' area of influence, populated areas, direct human impact
Marine Realm	scuba diving, recreational motor boating, larger estuaries (population concentrations), direct human impact, human trampling, coastal population density, research wildlife sacrifice, research diving, research equipment installation, recreational sport activities, use of beaches, coastal infrastructure (shore access), boat anchoring, population density
Freshwater Realm	Trail density (4wd roads & walking trails)
Natural System Modifications	
Terrestrial Realm	Cover dominated by introduced species, dams, reservoirs, disturbed forested lands, fires, impounded inland water, land transformation, wildfires, continuous flooding (more than 75% open water), Discontinuous flooding (less than 75% open water), Barren tundra (caused by previous flooding), blue water consumption, irrigation canals
Marine Realm	coastline artificialization, artificial reefs, small estuaries and coastal lagoons (ecological quality), bulkheads and other forms of shoreline hardening, coastal engineering, Sediment Increase, Sediment decrease, coastal erosion, coastal aggregation, ocean engineering, ocean deposition, physical submarine and shoreline structure, abrasion of seabed, sealing of seabed, changes in thermal regime, changes in salinity regime, changes in siltation, land reclamation projects, man-made coastline, coastal dams, coastal erosion defense structures, beach replenishment, coastline exploitation
Freshwater Realm	human water stress, agricultural water stress, dams, river fragmentation, impervious surfaces, wetland disconnectivity, consumptive water loss, soil salinization, potential acidification, thermal alteration, flow distribution, gully dissection density, eroded soil area %, portion of streams behind dams, groundwater withdrawal, registered surface water withdrawal, canals, diversions, irrigation canals

Invasive & Other Problematic Species, Genes & Diseases	
Terrestrial Realm	biological invasions, weeds, feral animals, introduced palm, insects, disease, exotic vegetation that has displaced native species, invasive species
Marine Realm	presence of invasive species, alien species, introduction of microbial pathogens
Freshwater Realm	facilities discharging pathogens, non-native fishes(%), non-native fishes(no)
Pollution	
Terrestrial Realm	thermal, gravel and construction debris, heavy dust or dust-killed tundra, Barren tundra (caused by oil-spills, burns blading ect.), light pollution, agricultural phosphorus application by fertilizer and manure, agricultural nitrogen application by fertilizer and manure, NH3, NO, SO2, CO2, GHG-CH4, GHG-N2O
Marine Realm	shipments of toxic substances (e.g. toxic waste, radioactive waste and fertilizers) and other ocean-based pollution from shipping traffic, deposition of heavy metals, deposition of inorganic nitrogen, nutrient runoff, hypoxia, sewage, dredging deposition, ocean pollution, ocean dumping, log dumping, sedimentation from forestry, disposal sites, nutrient pollution, organic pollution (nonpoint source and point source), inorganic pollution (nonpoint source and point source), light pollution, nutrient input (fertilizer, manure and atmospheric deposition of nitrogen, potassium), noise pollution, atmospheric deposition of pollutants, marine debris (trash), pesticides, oil spills, ship-based pollution, coastal waste, sediment runoff, disposal at sea, submarine sewage outfall, stream pollution, bathing water quality, marina (water quality), urban and industrial runoff, shipping accidents, agricultural runoff, wastewater discharges, introduction of synthetic compounds, introduction of non-synthetic substances and radio-nuclides, smothering by dumping material, localized hydrocarbon contamination, urban effluents, industrial effluents, disposal of dredged matter, waste water treatment plants
Freshwater Realm	area with animal facility nutrient treatment application, manure leaching and runoff, nitrogen fertilizer (application, leaching, runoff), pesticide (use, leaching and runoff), phosphorus fertilizer (application, leaching, runoff), Sediment rank (loading, erosion and runoff in streams), herbicides, deposits from atmosphere (calcium, chloride, hydrogen ion, potassium, magnesium, sodium, ammonium, nitrate, sulfate), inorganic nitrogen deposition, facilities discharging materials (chlorinated compounds, hydrocarbons, heavy metals, nutrients, particulates, pharmaceutical compounds, salts, solvents), sewerage systems, power plant emissions (CO_2, NO_x, SO_2), nitrogen loading, phosphorus loading, mercury deposition, organic loading, National Pollutant Discharge Elimination System permit sites, non-point discharge elimination system, waste facilities and landfills

Climate Change & Severe Weather	
Terrestrial Realm	climate change, sea-level rise, climate stress
Marine Realm	the intensity of ultraviolet (UV) radiation (increases), ocean acidification, sea level rise, sea surface temperature anomalies (increases), sea surface temperature anomaly: disease, bleaching, climate change
Freshwater Realm	acidification index, global temperature, global precipitation
Other Options	
Terrestrial Realm	unknown, natural land loss, fragmentation index, fragmentation, habitat loss
Marine Realm	habitat degradation, aggregates
Freshwater Realm	None listed

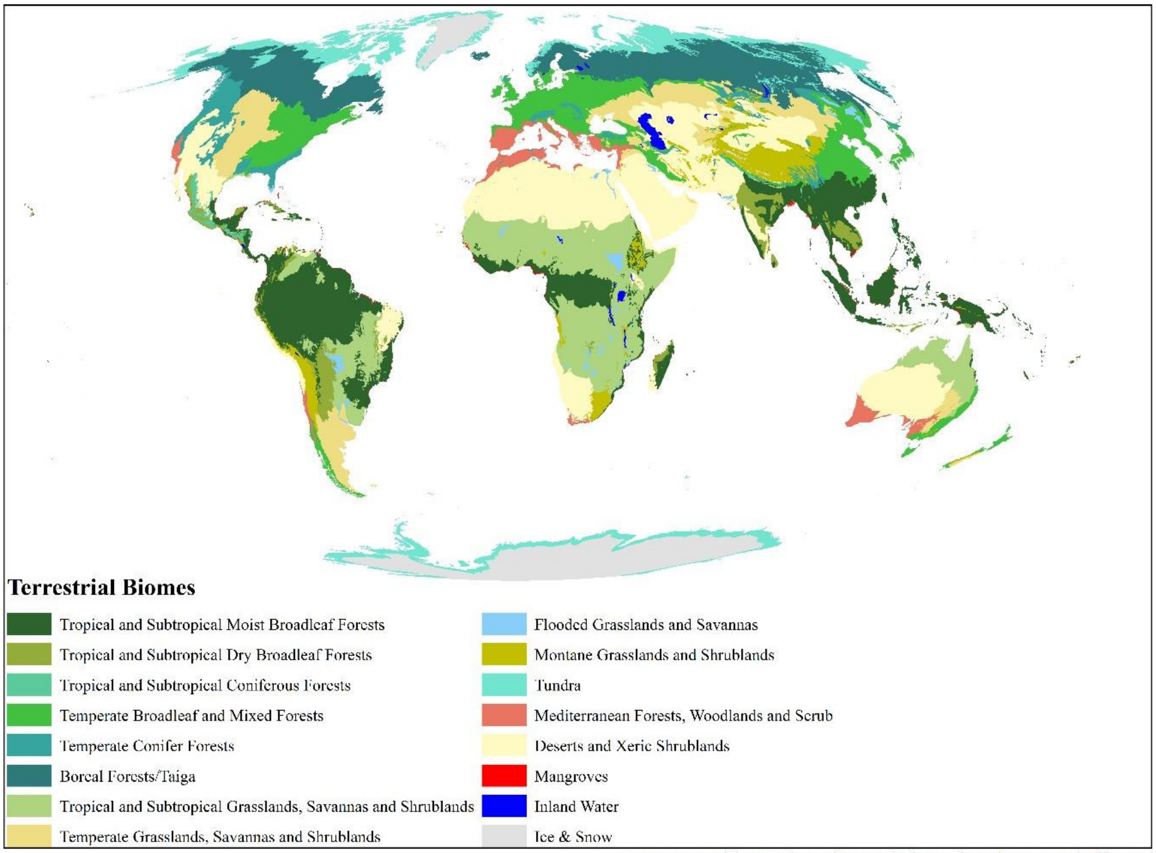
Appendix 6.3

Number of studies in each Terrestrial Biome (not including Global Studies). Map of the Terrestrial Biomes of the world in World Mollweide Projection are also provided.

When studies span more than one biome, they were included in each of the respective biomes (WWF 2012).

Terrestrial Biomes	Frequency of study
Tropical and Subtropical Moist Broadleaf Forests	11
Tropical and Subtropical Dry Broadleaf Forests	10
Tropical and Subtropical Coniferous Forests	8
Temperate Broadleaf and Mixed Forests	13
Temperate Conifer Forests	15
Boreal Forests/Taiga	7
Tropical and Subtropical Grasslands, Savannas and Shrublands	9
Temperate Grasslands, Savannas and Shrublands	9
Flooded Grasslands and Savannas	5
Montane Grasslands and Shrublands	3
Tundra	7
Mediterranean Forests, Woodlands and Scrub	11
Deserts and Xeric Shrublands	12
Mangroves	5
Inland water/ Lake	7
Rock and Ice	7

Terrestrial Biomes of the World



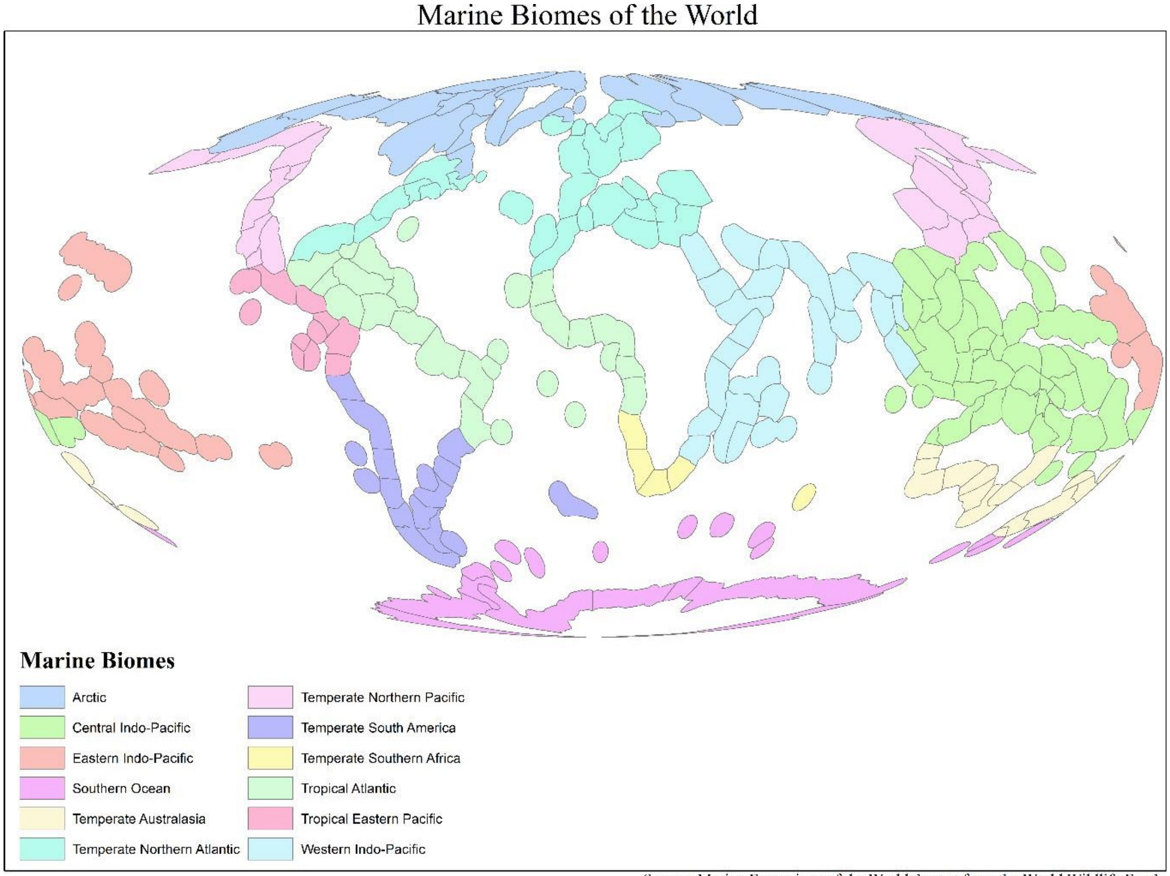
Source:Terrestrial Ecoregions of the World dataset from the World Wildlife Fund

Appendix 6.4

Number of studies in each Marine Biome (not including Global Studies). Map of the Marine Biomes of the world in World Mollweide Projection are also provided.
When studies span more than one biome, they were included in each of the respective biomes. (WWF 2007).

Marine Realms	Frequency of study
Temperate Australasia	1
Temperate Northern Atlantic	11
Temperate Northern Pacific	10
Eastern Indo-Pacific	1
Central Indo-Pacific	2
Arctic	1

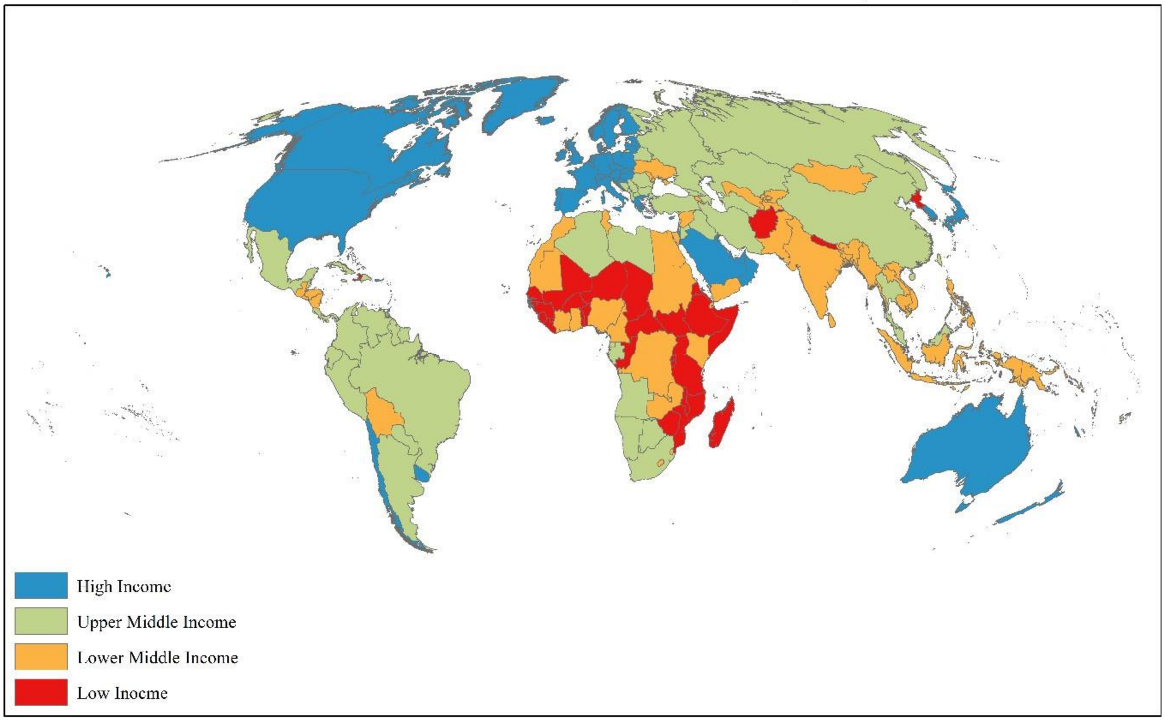
Marine Biomes of the World



Source: Marine Ecoregions of the World dataset from the World Wildlife Fund

Appendix 6.5

World Countries and their Income Class (2015)



Source: ESRI World Country Shapefile and World Bank OG History file for Country income class (2015)

Appendix 6.6

Visual interpretation of satellite images for mapping human threats (Adapted from Venter et al. 2016)

When interpreting images, interpreters can zoom in, zoom out and pan around to identify threats. For sample areas where only coarse scale Landsat images are available (i.e. 15 m resolution), images can be used if it is deemed that they are sufficient to allow classification for the area, which may be possible in highly green wildernessareas or in high latitudes where inhabitants are low. Often, when zoomed out in coarse resolution, it is possible to be certain of human threats. If after zooming and panning it is impossible to be certain, the data should be left blank and marked uncertain. For small areas within plots that have identified human threats, these areas are often assigned the land cover category of the wider landscape, i.e. urban, forestry or crops. For example, if there is bare ground across a plot within farmland, it is likely to be tilled farmland, likewise a brown patch in a forested landscape is likely to be a recently felled clear cut. Distinguishing between crops and pasture is a challenge, zooming in to look for linear planting lines or signs of cattle trails or their feeding/drinking points may help. Some land cover types are not mutually exclusive, for instance, urban areas may also be scored as high density for roads and human dwellings. Crops, pasture, urban and forestry are mutually exclusive at a site, but can co-occur within a $1km^2$ or $100km^2$ sample area. Following visual interpretation, interpreters should mark their interpretation as ‘certain’ or ‘not certain’. Certain means that 95% of the time you will be right. The resolution and year of each image will be recorded for all plots, whether or not they have data entered and are certain or not.

The samples are selected using a random sampling. Those are automatically overlaid with ESRI high resolution images within ArcGIS 10.5.1, allowing a rapid access to recent remote sensing images with zooming capabilities. If using ArcMap, ensure the plots are projected on the fly and the basemap is the source determining the projected coordinate system to speed up the process.

Figure 6.6.1 The level of detail of images available in many locations. In the first panel, horses can be seen grazing in front of the farm house, and hay bales can be seen wrapped and stacked to the right of the barn. In the second panel, the uniform grey of concrete, as well as individual containers and the cranes used to move them can be seen. Shape, size, texture and colour are important characteristics for identifying human threats on the environment.

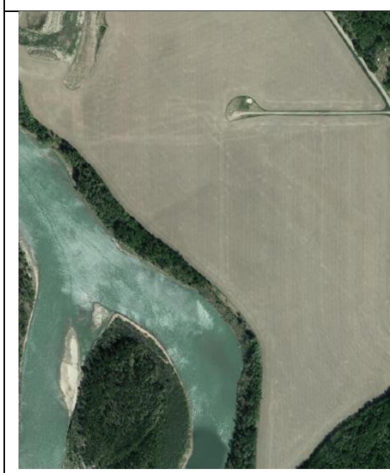
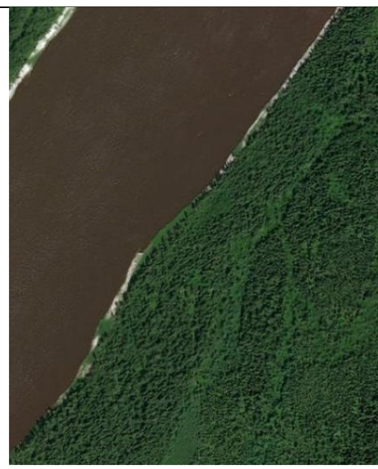
Threat	**Description**	**Scoring**
Built Environments	Built environments are human produced areas that provide the setting for human activity. These are primarily urban settings, including buildings, paved land and urban parks, and excludes isolated roads and isolated housing. These also include areas such as airports and unidentified industry. They are easily identified by sharp contrasts in tones, widespread homogeneous grey surfaces, and recognizable human constructed shapes. They are scored based on polygon scoring, a percent of the total image covered. Urban parks, golf courses, shopping centers are all examples of built environments.	None = 0, sparse = 1, <12.5% medium = 2, >12.5% dense = 3, >50%
		

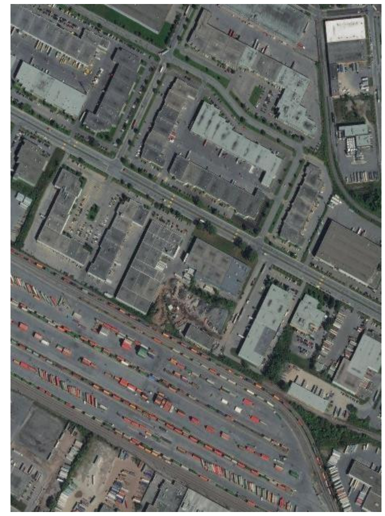
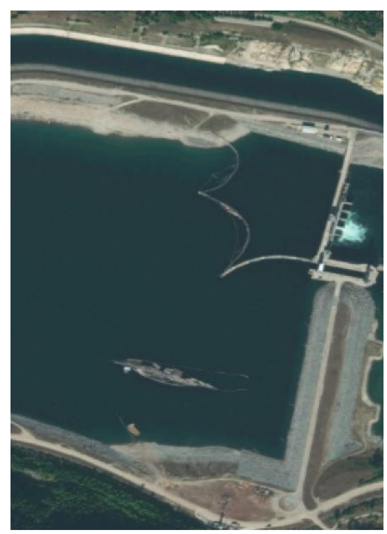
Crops	Crop lands are cultivated areas used for annual or perennial crops, such as orchards or vineyards. Typically exhibit a checkerboard pattern of crop land pattern from different crop stages (exhibited by varying grey tones) and differences in tillage directions. Crop land areas, generally devoid of trees, possess a smoother texture than pasture land areas and often have linear markings from planting, harvesting or tilling lines.	None = 0, sparse = 1, <12.5% medium = 2, >12.5% dense = 3, >50%
		
Pasture	Land covered with grass and grazing animals, especially cattle or sheep. Often characterized by fencing without linear cropping, but often with linear changes in vegetation blocks along fence lines. Cattle or their tracks, as well as vehicle access tracks may be visible.	None = 0, sparse = 1, <12.5% medium = 2, >12.5% dense = 3, >50%

		
Roads-paved, unpaved and private	Linear infrastructure with a wide homogeneous grey surface, and often a disturbed vegetation or bare earth band in parallel. Paved roads have a grey surface, unpaved roads have a brown surface. Unpaved logging roads can often appear grey, but can be determined unpaved by proximity to urban centers and general appearance of the surrounding landscape. Private roads are not used for transportation by the public, but rather provide private access, such as access to farm fields.	None = 0, sparse = 1, at least one road visible medium = 2, roads with length that traverses the image twice dense = 3, roads with length that traverses the image 5 times

		
Forestry	Harvesting of natural or plantation forest. Can be clear-fell harvesting, common in temperate forests, or selective logging. Clear-fell harvesting characterized by large patches of felled forest of often irregular shape following topographic features. Selective harvesting characterized by much smaller harvest patches, a network of dirt roads with noticeable small cleared areas with dirt surface used for landing logging. Plantation forests can be distinguished by their uniform tree cover, and sometimes linear planting rows. If an area has a threat from forestry, it is given an overall score for any and all forestry present there. If there are cutblocks that are recent such that slash piles and bareland is present, or bareland between the young light green trees, this is also given its own score for recent cut forestry. It is possible to have both categories scored as a 3, 2 or 1, or any other combination.	None = 0, sparse = 1, <12.5% medium = 2, >12.5% dense = 3, >50%

		
Human dwellings (looks at population density)	Human dwellings, including dense urban areas with apartment buildings, and sparser suburban and rural housing. It is only being assessed for number of human dwellings and no other infrastructure included.	None = 0, sparse = 1, <4 single-family dwellings per km^2 medium = 2, <20 single-family dwellings per km^2 dense = 3, >20 dwellings per km^2, or 1 apartment building per km^2
		

Navigable waterways	Navigable waterways appear wide and deep enough for a vessel to travel, and lack impassable areas of whitewater. Signs of human activity along the shoreline, such as human structures or roads leading to the water within 40km of the sample plot mean the waterway is likely to be navigated. This threat is scoring for access, not size of water body. If the entire image is water (ie: ocean) it only gets a score of 1 as there is still only one stretch of access points that it provides.	None = 0, sparse = 1, at least one navigable waterway medium = 2, navigable waterways with length that traverses the image twice dense = 3, navigable waterways with length that traverses the image 5 times
		
Railways	Linear infrastructure with a wide homogeneous grey or brown surface, and often a disturbed vegetation or bare earth band in parallel.	None = 0, sparse = 1, at least one railway medium = 2, rail with length that traverses the image twice dense = 3, rail with length that traverses the image 5 times

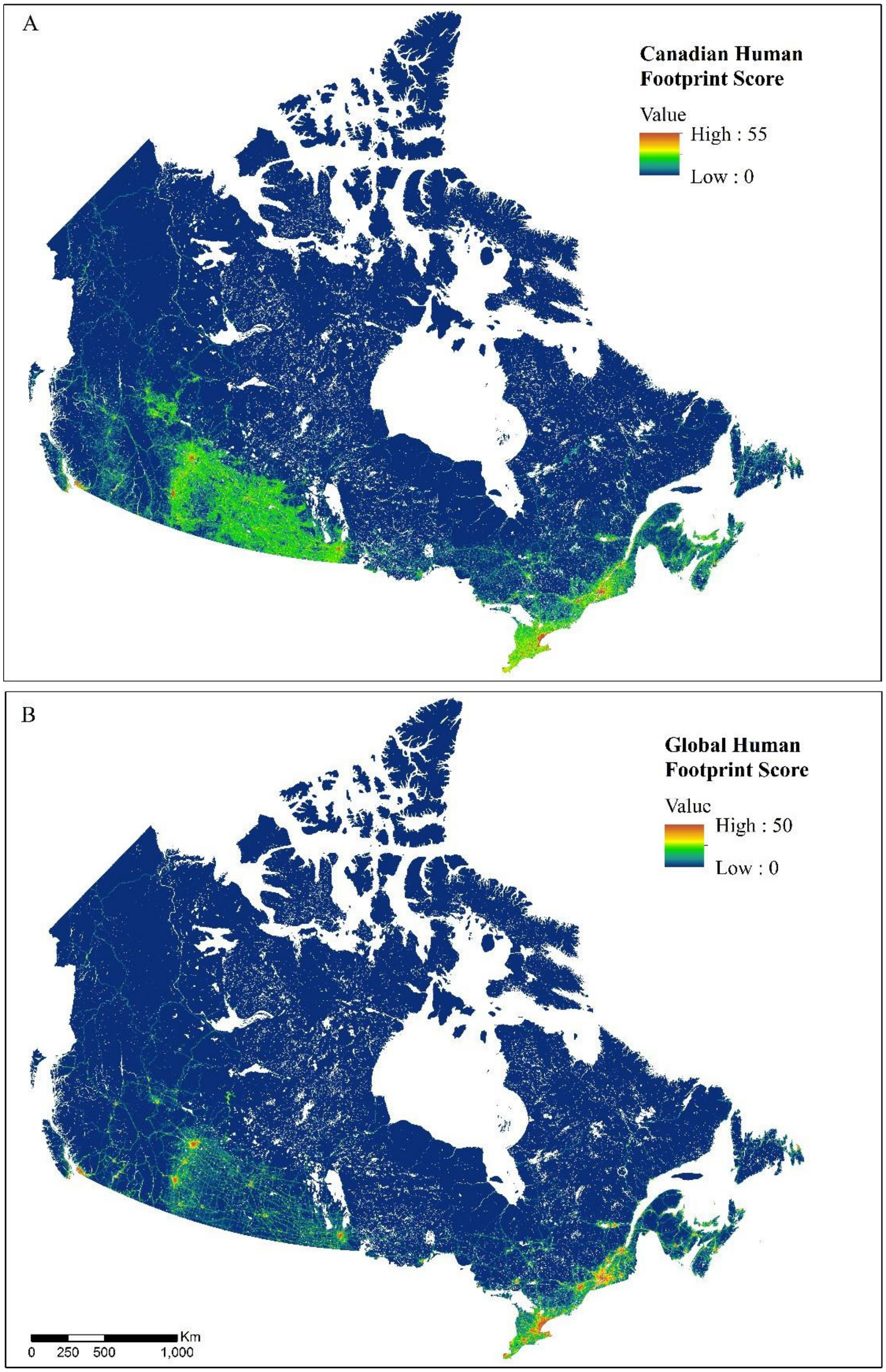
		
Dams	Linear infrastructure crossing a body of water, often grey in colour. Often associated with flooding on one side of the dam.	None = 0, sparse = 1, at least one dam visible medium = 2, dams with length that traverses the image twice dense = 3, dams with length that traverses the image 5 times
		
Mining and associated infrastructure	Areas of mining are often cleared of vegetation and appear grey in colour. Often associated with a few private roads connecting different sites and facilities.	None = 0, sparse = 1, <12.5% medium = 2, >12.5% dense = 3, >50%

		
Oil and gas extraction and associated infrastructure	Series of well pads and connecting linear infrastructure between areas. Often light grey as vegetation has been cleared from surrounding area. Two columns exist for this: linear infrastructure and polygon infrastructure (well pads, buildings, parking lots etc.) and should be scored separately.	Linear: None = 0, sparse = 1, at least one linear oil and gas feature medium = 2, linear oil and gas feature with length that traverses the image twice dense = 3, linear oil and gas feature with length that traverses the image 5 times Polygon: None = 0, sparse = 1, <12.5% medium = 2, >12.5% dense = 3, >50%
		

Seismic	Linear features of cleared land. Often narrow, perfectly straight and numerous. If followed for several kilometres, they may end abruptly. Associated with oil and gas but not always. Can be found in any landscape. Can run right through features such as lakes, but also can be wavy and seen to go around important ecological features. Minimum width is 1.5 metres and maximum is typically 8 metres for older seismic lines.	None = 0, sparse = 1, at least one seismic line visible medium = 2, seismic lines with length that traverses the image twice dense = 3, seismic line with length that traverses the image 5 times
		
Electrical infrastructure	Linear swath of cleared vegetation to support the passing of a power line or electrical infrastructure.	None = 0, sparse = 1, at least one transmission line or utility feature visible medium = 2, transmission line or utility feature with length that traverses the image twice dense = 3, transmission line or utility feature with length that traverses the image 5 times

Appendix 6.7

Comparison between the Canadian human footprint (A) and the Global human footprint clipped to Canada (B).



Appendix 6.8

Sensitivity analysis of the Cohen Kappa Statistic (y-axis) with the Percent Agreement (x-axis) between visual score and Canadian human footprint value. The strength of agreement ranges, appearing as the coloured dashed lines, are as defined by Landis & Koch (1977).