OBJECT-BASED IMAGE ANALYSIS PROTOCOL FOR HISTORIC TREND ANALYSIS OF FOREST STRUCTURE IN CUMULATIVE EFFECTS ASSESSMENT OF FOREST BIODIVERSITY: A FEASIBILITY ANALYSIS

by

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Abstract

This research examined the feasibility of a geomatics solution to establish baseline conditions in forest structure using historical aerial photography and to assess trends in forest structure over time. The Geomatics Feasibility Assessment Framework (GFAF), designed for this research, has 3 components that work in a linear direction to assess conceptual and practical feasibility.

Gap/opportunity analysis: Forest biodiversity is linked to the provision of ecosystem services (Millennium Ecosystem Assessment, 2005) and is a value in the Cumulative Effects Framework (CEF). Limitations to forest biodiversity assessment stem from the use of age-based inventories (e.g. VRI) and HRV-derived benchmark conditions. The Historic Aerial Photograph Heterogeneity Analysis (HAPHA) designed by Morgan & Gergel (2010, 2013) was identified as a potential solution. This conclusion is supported by: objective, efficient and reproducible analysis of historic photos using OBIA methods, and; the unique quantification of ecologically relevant metrics (i.e. heterogeneity).

Pilot Study Design: A normative research design was constructed for the pilot studies. The design consists of a stratified sampling scheme, a comparative accuracy assessment and, a multi-variate mixed-effects (hierarchical) regression analysis. Based on data requirements of the research design, the GIS-based multi-criteria evaluation identifies two potential study areas: Opax/Isobel silvicultural research sites and Arrowstone Provincial Park. The sites were selected based on distinct anthropogenic and natural disturbance histories, existing data, consistent aerial coverage, and a shared BEC subzone.

Cost/Benefit Analysis: Costs were estimated using a bottom-up estimation technique and expert judgement. For a single study area, a pilot study would cost between $13,900 and $21,400. Benefits were estimated through a comparative analysis of relatable research and assigned a

likelihood based on a unique set of evaluative criteria and likelihood rubric. The potential benefits of this approach are being able to establish baseline conditions from historical imagery, quantify unique ecologically relevant metrics (i.e. heterogeneity) and identify trends in forest structure over time. Altogether the benefit is a unique assessment of forest structure that can be used to guide forest management activities including, but not limited to, cumulative effects assessment of forest biodiversity. The results indicate the benefits are achievable and pilot studies should be conducted.

Lay Summary

Natural resource managers deal with complex systems and must routinely make difficult decisions about the future of natural resources. The value of information that can help managers visualize the state of a resource cannot be underestimated. British Columbia’s forests are an invaluable resource that provide a range of benefits to diverse users. The main goal of forest managers is to maintain healthy forests to sustain long-term benefits. The BC government’s new Cumulative Effects Framework is a tool available to managers that describes the condition of forests in relation to the many activities (large and small) that have occurred over time and space. This can support a holistic perspective which allows managers to make more informed decisions. This research examined the feasibility of using historical aerial photography to evaluate trends in important forest structure to improve cumulative effects assessment. A unique feasibility framework for geomatics solutions was developed for this research.

Preface

This research did not involve human subjects and did not require approval from the University of British Columbia Okanagan Research Ethics Board (REB). The information provided regarding cost and time estimates for the Pilot Studies was provided by UBC and four firms. Tri-Council Policy states that in some cases, research may involve interaction with individuals who are not themselves the focus of the research in order to obtain information. Information was by personnel authorized to release information or data in the ordinary course of their employment about organizations, policies, procedures, professional practices or statistical reports. Such individuals are not considered participants for the purposes of this Policy. This is distinct from situations where individuals are considered participants because they are themselves the focus of the research. Portions of the Literature Review (Chapter 3:) are adapted from research papers completed for courses in *Dynamic Modelling of Human-Environment Systems (ENVI544)* and *Complex Social and Ecological Systems (ENVI 551D)* and from the unpublished work *Status of Cumulative Effects Assessment in Canada* by DeWolfe, Gregg, and Vlasschaert (2014). Maps throughout this thesis were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. For more information about Esri® software, please visit www.esri.com.

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Glossary

BGB	Biodiversity Guidebook
BGC	Biogeoclimatic
CE	Cumulative Effects
CEA	Cumulative Effects Assessment
CEF	Cumulative Effects Framework
FBCEA	Forest Biodiversity Cumulative Effects Assessment (procedure)
(M) FLNRO	(Ministry of) Forest Lands and Natural Resource Operations
GIS	Geographical Information Systems
GFAF	Geomatics Feasibility Assessment Framework
HAPHA	Historic Aerial Photography Heterogeneity Analysis
HRV	Historic Range and Variability
OBIA	Object-based image analysis
OBM	Object-based metrics
RS	Remote Sensing
VRI	Vegetation Resource Inventory

Coarse-filter approach	A coarse-filter approach targets large-scale forest attributes that can be used as surrogate measures for the diversity of forest species.
Definiens (eCognition)	Definiens is the software that supports the multi-resolution procedure. eCognition is an earlier version of the software.
Ecosystem Services	The benefits that humans derive from ecosystems. These include provisioning services (e.g. food, fuel), regulating services (e.g. erosion protection), cultural services (e.g. recreation) and supporting services (e.g. soil production).
Forest Biodiversity	Forest biodiversity in this thesis refers to forest ecosystem biodiversity as a surrogate for forest structure that species and processes rely upon.

Geomatics	Referring broadly to geospatial technologies, particularly remote sensing and GIS methods, software, and hardware.
Historic Aerial Photography	This term is used broadly to refer to any photograph that is taken in the past and does not reflect current conditions. While some photos do date back to the 1920s in some places, for assessing forest structure, photos from a more recent past could still yield beneficial information.
Historic Range of Variability	An approximation of the natural range of landscape composition/ ecosystem characteristics caused by a natural disturbance regime over appropriate time and space scales.
Natural Range of Variability	Range in the structure, processes, and composition of landscapes over time, in the absence of anthropogenic disturbance.
Object-based image analysis	A method of analyzing remote sensing imagery and creating meaningful image objects based on spectral, spatial and temporal characteristics of the image. Also known as object-oriented classification method or geographic object based image analysis (GOBIA).
Residual Structure / Biological Legacies	Elements of forest structure that remain after disturbance including snags, downed logs, and large trees. These structures provide crucial habitat and perform other essential functions such as carbon sequestration.

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Dedication

for William T. Gregg

Thank you for your unconditional support, your love of learning and your passion for my education.

Chapter 1: Introduction

Managing the cumulative effects of natural resource development is a key issue in the Canadian impact assessment discourse. Cumulative effects refer to the combined impact of past, present and future actions on environmental, social and economic values (FLNRO, 2014). In British Columbia (BC) an increase in the quantity and diversity of development activities (particularly mining and liquid natural gas [LNG] exploration and development) as well as environmental pressures (e.g. climate change, mountain pine beetle, species decline and others) results in an increased risk for cumulative effects (Forest Practices Board, 2011). Existing tools for mitigating negative effects and sustaining benefits, such as environmental assessment, focus on large-scale activities and projects and do not account for the synergistic impacts of many smaller activities (Noble, 2010). This sector or project-based approach to natural resource management is not conducive to a comprehensive evaluation of the environmental effects of resource management decisions within BC's characteristically complex and contentious socioeconomic, political and environmental settings (Noble, 2008). In recognition of the inadequacy of current infrastructure to address concerns regarding cumulative effects, the Ministry of Forest Lands and Natural Resource Operations (FLNRO) spearheaded the development of a new Cumulative Effects Framework (CEF) (FLNRO, 2014).

The CEF is a policy and decision support tool supported by integrated data systems that enables decision makers to have a holistic understanding of current conditions and likely impacts from future actions. The CEF rests on a foundation of environmental components called 'values'. For ease of implementation CEF values are broadly defined and ideally align with the objectives of existing legislation, policies, land use plans and key agreements (e.g. with First Nations) (FLNRO, 2014). Values include important ecosystems (forest, riparian, watersheds), priority fish and wildlife species, air and water quality, and social and economic wellbeing (FLNRO, 2014). The CEF relies on strategic-level cumulative effects assessments of values that collates and analyses historic and current indicator data for trends to assess risk, so that management can take action to achieve set targets (Noble, 2010). Strategic-level CEA leverages the capabilities of Geographical Information Systems (GIS) to store, manage, analyze, display and communicate data. The ability of GIS to incorporate temporally and spatially diverse data on a range of variables from a variety of sources is a critical advantage in cumulative effects assessment (Canter & Atkinson, 2011). Better data integration into CEA practice can help connect knowledge about the complex social-ecological-spatial relationships to assessment practice (Turner & Gardner, 2015).

The CEF recognizes forest biodiversity as an important value. Biodiversity has important ecological, social and economic implications and is globally recognized as being intertwined with human well-being (Millennium Ecosystem Assessment, 2005; Environment Canada, 1995; Noss, 1990; United Nations, 1992, 2011). Biodiversity is essential for the functioning of ecosystems and consequently the provision of ecosystem services: the benefits that people receive from ecosystems (Turner et al., 2013; Millennium Ecosystem Assessment, 2005). Ecosystem services include: the provisioning of food, water and fuel; regulating climate and water; culturally important opportunities for recreation and education; and supporting ecologically important processes such as soil formation (Millennium Ecosystem Assessment, 2005). In BC, the importance of forest biodiversity is formally expressed through various legal and management objectives. The *Forest & Range Practices Act* and the *Wildlife Act* are examples of legislation that include provisions that are meant to support the conservation of biodiversity, such as the establishment of Old Growth Management Areas and Wildlife

Management Areas (Government of British Columbia, 2002;OAGC, 2013a). In addition, virtually every land use plan in the province has as its objective *to maintain or conserve biodiversity* (BC Government, 2018).

Biodiversity is a broad term that encompasses the diversity of genes, species and ecosystems (Bunnel & Dunsworth, 2009; Norberg, 2004). To set manageable and measurable objectives, forest biodiversity management in BC adopts a coarse-filter management approach. A coarse-filter approach targets large-scale forest attributes that can be used as surrogate measures for the diversity of forest species. In BC and elsewhere in North America efforts have focused on ecosystem diversity and landscape level patterns (Bollenbacher et al., 2014; Cyr et al., 2009; DeLong, 2011; Hessburg et al., 2013; Thompson et al., 2006; Tinker et al., 2003; Wimberly et al., 2000). This ecosystem management approach can focus on providing suitable habitat conditions for all native species, rather than developing strategies for individual species (BC Ministry of Environment, 1995; Turner et al., 2013). This approach is supported by the historical range and variability (HRV) ecological concept. The HRV concept assumes that forest structure varies spatially and temporally in response to natural disturbances, and within this historic range of conditions ecosystems are self-sustaining and resilient (Keane et al., 2009). Management from an HRV perspective assumes that if managed forests are made to resemble the amount and pattern of forests established from natural disturbances, it is more likely that all native species and ecological processes will be maintained (BC Ministry of Environment, 1995; Keane et al., 2009; Landres et al., 1999). Risks to forest biodiversity can then be estimated by using GIS-based indicators to calculate the deviation of current forest conditions from expected HRV conditions (Keane et al., 2009; Tinker et al., 2003). In practice, applying the HRV theory to define benchmark conditions is difficult. A comprehensive quantification of HRV requires temporally and spatially extensive historical data that is rarely available (Keane et al., 2009). Many existing methods model the expected age distribution of forest based primarily on the prevalence of stand-replacing disturbances (e.g. Demeo et al., 2018 & Didion et al., 2007). This approach to biodiversity management was first advocated in BC by the Biodiversity Guidebook (BGB), a leading documentation on forest biodiversity management in BC (BC Ministry of Environment, 1995). BC is categorized into five broad natural disturbance types based on intensity and frequency of disturbances. An expected age distribution is calculated for these different disturbance regions to help set management targets. However since then, our knowledge of disturbances has improved and we now recognize that disturbances range in severity and frequency and are not limited to stand-replacing events (Marcoux et al., 2015; Timpane-Padgham et al., 2017; Tinker et al., 2003).

Historic disturbances (both natural and human-induced), particularly in the recent past, have **not** been stand-replacing. Partial natural disturbances (insects, wind, wildfires) and human land-uses that retain residual structure are significant drivers of landscape change (Gillanders et al., 2008). As a result, forest structure is much more heterogenous and complex than the age-based approach implies (Lindermayer et al., 2006). Anthropogenic disturbances that have attempted to replicate natural disturbances (as per the HRV concept) have tended to replicate stand-replacing disturbances (i.e. clear cuts) (BC Ministry of Environment, 1995). This leads to homogenization in stands and throughout the landscape that can impact ecosystem resilience and ecosystem services (Cyr et al., 2009). Providing baseline information for forest structure that captures the complexity of partial disturbances and residual structure better than age as a surrogate would help inform management practices (Klenner et al., 2008; Williams & Baker, 2012).

The analysis of baseline conditions and long-term trends is a fundamental component of cumulative effects assessment. However, a focus on age-based distributions and stand replacing events does not adequately establish historical conditions (Noble, 2010, 2015b; Whitelaw & McCarthy, 2016). In BC, the Vegetation Resource Inventory (VRI) data used to assess the current condition of forest biodiversity lacks the temporal range to establish conditions beyond 2003 (Sandvoss et al., 2005). This temporal scale is relatively short in comparison to the timeframe it takes for some forest structural attributes to accrue (Clark et al., 1998; Reilly et al., 2015). Furthermore, VRI data does not contain ample information on stand level attributes such as residual canopy after disturbance (Lewis, 2016a); VRI-derived age estimates are used as a surrogate for structural complexity within stands. This does not account for the impact of various partial disturbances on associated residual structure. Using HRV-based estimates as an ecological benchmark is a good proxy in place of missing information; however, they are not sufficient to capture the complexity of reality (Wong et al., 2004). Without assessing current conditions relative to actual past conditions, there is no indication of rate and direction of change, and whether the current regime has led to improved or diminished conditions. This is a significant omission as rate, size and temporal correlation of habitat disturbances, together with the rate and longevity of forest patches are central aspects of biodiversity (Bunnel & Dunsworth, 2009; Innes & Koch, 1998; Perera et al., 2004).

The research identifies and assesses a GIS/Remote Sensing (RS) protocol capable of assessing forest structure/complexity using historical aerial photography. A coherent, structured method of identifying an appropriate protocol does not exist. This study establishes a systematic approach for identifying technologies and procedures that have the potential to achieve this aim and specifically how this would benefit initiatives such as BC’s Cumulative Effects Framework.

In addition to its utility in this research project, the Geomatics Feasibility Assessment Framework (GFAF) could serve as a framework for organizations looking to integrate new geomatics technology into their procedures. This framework considers whether potential applications balance ease of implementation, consistency and replicability, with worthwhile results (Morgan & Gergel, 2013).

The GFAF was used to identify the object-based image analysis (OBIA) method employed by Morgan & Gergel (2010; 2013). Morgan & Gergel use the same underlying OBIA procedure to generate unique, quantitative definitions of heterogeneity (2010) and to classify forest polygons according to BC forest and terrain schemes (2013). Their approach has several characteristics that position it to address the limitations in the way we characterize forest structure when using HRV as a benchmark in forest biodiversity assessment:

- Objective and efficient assessment of historical aerial photography in a reproducible manner to establish historical baseline conditions;
- Ability to incorporate contextual information and ancillary data to establish trends in forest structure over time in relation to cumulative impacts (e.g. land uses and natural disturbances); and
- Quantifiable ecologically relevant metrics (e.g. heterogeneity).

Aerial photographs do offer significant contributions to forest management in the form of quantitative data, and repetitive and synoptic coverage of vegetation cover and condition dating back to the 1920's in some regions (Franklin, 2001; Morgan, Gergel, & Coops, 2010). This information is important for assessing vegetation condition and landcover over time, monitoring landscape and ecosystem change and estimating the historic range of variability within a system (Franklin, 2001; Landres et al., 1999). Morgan & Gergel (2010; 2013) present an objective and repeatable solution for harnessing the underutilized data in federal and provincial aerial photograph collections. Furthermore, the quantification of ecologically relevant metrics could help identify the cumulative effects of various partial and complete disturbances on forest structure that may affect forest biodiversity and the support of ecosystem services (Carnus et al., 2003; Gergel & Turner, 2002; Lindenmayer et al., 2006; McGarigal et al., 2009; Rich et al., 2010; Turner, 1987; Turner et al., 2003; Turner et al., 2013). In particular, the unique quantification of heterogeneity using this method is promising. Heterogeneity is broadly defined as the degree of spatial variability of some property within a system (Norberg, 2004; Turner, 1987). Some see it as the ultimate source of biodiversity, influencing species diversity, resilience and ecosystem function, and making it very relevant for sustainable forest management (e.g. Carnus et al., 2003; Gergel & Turner, 2002; Lindenmayer et al., 2006; McGarigal et al., 2009; Rich et al., 2010; Turner, 1987; Turner et al., 2003; Turner et al., 2013). Changes in heterogeneity over time in response to human activity can be used to gauge the cumulative effects of these activities on ecological function and complexity (Morgan & Gergel, 2010; Turner, 1987; Turner et al., 2013).

Chapter 2: Research Questions

Cumulative effects assessment can be an important resource management tool. This is particularly true in the context of BC's forests where a broad range of interests compete for the use of the resource, and understanding the cumulative and synergistic impacts of change should be a key part of planning and decision-making. Development activities range in scale and vary temporally and spatially on the landscape. To sustain long-term benefits for all users, managers must consider how the cumulative impacts of development and other activities affect the forests' ability to provide ecosystem services. Ecosystem services are the benefits the humans receive from ecosystems (e.g. climate regulation, food, water and economic resources) and are inextricably linked to forest biodiversity (Millennium Ecosystem Assessment, 2005). Forest biodiversity is seen by government as being *important to the people of British Columbia,* and was incorporated as a key value in the Cumulative Effects Framework (CEF).

A common approach to forest biodiversity assessment is to assess the current state of forest biodiversity against benchmark conditions set using historical range and variability (HRV) estimates. In BC, this approach relies on VRI data, which lacks the spatial resolution to capture change in forest structure and has a restricted temporal range limiting the capacity to establish trends in forest structure in relation to cumulative effects. However, historical aerial photography in BC predates VRI information by as much as 80 years in some locations. Theoretically, this resource could be used to estimate past forest condition and establish a baseline from which to assess cumulative change in forest structure.

This research examines the potential value of integrating historical aerial photography into biodiversity assessment and the overall ability to estimate forest structure using a unique approach. Specifically, this thesis answers two research questions with an additional research question addressing feasibility assessment:

The first research question looks at a solution from more of a conceptual perspective.

1. What is an appropriate geomatics solution for incorporating historical aerial photography to establish trends in forest structure?
    a. How would this aid the cumulative effects assessment of forest biodiversity?

The second research question examines the problem from more of a practical standpoint.

2. Would this protocol be feasible given associated costs, existing capacity, data needs/availability and expected benefits?
    a. What are the required inputs (e.g. data) and costs (e.g. software, consultants) associated with implementing this procedure?
    b. To what extent (scale, detail, and accuracy) and is it feasible to identify and delineate historic changes in land use, management practices and other events on the landscape towards understanding the cumulative effects of these changes on forest biodiversity?
    c. Do expected benefits justify the costs and time required?
    d. How confident can we be in the ability of the proposed procedure to work?

The context for addressing the first two research questions is as an exploratory analysis of feasibility prior to investment. Therefore, an additional research question is to examine standard methods for the feasibility assessment of geomatics technology.

3. What are appropriate methodological components for identifying a geomatics protocol to meet CEF needs and assessing the feasibility of this protocol?

Feasibility in its simplest sense relates to if an undertaking or idea is possible or reasonable. A feasibility assessment therefore considers what the outcome of that undertaking/idea is likely to be. Depending on the context, the factors, which will ultimately affect the outcome, can be broad and multi-faceted. It is therefore important to bound the concept of feasibility by the factors that are most important and relevant to the context and the resources of the users.

a. What is an appropriate definition of feasibility in this context?

While there is a specific context in mind for this feasibility assessment, an additional consideration of this research is how it could be applicable to other contexts. In other words, what would a standard feasibility assessment framework look like for geomatics technology?

b. How can a feasibility assessment procedure be related to other contexts?

Chapter 3: Literature Review

Environmental impact assessment, or environmental assessment (EA), is a tool to help improve informed decision-making concerning development (Hanna, 2016). The practice of conducting EA's ideally considers the social, environmental and economic impacts of a project, such as a mine or dam, to inform decision makers of the potential negative impacts of a project prior to these impacts occurring (Hanna, 2016). This knowledge can then be used to identify projects that should not proceed, or inform the mitigation measures that will ensure a project will not have significant adverse effects. In Canada, EA has a relatively long history in practice, and EA laws exisit at provincial, territorial and federal levels. In each jurisdiction a separate piece of legislation is in place that captures different projects and has different requirements (Hanna, 2016). Some of these differences are reflective of various social, ecological, economic and political contexts; however some represent deficiencies in the EA process (Cashmore et al., 2010; Jay et al., 2007; Sadler, 1996).

EA research seeks to advance best practices in assessment practice so that EA can be efficient and effective in various contexts. Researchers have focused their energies on many different aspects of EA (Noble, 2015a): participation (O'Faircheallaigh, 2010; Odparlik & Köppel, 2013), follow-up (Marshall et al., 2005), indigenous engagement (Hanna & Vanclay, 2013), effectiveness (Barnes & Boyle, 2015; Hanna & Noble, 2015), social impact assessment (Esteves et al., 2012; Vanclay, 2006), and cumulative effects assessment (Baxter et al., 2001; Therivel & Ross, 2007). This research is situated within the cumulative effects assessment literature, an area of research that has "gained considerable attention from practitioners, regulators and communities" (Noble, 2015a).

The literature review summarizes the main concepts of cumulative effects assessment (CEA), BC's new Cumulative Effects Framework (CEF) and the importance of GIS and remote sensing technology (RS) to CEA.

3.1 Cumulative Effects

3.1.1 What are cumulative effects?

An environmental effect in EA must be distinguished from environmental change. Noble (2015) defines change as the "difference in the condition of a particular environmental or socio-economic parameter … over a specified period of time" (p. 4). Environmental change may be the result of anthropogenic actions or natural processes, and is typically defined in terms of a process (such as soil erosion) (Noble, 2015b). The observed rate of environmental change is used to determine the expected condition of the environmental parameter in the absence of a project-induced stressor. An environmental effect is the difference in the condition of the environmental parameter that would be expected as a result of environmental change, and the condition of the parameter as a result of project-induced change (Noble, 2015b). While an environmental effect is typically considered as an individual impact from a single project, cumulative effects consider the impact on environmental components from a multitude of stressors over broad spatial and temporal scales (Hegmann et al., 1999).

There is no single definition of cumulative effects (Gunn & Noble, 2011; Jones, 2016). The term is adaptable to different contexts and as such the scope and definition varies by jurisdiction and application. Particularly, the inclusion of biophysical, social, cultural and economic aspects varies based on the intent of the study (Canter & Atkinson, 2011; Lucchetta, 2016; Steffensen, 2016). Gunn & Noble (2014) argue that a standard definition of cumulative effects must be independent of a specific context and embody recurrent themes in the cumulative effects literature: "incremental and combined impacts; past, present and future actions; multiple activities in the landscape; and high-frequency impacts, spatially and temporally overlapping" (Whitelaw & McCarthy, 2016). Gunn & Noble (2014) define cumulative effects as "a change in the environment caused by multiple interactions among human activities and natural processes that accumulate across space and time". The fundamental concept here is that the effects of any particular project must be considered as part of the cumulative impact of projects and activities which are related temporally and spatially.

Cumulative effects were originally understood as being primarily additive—that is, the cumulative consequence of all stressors could be no greater than the sum of each individual impact (MacDonald, 2000). However, cumulative effects can climax in more complex ways. Noble (2010) outlines 4 broad types of cumulative effects:

- linear additive effects: "incremental additions to, or deletions from, a fixed storage where each increment or deletion has the same individual effect";
- amplifying or exponential effects: "each incremental addition to, or deletion from, a resource base has a larger effect than the one preceding";
- discontinuous effects: "incremental additions have no apparent effect until a certain threshold is reached, at which time change occurs rapidly" and;
- structural surprises: "changes occur as a result of multiple stressors or activities in a defined region".

The proper characterization of cumulative effects is important for communicating the depth and nature of the issues to decision makers and identifying the appropriate management measures (Noble, 2015b). Furthermore, cumulative effects are best understood with respect to a specific environmental component or process. Valued Ecosystem Component (VEC) is a term that denotes specific components of the environment (e.g. air, water, wildlife, vegetation and resource use) that are considered important by proponents, the public, scientists and/or government (Hegmann et al., 1999). Identifying VECs is a means of focusing the assessment of effects which is needed to better implement the appropriate management strategies (Duinker & Greig, 2006; Hegmann et al., 1999). Cumulative effects must consider the full range of stresses on VECs and not just the impacts of a single project if the sustainability of VECs is indeed the main concern (Duinker & Greig, 2006). This is the basis for understanding cumulative effects: when assessing environmental effects, considering individual impacts will not be sufficient to understand the full cumulative impact on that VEC (Baxter et al., 2001). Thus cumulative effects are understood as the change in the condition of a VEC as a result of linear additive effects, amplifying or exponential effects, discontinuous effects, and/or structural surprises over broad spatial and temporal domains.

3.1.2 Cumulative Effects Assessment

Cumulative effects assessment (CEA) is the process of systematically identifying and evaluating environmental change, and the pathways that lead to those effects, in order to avoid or mitigate cumulative effects (Noble, 2010). It is a means of accounting for the many changes to the environment of varying scale and impact that may be deemed inconsequential if viewed in isolation but in combination may have detrimental impacts. CEA is endorsed as a more holistic approach to anticipating and mitigating potentially significant negative environmental effects and is broadly recognized as an integral component of effective environmental impact assessment (Greig & Duinker, 2014; George Hegmann & Yarranton, 2011).

Ideally, effective CEA must be inclusive of potential stressors on broad temporal and spatial scales (Noble, 2010, 2015b; Therivel & Ross, 2007). It is believed this broad focus is better situated to achieve sustainability goals and for strategic assessment (Duinker & Greig, 2006; Jones, 2016; Noble, 2008). In practice however CEA faces implementation obstacles, and falls short of its potential (Duinker & Greig, 2006; Noble, 2010).

Fundamental issues regarding CEA range from its sector-specific application, spatial and temporal focus and associated limitations, and inherent difficulties associated with predicting future development trends (Jones, 2016). It contains complex and undefined procedural metrics and definitions of acceptable and successful outcomes, and enormous difficulties associated with determining the effects from other projects and subsequent alternative future scenarios (Duinker & Greig, 2006; Harriman, 2008; Noble 2010). Perhaps the most overarching obstacle for CEA application remains its conceptual and operational consideration as a component of small-scale project-specific EAs (Noble, 2015a). Typically, CEA takes place within a project setting mandated by a legislative or regulatory process and is concerned with identifying how project-related stressors may interact with other local environmental components and manifest in undesirable environmental change (Duinker & Greig, 2006). However this approach is not sufficient to capture the whole of all impacts on a VEC (Duinker & Greig, 2006). Lastly, project proponents are often focused on achieving expeditious project approval and many proponents demonstrate a tendency to complete only the minimum requirements as stipulated by the respective EA legislation, with CEA weighted low as a decision-support tool. Thus, project-based CEA contributes little strategic advice regarding temporal impacts and guidance to future developments (Duinker & Greig, 2006).

The relative failure of CEA as a component of broader EIA legislation has led to a sustained effort to build CEA capacity elsewhere. Agencies have worked to develop guidance material for implementing CEA and there has been a surge of conceptual CEA frameworks being implemented by practitioners (Ball et al., 2013; Gunn & Noble, 2009; OAGBC, 2015). In Canada, the agencies responsible for building CEA capacity have typically been resource management agencies often working in collaboration with other organizations, First Nations, and industries (Hanna et al., 2016). BC's new Cumulative Effects Framework is one such example.

3.2 The BC Case and the Cumulative Effects Framework

It is an understatement to characterize land use planning and resource management in BC as conflict prone. The province has a long histroy of acrimonious disputes and disagreements over the use of forest resource in particular (e.g. Penner, 2018; Seymour, 2018; Lamb-Yorski, 2018; CBC, 2017). There are many stakeholders with interests that cover a broad spectrum of activities including mining, energy, agriculture, water use, quarries, oil and gas (exploration, drilling, pipelines), recreation, conservation, traditional uses and historical significance (BC Ministry of Forests, 2003, 2004; Marchak, 1983). Large resource development projects (e.g LNG Kitimat [Reuters, 2018] or the Site C Dam [Site C, 2018]) are often the center of attention, however the needs and cumulative impact of the many small individual resource users cannot be overlooked. Any meaningful sustainability policy would necessarily inlcude attention to the cumulative impacts of development and recent Supreme Court decisions in favour of First Nations will now require the government to do so (e.g. William v BC, 2007; West Moberly First Nation v. BC, 2011). The inadequate assessment of cumulative effects in BC has been widely recognized as an imminent threat to the long-term health of the natural resources that continue to play a central role in BC's economy (Forest Practices Board, 2011; OAGBC, 2015; OAGC, 2013). A report by the Forest Practices Board (2011) identified a number of key structural impediments to the appropriate assessment and managament of cumulative effects in BC. Primarily a project-specific context that requires CEA for only large projects and not for the many smaller activities that are authorized within their respective legal and policy environments more or less in isolation (Forest Practices Board, 2011). One notable limitation to this approach is that baseline information is not systematically collected resulting in significant gaps in knowledge. Furthermore, for the assessments that are completed, complete baseline information at the appropriate scale cannot be adequately incorporated (Forest Practices Board, 2011). The FPB report also noted that it is not necessarily the assesment tools for CEA that are lacking, but more importantly a comprehensive land management framework in which to consider cumulative effects (Forest Practices Board, 2011).

In an effort to improve the consistency and efficiency of cross-sector natural resource management and decision-making, the Ministry of Forest, Lands and Natural Resource Operations (FLNRO) was created as a central agency to establish the policy and conditions for access to and use of the province's forest, land and natural resources (FLNRO, 2018). The Ministry acts as a single legislative authority for provincial permitting and licensing activities and uses, coordinating the processes of numerous other agencies (FLNRO, 2018). FLNRO and the Ministries of Environment are currently in the process of developing and implementing a province-wide Cumulative Effects Framework (CEF). The framework seeks to address the inadequacy of project-by-project evaluations to assess cumulative effects through policies and tools that enable the periodic assessment of cumulative effects at a broad, strategic scale (FLNRO, 2014). Implementation of the CEF is progressing. A CEF Interim Policy has been approved that enables CEF to be integrated into existing natural resource decision making and processes (FLNRO, 2016). The interim policy allows for continued evaluation of the framework by First Nations and stakeholders to confirm the tools for data management, access and analysis; refine the values foundation; assess the effectiveness of the CEF in decision support; and develop the standards, roles, responsibilities, regulatory framework and capacity for assessment using CEF (FLNRO, 2017).

CEF's stated purpose is to improve the assessment and management of cumulative effects in natural resource decision-making by avoiding unintended impacts to economic, environmental and social values, streamlining onerous and lengthy permitting processes, mitigating conflicts among tenure holders, and eliminating the need for corrective actions (FLNRO, 2014). EA legislation that requires cumulative effects assessment on a project-by project basis has proven difficult to implement and inadequate in its application (Hanna et al., 2016). The CEF seeks to shift CEA into a broader context (regional planning), which centers on an integrated data/information system.

The core elements of the CEF are Values Foundation, Assessment, and Decision Support (FLNRO, 2014). 'Values' are defined as:

> The things that the people and government of British Columbia care about and see as important for insuring the integrity and well-being of the provinces people and communities, economies, and ecological systems, as identified in existing legislation, policy and/or land use plans, and other agreements. (FLNRO, 2014, p. 7)

The key takeaway of this definition is that values must have approved management objectives (e.g. in Legislation, Land Use Plans, Agreements or support Aboriginal or Treat Rights) (CEF, 2017). For ease of implementation CEF values must also be broadly defined so that finer-scale values can be nested within as indicators (e.g. old-growth is nested under forest biodiversity) (FLNRO, 2014). Values must also be spatially mappable with robust existing data for essential mapping and analysis purposes (FLNRO, 2014). Baseline quantitative and contextual information that provides insight into broad social, economic and environmental trends is collected from existing monitoring programs and inventories and integrated into a central database (FLNRO, 2014). GIS-based tools are essential for this purpose. They provide the infrastructure to house all of this data and the tools to integrate and make sense of it. GIS-based models can be used to assess trends and predict change in relation to different factors.

'Objectives' associated with each value are the condition or outcome identified by society (through legislation, policy, and planning or plans) as critical for sustaining long-term benefit from that value (Atkinson & Canter, 2011; FLNRO, 2014). A systems approach is used to assess the condition of values and manage activities to meet objectives (FLNRO, 2014). The condition of values is assessed using indicators (surrogate measures for directly assessing the condition of value) and compared against an 'acceptable condition' (threshold beyond which integrity of the value is compromised) (OAG, 2015). Measurable levels of the indicator are set as 'management triggers' to initiate a management action if the condition of the value is at high risk.

This research focuses on forest biodiversity. **Forest biodiversity** is an important ecological, social, cultural and economic 'value' due to its importance to BC society and decision makers expressed through various legal objectives (Higher Levels Plans or Land Use Order Regulations under the *Land Act*) and in existing regulations established under the *Forest and Range and Practices Act (FRPA),* and *Forest Practices Code of BC Act* (e.g. *FRPA Default Provincial Old Growth Objectives* and *FRPA/Oil and Gas Activity Act (OGAA) Land Use Objectives for Old, Mature and Early Seral Forest Representation*) (FLNRO, 2014; Lewis, 2016). There are also ample data related to forest biodiversity (e.g. Biodiversity EIRS e-Library [Ministry of Environment and Climate Change Strategy, n.d.]) and established data collection infrastructure to map and analyze forest biodiversity spatially (e.g. VRI sampling data [Sandvoss et al., 2005]). The legislated value of forest biodiversity and existing spatial information made it compatible for integration into the CEF.

3.3 Forest Biodiversity

Biodiversity is a key indicator of forest health (Carnus et al., 2003). Biodiversity is the diversity of plants, animals and other living organisms in all their forms and levels of organization and includes the diversity of genes, species and ecosystems as well as the evolutionary and functional processes that link them (Bunnel & Dunsworth, 2009; Norberg, 2004). Ecosystems provide important services such as the regulation of runoff, erosion and flooding, nutrient cycling, oxygen production, food, fiber, fuel, freshwater, as well as spiritual and recreational services (Campbell et al., 2009; Millennium Ecosystem Assessment, 2005; Timpane-Padgham et al., 2017; United Nations, 1992). Biodiversity increases the resiliency and self-organization of species and ecosystems across spatio-temporal scales, improving the likelihood that these services will be sustained (Holling, 2001; Peterson, Allen, & Holling, 1998). Yet, biodiversity is the single most threatened resource for humanity (Blasi et al., 2010). Given the importance of biodiversity, commitments to protecting biodiversity have been made at global, continental and national levels, calling for an evidence-based approach to conservation (Environment Canada, 1995; Noss, 1990; United Nations, 1992, 2011).

Globally, forests are an important source of social, environmental and economic ecosystem services. Forests clean water and air, prevent soil erosion, provide habitat for a host of species, and provide medicine and food (Drushka, 2003). Economically, forests are an important renewable resource providing building material, energy, heat and other material needs as wood, paper, and pulp (FLNRO, 2016). The harvesting and processing of our forests creates many jobs and revenue for British Columbians and is closely tied with our identity (BC Ministry of Forests, 2003; FLNRO, 2016). Forests also provide spiritual, aesthetic and recreational havens for many Canadians (Fisher et al., 2009). Therefore it is crucial that forests are managed in a way that maximizes the social, economic and environmental benefits and is sustainable in the long-term.

Over the years the pressures on our forests have accumulated. Access to forests for competing uses (FLNRO, 2016), an intensified natural disturbance regime spurred on by climate change (e.g. mountain pine beetle and wildfires) (BC Ministry of Environment, 2016; Thom & Seidl, 2015), and loss of forested land for agriculture, urbanization and resource exploration (e.g. mining, oil exploration) have put pressure on forests to produce the goods and services that people value (Rockstrom, 2015). In addition, understanding of our forests has increased through scientific disciplines such as ecology, hydrology, silviculture, conservation biology, landscape ecology, complexity science, as well as through traditional ecological knowledge (Boutin & Hebert, 2002; Bunnel & Dunsworth, 2009; McPherson & DeStefano, 2003; Puettmann, Coates, & Messier, 2009). These influences are currently shaping approaches to forest management in a way that recognizes that forests are complex systems and in order to sustain the benefits we receive from forests, management decisions need to focus on maintaining ecological functions and not just marketable wood (Puettmann et al., 2009).

The dominant approach to forest biodiversity management in BC is an ecosystem approach that focuses on providing appropriate habitat conditions for all native species (BC Ministry of Environment, 1995). Relevant habitat conditions are species dependent and therefore forest management must consider a broad range of structural components such as tree species composition, age, connectivity and stand size (Bissonette & Storch, 2003). A key focus of the conservation strategy is the seral stage of forests (BC Ministry of Environment, 1995; Lewis, 2016). The rationale is that different seral stages contain important habitat attributes such as downed wood, coarse woody debris, and snags (Yearsley & Parminter, 1998). As well, the interior of differently aged forest will have different microclimatic conditions (Carnus et al., 2003; Forest Practices Board, 2012). From this rationale, the logical management question is: how much forest of each age class is required to maintain an ecosystem that is sustainable in terms of its structure and function overtime (BC Ministry of Environment, 1995; Wong et al., 2004)?

One approach to determining an appropriate mixture of ecosystem variability is to try and emulate historical conditions, or the 'historic range and variability' (HRV)[1] (Keane et al., 2009; Landres et al., 1999). This approach acknowledges that in the absence of anthropogenic disturbance, spatio-temporal variability in forest structure is largely an artefact of natural disturbances – such as wildfire, windthrow, insect infestations and disease (Wong et al., 2004). Further, the HRV concept accepts this natural variability as a vital attribute of nearly all ecological systems and therefore knowledge of past processes and conditions provides appropriate guidance and context for management (Landres et al., 1999).

The Biodiversity Guidebook (BGB), a leading documentation on forest biodiversity management in BC, adopts the HRV perspective stating that "the more that managed forests resemble the forests that were established from natural disturbances, the greater the probability that all native species and ecological processes will be maintained" (BC Ministry of Environment, 1995, p. 4). Management objectives for seral stage are set according to the natural disturbance regime for a particular landscape unit. The BGB defines natural disturbance regimes based on intensity and frequency of disturbances using a long-term average return interval between stand-replacing events. A negative exponential equation is then used to calculate an age

[1] HRV is also referred to as range of natural variability and reference variability

distribution based on this return interval. Forest ecosystems with different natural disturbance regimes are then managed according to the benchmark conditions defined by these calculations (e.g. designing cutblocks and determining old growth reserves) (BC Ministry of Environment, 1995; Forest Practices Board, 2012).

The HRV approach is an example of a coarse-scale approach to forest biodiversity management. A coarse-scale, multi-disciplinary approach to forest biodiversity management that takes into account forest structure and composition is an effective means of monitoring forest biodiversity (LeMay et al., 2008). Forest ecosystem diversity is easier to measure, more cost effective, scientifically sound, and integrative of functional ecological relationships, making it an effective indicator for sustainable forest management (Franklin, 2001). A coarse-scale filter can be employed as a hierarchical approach to forest biodiversity assessment by identifying high-risk areas for more detailed assessment (Burrascano et al., 2013). Alternatively, (or in addition) it can be used as a stand-alone assessment by acting as a surrogate for fine-scale information. For example, stand structure (e.g. number of large living trees, coarse woody debris, snags) is an important indicator of forest biodiversity, that can indicate overall species diversity in forested ecosystems (LeMay, Maedel, et al., 2008). Research has shown that despite geographical, compositional, and climatic influences, old- growth forests have global commonalities in stand structure when compared to mature forests (e.g. higher densities of large living trees and higher amounts of coarse woody debris) (Turner et al., 2003). This knowledge of ecosystem type (e.g. old growth) can be used to estimate within-stand detail, information that has become increasingly important as part of information needs for improved land management (Turner et al., 2003).

3.4 Remote Sensing and GIS in CEA of Forest Biodiversity

Spatially detailed assessments of biodiversity covering large temporal spans are necessary for scientifically sound and meaningful cumulative effects assessment (Atkinson & Canter, 2011). Biodiversity measurements can be categorized broadly as either: direct measurement of individual organisms, species assemblages or ecological communities, or; indirect measurement of surrogate environmental parameters, e.g. assessing habitat suitability for species using landcover maps derived from satellite imagery (Turner et al., 2003). Direct measurements of species numbers and distributions can be prohibitively expensive to collect directly; indirect measurements of the distribution and status of surrogate measures is a more cost effective and resource efficient method to assess biodiversity (Dorren et al., 2003). The coarse-filter approach to forest biodiversity management adopted by the CEF (following the HRV perspective outlined in the BGB) is an indirect means of managing forest biodiversity. The data and analytical needs of this approach are best served using GIS and remote sensing (airborne or satellite sensors) technology.

Geographical Information Systems (GIS) is a powerful system for the storage, analysis and display of spatial data and is the principal tool at the CEF's disposal. It is the pillar supporting the collation and analysis of data related to the Framework's values. The capacity of GIS to incorporate temporally and spatially diverse data on a range of variables from a variety of sources is a critical advantage in cumulative effects assessment, and is particularly conducive to effective forest and land management (Atkison et al., 2008; Franklin, 2001; LeMay et al., 2008; Phan et al., 2004; Wulder & Boudewyn, 2000). GIS makes relevant information (e.g. geology, soils, leading species, linear facilities, quarries, mines and other developments) readily available to forest managers and provides them with the tools to answer questions ranging in complexity (e.g. total length of roads in watershed vs. likely wildlife corridors for moose) (Crossland, 2008; Foody, 2015; “GIS and Spatial Data Analysis,” 2013). This information can be tracked over time and space to assess and/or predict the cumulative impacts of development (e.g. how has the increase in total road length over time affected moose wildlife corridors?) (Atkinson & Canter, 2011; Atkison et al., 2008; Parker & Cocklin, 1993; Phan et al., 2004).

Remote sensing refers to either air-based or satellite based sensor technology that is used to capture information about the earth’s surface (Lillesand et al., 2008). The field of remote sensing began with manual interpretation of aerial photographs but progressively more complex methods and technology for data collection and analysis have been developed (Khorram et al., 2012). While remote sensing is not limited to forest applications, remote sensing has made significant contributions to the mapping and monitoring of forest resources and activities over the past few decades (Dorren et al., 2003; Franklin, 2001; Khorram et al., 2012). Remotely sensed data can be invaluable to forest management. It has been used to estimate stand structural attributes including species composition (Franklin et al., 2000), biomass and volume (Vohland et al., 2007); determine vegetation condition and landcover (Fraser et al., 2009), and; monitor landscape and ecosystem change over time and space (Franklin, 2001). As new data and methods evolve and improve it is reasonable to assume that remote sensing will be increasingly useful in satisfying needs for forest management information, particularly in providing baseline and temporal monitoring data for various forest area indicators, and structural data and context (Franklin, 2001; Morgan et al., 2010). Not only is remote sensing paramount to providing the coarse-filter information necessary for accurate, cost effective and time efficient measurement of forest resources, but the synoptic and periodic coverage of remote sensing data are a powerful tool for cumulative effects assessment (Wulder & Franklin, 2007; Fraser et al., 2009; Schroeder et al., 2014). The relative ease with which remote sensing data can be frequently collected for large areas is critical to understanding more fully the implications of forest changes and activities.

Remote sensing (RS) in conjunction with GIS are poised to make significant contributions to ecosystem-based forest management (Franklin, 2001; Khorram et al., 2012; Lillesand et al., 2008; Wulder & Franklin, 2007; Zlinszky et al., 2015). These technologies can deliver area-covering information on relevant variables and also allow optimization of fieldwork by pre-selecting sites of interest based on change detection (Zlinszky et al., 2015). GIS and RS procedures can be designed to present and report on relevant criteria and indicators, as well as support modelling and projections of forest conditions at a variety of scales based on the information they generate and common biophysical and ecological principles (Meaden & Aguilar-Manjarrez, 2013). Confidence in GIS/RS based assessments of forest biodiversity is only expected to improve as research continues to explore the relationship between GIS/RS indicators and ecological parameters (Meaden & Aguilar-Manjarrez, 2013).

Chapter 4: Methods – Geomatics Feasibility Assessment Framework

A key contribution of this research is the geomatics feasibility assessment framework (GFAF). The purpose of this research is to investigate if/how historical aerial photography can be used to measure baseline forest structure/complexity to assist in evaluating impacts to forest biodiversity within the Cumulative Effects Framework. This study is a scoping exercise to identify potential geomatics solutions and compile information that will help decision makers determine if the initiative is possible and if it is a worthwhile investment. A standard approach for conducting this feasibility assessment did not exist. In response, a structured methodology (GFAF) was formulated around common themes and methods found in relevant literature (including implementing information/management systems [e.g. (King & Schrems, 1978)], GIS [e.g. (McInnis & Blundell, 1998)] and the application of remote sensing technologies [e.g. (Dekker & Hestir, 2012)]. The GFAF has three main assessment components: Gap/Opportunity Analysis, Pilot Study Design and Cost/Benefit Analysis. Each component consists of a set of criteria and tools designed to assess the relevant aspects of feasibility (e.g. cost estimation for economic feasibility within the cost/benefit analysis). These components work in a linear direction, with each component developing the idea further. The gap/opportunity analysis identifies management needs and potential solutions to fulfill that need using a structure literature review. A pilot study is the test that is needed to verify the assumptions of the literature review. The pilot study design is a thoughtful consideration of the requirements for a sound research design that will support the pilot studies and an identification of potential study areas. The cost/benefit analysis is used to estimate the costs of the pilot study and assign a likelihood rating to the desired benefits. Together, these three components address the feasibility of a geomatics solution within a specific context. The GFAF summarizes the necessary information for decisions makers to decide if further investment is warranted. If it is decided to investigate further, the results of this framework can be used to guide further assessment of the concept, and/or assist and guide eventual implementation.

This section begins with a definition of feasibility followed by a detailed description of the three main assessment components and complimentary criteria and tools.

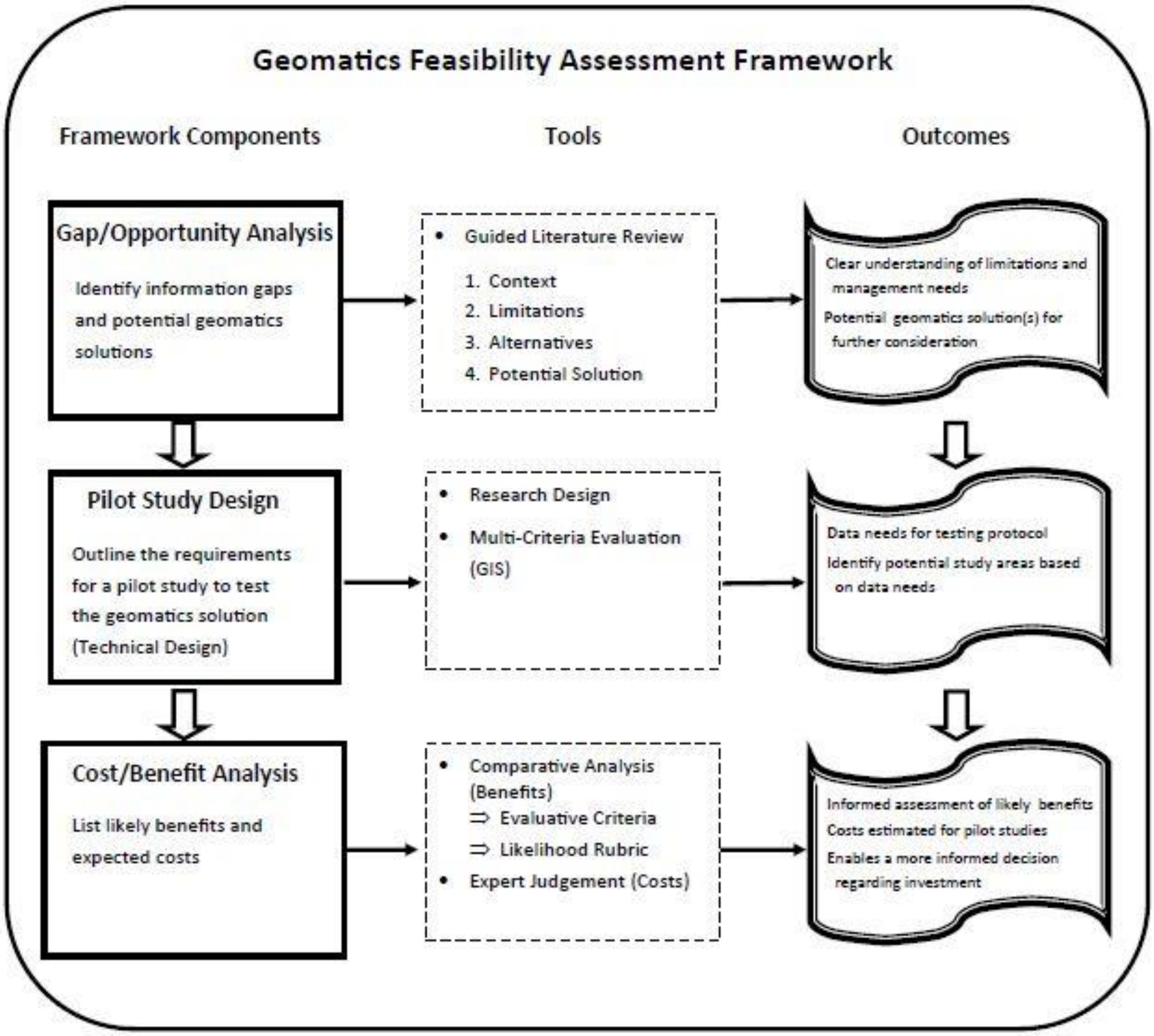

Figure 4-1: Geomatics Feasibility Assessment Framework Diagram

4.1 Feasibility

The dictionary definition of feasibility is the possibility of whether something (such as a plan, idea, technology, or project) can be done, made or achieved, is suitable to a particular context, or is reasonable (Cambridge, 2018). A feasibility assessment can therefore be understood as a formal assessment of whether something is possible and/or suitable to a specific context. In practice assessing feasibility can be cumbersome. There are potentially many different factors related to the success or failure of a particular endeavor (Katimuneetorn, 2008; Meaden & Aguilar-Manjarrez, 2013). Carefully defining what is meant by feasibility is necessary to focus the assessment. For the GFAF, feasibility is synthesized into two overarching categories: conceptual and practical feasibility (Katimuneetorn, 2008).

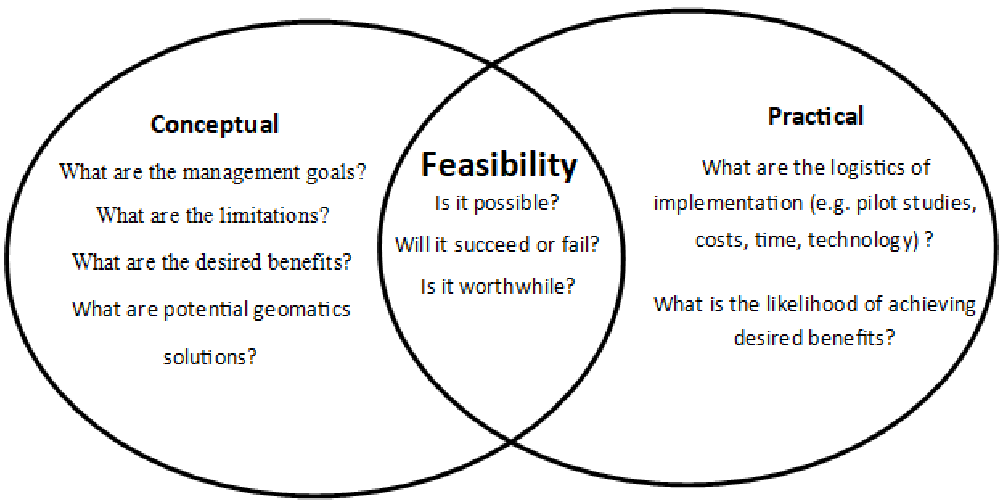

Figure 4-2: Feasibility Diagram

Conceptual feasibility addresses the theoretical assumptions of the project. This aspect of feasibility is concerned with matching a geomatics technology with end-user/management objectives and needs. Conceptual feasibility considers whether the proposed project is likely to solve or take advantage of opportunities created by inefficiencies or limitations in the current approach (Katimuneetorn, 2008). Conceptual feasibility also considers if, and how, the proposed approach would support existing tools and fit into the overall assessment structure (e.g. the CEF). In terms of forest biodiversity assessment, this type of feasibility is concerned with identifying a geomatics solution capable of generating new information that would address data limitations related to quantifying historic baseline and trends in forest structure as a solution or alternative to age-based approaches.

Practical feasibility addresses the applied components of the proposed geomatics solution. It considers the logistics of implementation that, depending on the nature of a project and the context, could be cumbersome (e.g. political, legal, employee structure) (Katimuneetorn, 2008). For this context practical feasibility is distilled into three facets: temporal, technical and economic feasibility:

- Temporal feasibility considers the timeframe for the implementation of the project (Katimuneetorn, 2008). This considers when the project would be fully operational, including the learning curve of the new technology for those using it. This facet of practical feasibility considers whether the time commitment will negate the usefulness of the project.
- Technical feasibility considers the adequacy of a proposed project to meet performance objectives (Tomlinson, 2007). It is concerned with the technological specifications, the reliability and effectiveness of the approach, and limitations or constraints. Given the technical requirements, this facet of practical feasibility would also consider whether the organization has the capacity to leverage the benefits of this technology.
- Economic feasibility considers whether the expenditure of funds and other resources on the project is worthwhile in light of expected future benefits, whether they are profits,

cost savings, or intangible benefits such as improved decision-making (Tomlinson, 2007). Many feasibility assessments will consider economic feasibility strictly in terms of factors that are quantifiable, measurable and comparable in monetary terms (Tomlinson, 2007). However in the GFAF, what is 'economic' will necessarily consider intangible factors in equal standing. Cost is a difficult criterion since it may be relative to the social-political context of the users and resource availability. A relatively expensive tool may be chosen because the budget is available, the tool is perceived to be the best choice, and/or the organization is willing to and can spend the money. Alternatively, cost may be a substantial barrier. The resources available to the organization may simply not support the use of the tool, regardless of how effective or appropriate it is.

These three parts of practical feasibility encompass both tangible and intangible factors such as time, resources, improved decision-making and capacity. Determining practical feasibility will involve matching analytical needs with the right hardware and software; identifying capital and operating costs; conducting a pilot study that would ascertain full operational requirements; and ensuring capacity to implement the protocol (e.g., right skillset within the organization, and sufficient training, background support and hands-on experience available). Meaden & Aguilar-Manjarrez (2013) state that failure to include these considerations in the preliminary stage of planning often leads to failure of the project.

The components of the feasibility assessment described in the following sections address the conceptual and practical components of feasibility and define criteria to examine these concepts more objectively. Conceptual feasibility is predominately assessed in the gap/opportunity analysis section of the methodology and also the benefits. Practical feasibility is assessed in the cost/benefit analysis and pilot studies design.

4.2 Gap/Opportunity Analysis

The gap/opportunity analysis considers the problem conceptually. From the perspective of a decision maker the concern is what information is needed to make an informed decision and whether it is worth pursuing the proposed approach as a solution to existing data sources. The purpose of this component of the GFAF is to distinguish the information gaps facing forest biodiversity assessment and identify a geomatics solution that can address these gaps. A common first step in feasibility assessments of geospatial technologies (GIS or remote sensing) is conducting a literature review to clearly define the problem and systematically select methods to address this problem (Anderson & Al-thani, 2015; Chian & Wilkinson, 2015; Dekker & Hestir, 2012; Durand, 2000; Koponen et al., 2001; McInnis, 1998; McVicar & Jupp, 1998; Meaden & Aguilar-Manjarrez, 2013; Metternicht, Hurni, & Gogu, 2005; USGS, 2009).

The gap/opportunity analysis is structured around four key questions that clearly define limitations (gaps) and identify the best potential solution (opportunity) (Table 4-1). To identify the information gaps, it is first (1) necessary to understand the context in which this information is used (Meaden & Anguilar-Manjarrez, 2013). The objectives and end-user requirements must be clearly articulated for the nuances and interconnectivity of the problem to be clearly understood (Anderson & Al-thani, 2015; Dekker & Hestir, 2012). With this understanding it is possible to (2) explicitly outline the nature of the problem and where efforts are lacking (Meaden & Aguilar-Manjarrez, 2013; Dekker & Hestir, 2012).

Once the problem is clearly understood, the next step is to (3) broadly link the issues to a technological/methodological approach. This is done using a review of methods that have demonstrated application within the given field or have been used for similar applications and have the potential for adaptation (Chian & Wilkinson, 2015; Durand, 2000; McVicar & Jupp, 1998; Meaden & Aguilar-Manjarrez, 2013). Finally, (4) a specific selection of methods and technological approaches (systems, hardware, software and data requirements, functional tools and techniques) is chosen (Meaden, 2013) based on limitations of relevant methodologies (McVicar & Jupp, 1998), advantages and disadvantages (Anderson & Al-thani, 2015; Chian & Wilkinson, 2015) and suitability of the methods/technology to the available data types (Durand, 2000).

Gap/Opportunity Method : Literature Review	
Gaps	**Opportunity**
Review of current assessment methods and key informational gaps. **Context** 1. What are the management/decision-making objectives? o Priorities / needs. o End-user requirements: environmental, political, legislative. **Limitations** 2. What are the key limitations in meeting these objectives? o Data availability/accessibility/quality /scale, and predictive/analytical capability.	*Review of methods with potential for addressing the identified gaps.* **Alternative approaches** 3. What methods and/or data might reasonably be expected to address the limitations facing management? o Technology and methods. o Data type. **Potential Solution** 4. What techniques are best suited to generating the information that is needed? o Data acquisition, interpretation and analysis procedures.

Table 4-1 Questions guiding the Gap/Opportunity Analysis literature review

4.3 Pilot Study Design

Pilot studies test the functionality and operational requirements of a procedure/ technology (Chian & Wilkinson, 2015; de Angelis et al., 2004; Meaden, 2013; Meaden & Aguilar-Manjarrez, 2013).These tests assess the validity and value (conceptually and visually) of the output; functionality in terms of hardware and software; accessibility to data; capacity to integrate, and; formatting and structure. It is a near certainty that pilot studies will meet challenges with steep and extensive learning curves (Meaden & Aguilar-Manjarrez, 2013). The results of the pilot studies would inform necessary changes to the project and help develop contingency strategies to ameliorate these obstacles.

The purpose of the pilot studies is to test the assumptions made in the gap/opportunity analysis and inform the cost/benefit analysis (such as whether or not the protocol is capable of meeting the objectives, and at what cost). These tests can be used to statistically analyze the accuracy and validity of the proposed geomatics solution to identify features of interest. It will also yield a better understanding of time and resources needed for further testing/implementation of the protocol.

In the GFAF, the first step towards conducting pilot studies is the pilot study design. This is the thoughtful consideration of an appropriate research design and identification of potential study sites. Designing the pilot study first will generate a realistic expectation of practical feasibility prior to investing in the analysis.

4.3.1 Research Design

A ***thoughtful research design*** is an important component of the feasibility assessment for three reasons. First, it generates realistic expectations of the requirements for testing the proposed geomatics solution. That is, how many study sites (how many photos) are needed to establish the calibration model, and how many sites exist that meet these requirements (particularly the reference data). Second, the research design helps inform the calculation of costs involved in a preliminary investigation. This will enable decision makers to assess the practical feasibility of investigating the protocol further. Third, the thoughtful construction of the research design will ensure that the pilot studies are conducted according to standard criteria and produce reliable evidence to support or negate the effectiveness of the proposed geomatics solution.

4.3.2 Multi-criteria evaluation

The multi-criteria evaluation is used to identify study areas to test the proposed geomatics solution. Multi-criteria evaluation is the identification of an area 'to suit a specific objective on the basis of a variety of attributes that the selected areas should possess' (Eastman, 1999; Greene, Devillers, Luther, & Eddy, 2011). The criteria for this evaluation are the data requirements needed to test the protocol identified in the research design. The necessary data layers were obtained and then combined in a Boolean analysis within ArcGIS. A Boolean analysis first converts all criteria into Boolean variables (true/false statements) and then combines all layers using intersection and/or union operators to identify the areas that suit all requirements (Dodgson et al., 2009). Specific geographic locations that have the potential to serve as a pilot study site are identified and conveyed using maps.

4.4 Cost/Benefit Analysis

The purpose of the cost/benefit analysis is to gauge how the inputs/investments (costs) compare to the expected outputs (benefits). Adequately considering relevant costs and benefits is an important exploratory step in a feasibility assessment to determine if it is a worthwhile venture (Meaden, 2013; Katimuneetorn, 2008; McInnis & Blundell, 1998). The cost/benefit analysis considers whether the expenditure of funds and other resources on the project is worthwhile in light of expected future benefits, whether they be profits, cost savings or intangible benefits (Katimuneetorn, 2008). In terms of economic evaluation, a cost-benefit analysis would consider primarily quantifiable, measurable and comparable factors to determine if the venture is profitable (Katimuneetorn, 2008). A classic cost/benefit analysis would assign an economic or financial value to all costs and benefits, and then compare the sum of each category. However, within the context of a true cost-benefit analysis for information technology (e.g. remote sensing, GIS) obtaining objective results is difficult (Maguire et al., 2008). This is because both tangible (e.g. financial) and intangible (e.g. better decision-making) costs and benefits should be considered. Financial costs and benefits may be measured and a value assigned, but better decision-making may be more difficult to measure. In fact, intangible considerations are often more important than the tangible, making the comparison more difficult (Meaden, 2013). The intangible nature of the costs and benefits leads to complications including the slow accumulation of some benefits, the dynamic relationship between costs and benefits over time (e.g. equipment devaluation, technical improvements) and variable outputs between applications of the project (Meaden, 2013). The exact number of costs and benefits for a particular project is impossible to calculate during this initial phase, and while the cost/benefit analysis will by no means facilitate an objectively quantified decision, this analysis will produce a list of advantages and disadvantages to the adoption of information system that will greatly aid in the final decision (Meaden, 2013).

The first stage in the cost/benefit analysis is to select relevant costs and benefits from a potentially broad range of considerations (section 4.4.1). The factors selected to be included in the final analysis should be based on relevance to the particular application and the level of detail desired/possible given time, resources and expertise. The next component of this section reviews the techniques employed for estimation of costs and benefits. The final section explains how the costs and benefits are assessed with respect to the objectives of the protocol.

4.4.1 Selecting Costs & Benefits

Costs and benefits can be both tangible and intangible (McInnis & Blundell, 1998; Meaden, 2013; Meaden & Aguilar-Manjarrez, 2013; Silva, 1998). In this particular application costs are considered primarily in tangible terms while benefits are overwhelmingly intangible.

This is because the context of this feasibility assessment is resource management in the public sector. The objective of the protocol to be assessed is to improve decision-making, and there is no marketable product, or sales. Therefore quantifying benefits would yield, at best, subjective estimates and the time and effort would not be justified by the outcome.

Costs and benefits are structured into overarching categories with supplementary criteria to define inclusion in these categories (Table 4-2). These categories and criteria are designed to address the most notable elements in the implementation of geomatics tool. The purpose of the framework is a cost-effective preliminary investigation of feasibility, and therefore the expertise and resources required to estimate the full range of costs and benefits is counterintuitive. A fully comprehensive assessment of costs and benefits may be impractical at this stage. Selection of costs and benefits should focus on relevance to the feasibility assessment and will reflect the time, resources and expertise available.

Costs are divided into implementation and maintenance costs (Korte, 1996; McInnis & Blundell, 1998; Silva, 1998). Implementation costs refer to the initial testing and integration of the protocol, while maintenance costs refer to the ongoing costs of the protocol once it is established. Implementation and maintenance costs are further characterized by time and resource requirements (Katimuneetorn, 2008; Korte, 1996; McInnis & Blundell, 1998; Meaden, 2013). Examples of these costs are included.

Benefits are considered in the context of decision-making and management. Benefits are categorized as either efficiency or effectiveness benefits (McInnis & Blundell 1998; Obermeyer 1999; Gillespie 1994). Efficiency benefits accrue when the geomatics solution improves the performance of existing tasks, for example through reduced time of completion or enhanced accuracy (Gillespie, 1994). Effectiveness benefits accrue when a task that could not or would not be done without the new protocol is introduced (Gillespie, 1994). Effectiveness benefits are realized when new information is generated that fills gaps and leads to more informed decision-making. McInnis & Blundell (1998) lists four categories of effectiveness benefits: visualization, complex analysis, information access, and increased accuracy. These categories assess the nature of the information products that are produced, how these products are related to decision-making and the impact on the ability to meet a need (i.e. answer the desired question and support planning or decision-making).

Costs	Benefits
Implementation ➢ Resources o Hardware (network, server) o Software o Data (database creation) o Services o Contracted services o Personnel o Training o Application development ➢ Time o Testing (refining protocol) o Collecting data o Analysis o Training **Maintenance** ➢ Resources o Person power (additional staff). o Software maintenance (upgrades, license renewal, new licenses). o Hardware maintenance (replacements, updates). o Data maintenance/updates. o Training. ➢ Time o Annual/biannual analysis. o Time to make fully operational on provincial scale.	**Effectiveness** ➢ Visualization o Enhanced visualization of graphical data, quality products. ➢ Complex analysis o Improved analytical procedures, ability to generate new understandings. ➢ Information access o Better information flows, more consistent/easier access to data. o Rapid access to output. o More informed public decisions. o Gaps become apparent. ➢ Increased accuracy o The provision of better information. o Ability to integrate data from different sources (more useful data and products from integrated information). **Efficiency** o Reduced processing time. o Increased accuracy. o Reduction in overhead costs (e.g. software and labour). o Eliminating extraneous activities.

Table 4-2 Relevant costs and benefits identified in the literature

Efficiency and effectiveness benefits can be both intangible and tangible (Gillespie, 1994; McInnis & Blundell, 1998). However, benefits are considered mostly from an intangible standpoint because of the focus on decision-making in a resource management context. Also, the time and expertise required to quantify these benefits is beyond the scope of this research. Therefore, the discussion of benefits will overwhelmingly focus on intangible effectiveness benefits.

4.4.2 Estimation

A key component of any feasibility study is estimation. The variables discussed in the cost-benefit analysis must be estimated for the feasibility assessment to proceed. Estimates can be categorized as either ‘fair’, ‘rough’ or ‘ballpark’ estimates (Katimuneetorn, 2008):

- Fair estimates - within 25-50% of the actual value and are possible when the project is familiar and the details of its implementation are known.
- Rough estimates - ideally within 50-100% of the actual value and are possible when working with well-understood needs and familiarity with the relevant issues.
- Ballpark (or order of magnitude) estimates - within two to three times the actual value.

Ballpark estimates are most likely with completely new projects and are valuable in providing a general understanding of the problem. Based on the time, availability of data, expertise, and uncertainty the estimates for my research are between rough and ballpark estimates.

This research employs a bottom-up approach to estimation (Katimuneetorn, 2008). The project is broken down into the most essential tasks before accumulating the cost for the whole project. The techniques for estimation are a comparative analysis approach and expert judgement.

Comparative analysis is a technique used to better understand the causal processes of an event by observing similarities and differences between cases (Pickvance, 2005). For example, in ***Social Impact Assessment***, comparative analysis is commonly used to predict the likely impacts from development in communities based on case studies of communities that have undergone similar development (Asselin & Parkins, 2009; Becker et al., 2004; Burdge, 2004).

Case studies are a rich source of information for anticipating likely outcomes prior to implementation (Becker & Vanclay, 2003; Burdge, 2004). Comparative analysis is a means of drawing meaningful conclusions from case studies based on the systematic development of a framework for case selection and comparison (Walk, 1998). This is a particularly useful method for estimating intangible benefits associated with an application that has not been employed in a specific context (Chian & Wilkinson, 2015; Dekker & Hestir, 2012; McInnis & Blundell, 1998; McVicar & Jupp, 1998; Meaden & Aguilar-Manjarrez, 2013). While this can be an effective means of estimating costs and benefits, it must be approached with caution. Some projects are unique and/or differ in key ways and therefore lack any directly comparable cases (Rihoux & Ragin, 2009). Therefore, this method of estimation is intended as only a preliminary, cost-effective assessment of costs and benefits.

Expert judgement is a reliable and inexpensive method for deriving estimates (Hughes, 1996; Katimuneetorn, 2008; Meaden, 2013). Experts, by definition, have extensive experience in their field of expertise. In remote sensing applications the specific objective may vary but the overall process, from collection of the data through to final analysis, contains many similarities (Lillesand et al., 2008). Therefore by breaking the protocol down into its most basic components (bottom-up approach), experts within the field are able to produce realistic estimates of costs associated with each stage. Expert opinion will never be able to take into account all the variables at play (e.g. competence of the personnel administering the protocol, delays in obtaining data, hardware/ software malfunction). However, the estimates can be classified minimally as rough estimates (Hughes, 1996).

4.4.3 Analysis

Analysis of costs and benefits is a qualitative comparative assessment. Quantifying benefits would require a more in depth understanding of the organization’s priorities and expenditures. For example, McInnis & Blundell (1998) used detailed cost and benefit information from interviews with key figures in 62 separate cases of GIS installations to develop a regression model to estimate benefits. This depth of analysis is an unnecessary and inappropriate approach considering the purpose of the protocol being assessed. The purpose of the cost / benefit analysis is to systematically articulate costs and benefits to facilitate a more informed decision regarding this protocol, and not a quantitative assessment.

Total costs are calculated by breaking down the basic components of the protocol and using expert judgment to estimate the time and financial costs associated with each stage. These estimates are based off of the requirements of the pilot studies (see section 4.3.1). Benefits are framed according to the potential utility of information produced by the protocol in meeting CEF objectives (for example, how can the protocol improve upon the assessment of forest biodiversity?) and inferred through a comparative analysis of similar research. In a comparative analysis it is necessary to assess the reliability of the predictions (Rihoux & Ragin, 2009). To address this need, the likelihood of realizing each selected benefit is assessed qualitatively using a unique rubric designed for this research (Table 4-4). A rubric is a means of ensuring consistent evaluation of complex, subjective material by identifying key components of an ideal product and delineating evaluative criteria to assess each component (Herman et al., 1992). A range of standards for each evaluative criterion would then be used to categorize the performance of each component. For example, a common academic rubric for grading an essay might consider ‘writing mechanics’ as a key component of an essay. Grammar would be an evaluative criteria of writing mechanics that might be assessed by number of errors (e.g. ‘A’ = zero mistakes, ‘B’ = 1-3 mistakes, ‘C’ =4-6 mistakes, or ‘D’ = more than 6 mistakes). Using this analogy, the essay being graded is the protocol. The key components (writing mechanics) are the potential benefits to the CEF, and the likelihood of achieving that benefit is the grade. A comparative analysis of the literature is the basis for assigning likelihood, therefore the evaluative criteria (e.g. grammar) are the evidence to support or negate the likelihood of these benefits. The range of standards to assess these criteria, which in the example is number of grammatical errors, is the similarity of the comparative research in methods, objectives and results. In short, benefits are assessed based on a comparative analysis of similar applications; the more evidence of success in achieving the desired benefits using similar methodology, the higher the likelihood of achieving these benefits.

4.4. 4 Benefits Rubric

Rihoux and Ragin (2009) explain that in order to enable systematic comparative analysis, each case must be broken down into specific factors or conditions that lead to the outcome of interest. Assessing the similarity of these factors between cases is a critical component in comparative analysis (Asselin & Parkins, 2009; Burdge, 2004). In this case, the outcome of interest is the information generated from the geomatics solution and the associated benefit to decision-making. Therefore, the evaluative criteria reflect fundamental elements of remote sensing applications that affect the information that is created. These components are methods, context and results. Similarity in these three categories between the proposed protocol and examples in the literature is the basis for assigning the likelihood of achieving the expected benefit.

A successful remote sensing application – where data are converted to information for pragmatic purposes – proceeds from the design of the methodology (Franklin, 2001). Therefore comparative analysis of remote sensing applications will often focus on the advantages/disadvantages of different methods in meeting the same objective (Meera et al., 2004; Wang et al., 2005). However since the goal is to predict the benefits that will be realized as a result of the proposed protocol, comparing similar methodology is the most essential consideration for this comparative analysis. For the purpose of this feasibility assessment, methodological considerations have been distilled to three critical and interacting elements: analytical approach, data and scale.

The first methodological consideration is the analytical approach (interpretation and analysis). That is, the techniques employed to convert the image data into relevant information based on spatial and spectral pattern recognition. The number of techniques available is broad and complex, with each technique uniquely impacting the quality and complexity of the information that is produced (Franklin, 2001; Lillesand et al., 2008; Q. Weng, 2011). In the broadest sense, these techniques range from manual interpretation of data to automated interpretation using sophisticated algorithms. The feasibility assessment identifies similar analytical approaches taken to accomplish the specific tasks identified in the protocol (e.g. the use of manual interpretation vs. automated unsupervised classification to delineate landcover classes). The results of similar approaches, in terms of information generated, facilitate inferences about the likelihood of achieving the expected benefits (Asselin & Parkins, 2009; Rihoux & Ragin, 2009). The exact specifications of each technique (e.g. the calculation of parameters for use in a specific algorithm) will not be critical criteria for assessing similarity. Instead, data type and scale will further refine the comparison.

Evaluative Criteria	
Context	➢ Objectives / purpose o Factors of interest ➢ Study area
Methods	➢ Data type (satellite photos, aerial) ➢ Spatial scale ➢ Interpretation / analysis procedures o Reference data used
Results	➢ How were the results used in decision-making? ➢ Did the protocol produce information that improved decision-making? ➢ Issues and successes with the method? ➢ Limitations / uncertainties?

Table 4-3 Evaluative criteria for comparative assessment of remote sensing applications

The underlying process in remote sensing applications is the measurement of electromagnetic energy and subsequent conversion to useful information (Lillesand et al., 2008). Thus **data type** is a primary consideration when inferring the outcome of remote sensing applications. Different types of remote sensing data (e.g. aerial photography, satellite, LIDAR, SAR) capture varying degrees of electromagnetic data, ultimately dictating the quality and depth of information that can be extracted (Kennedy et al., 2009; Lillesand et al., 2008). The distinction between data types may be subtle (colour aerial photography vs. black and white) or more explicit (LIDAR vs. satellite). Given the same methods, this underlying difference could impact the output significantly, depending on the application (Lefsky & Cohen, 2003). For predicting the outcome of a specific method, comparison between different data types may be warranted in some instances (Maillet et al., 2004). For example, the comparison of aerial photography and satellite data may be warranted if the focus is on delineating landscape level patterns (Wulder & Franklin, 2007). If two different data types are used in comparison the reason must be clearly articulated.

Spatial scale is another important methodological consideration that affects the level of useful information that can be extracted from remote sensing images (Franklin, 2001; Lillesand et al., 2008; Woodcock & Strahler, 1987; Wulder & Franklin, 2007; Wulder et al., 2008). Spatial scale encompasses ‘grain’, the finest resolution of individual units of observation (i.e. spatial resolution), and ‘extent’, the size of the study area (Lillesand et al., 2008). The spatial scale of the image determines the objects and processes that can be detected. For example, small-scale images (<= 1:50000[2]) are conducive to large-area resource assessment and general resource management planning; medium-scale photos (1:12000 – 1:50000) enable identification, classification and mapping of features such as tree species, agricultural crop type, vegetation community and soil type; and large-scale photos (>= 1:12000) permit intensive monitoring of phenomena such as extent of damage from plant disease, insects or tree blowdown (Lillesand et al., 2008).

One way to understand the influence of scale is through ***hierarchy theory***. This theory explains that in an ecological system, the dominant phenomena being observed will change with the scale of observation (O’Neil & Smith, 2002). At different scales, the processes and patterns

[2] This numeric scale indicates that 1 unit on the image represents 50000 units on the ground e.g. 1cm = 50000cm or 50km

observed will differ. In other words, conclusions regarding the distribution, abundance, behaviour or dynamics of an ecological entity will vary depending on the scale of observation (O'Neil & Smith, 2002). Thus, while inferring results from a specific remote sensing method, scale must be carefully considered.

Context is important for gauging the relevance of similar methods. Similar methodological approaches - with similar data, scale and analytical approaches - may have little to no implications for the proposed protocol if the context is drastically different. For example, a comparison of methods between two forestry applications will enable more direct inference than between a forestry and urban application. The comparison of context will consider both the objectives/purpose of the research and the study area, to reflect the importance of similar geography and purpose in comparative cases (Burdge, 2004).

Objectives are important for differentiating between applications of similar methods. While the methodological approach may be similar (unsupervised classification), the objectives determine the way in which the methods are applied and the type of information that is generated (e.g. how many classes, and/or how detailed are the classes) (Weng, 2011). The objectives determine the factors of interest (landcover vs. species) and the level of analysis (landscape vs. stand) (Franklin, 2001). Research that employs similar methods with similar objectives to the proposed protocol will yield more relevant conclusions regarding the implications of certain methods in achieving the expected benefit (Rihoux & Ragin, 2009).

The **study area** is used to encapsulate the broad range of geographic factors that can affect the level of information derived using remote sensing techniques (e.g. topography, landcover type, socioecological impacts). This range of factors has confounding implications for the collection of remote sensing data (Lunetta et al., 1991; Proy et al., 1989). The application of certain techniques will have variable implications for data acquisition, depending on the geographic factors. Therefore, it is important to acknowledge the difference in study areas before drawing any conclusions between the example in the literature and the proposed geomatics solution. The more similar the study area, the more likely the results will be relatable. For example, a comparison of drainage analysis in an urban setting and a forest setting are not likely to have many similarities. Comparing drainage analysis techniques for boreal forest and coastal forests would be more relatable. Better yet, drainage analysis of different watersheds within the same forest would be the most comparable.

The methods and context are important for understanding if the research is comparable to the proposed protocol. The results are then the ultimate determinant of whether this research has negative or positive implications for the proposed protocol. Results refer to the data generated and the role that data played in meeting the objectives/answering the research questions (Franklin, 2001; Wulder & Franklin, 2007). The results indicate whether the methods in this comparative research are capable of generating the information necessary to achieve the desired benefits. Additionally, the results will help identify potential issues, limitations and/or uncertainties with the proposed methodology (Asselin & Parkins, 2009; Burdge, 2004; Rihoux & Ragin, 2009).

The rubric designed for this research combines these three evaluative criteria simultaneously (methods, context and results) to surmise the likelihood of achieving the expected benefits with the proposed protocol. The results indicate whether the expected benefit is likely or unlikely. The degree of similarity between methods and context dictate the relevance of the results and is reflected in the degree of likelihood. This is a qualitative comparative analysis of similar research to assess the potential implications of the proposed protocol. Its purpose is to facilitate a cost-effective, a priori evaluation of benefits. The rubric can also serve as a framework for future quantitative assessment of the protocol. This adjustment could be made by shifting the evaluative criteria to encompass the results of specific tasks demonstrated in the pilot studies. Likelihood could then be statistically evaluated based on these results.

Likelihood / Benefit	Very Unlikely	Not Likely	Somewhat Unlikely	Needs more research	Somewhat Likely	Likely	Very Likely
Method → Information product	Directly relatable research that demonstrates the proposed solution would not have the desired benefits.	There is similar research to support the conclusion that the intended application is likely to have many difficulties and will not have desirable benefits. - Similar methods. - Similar context. - Results are counter-intuitive to what is desired to achieve the benefit.	There is some similar research to support the conclusion that the intended application may have desirable benefits. However there are notable uncertainties and difficulties with the methods. ○ Methods are similar in approach but vary in key areas (e.g. Scale & data type). ○ Context may differ. ○ Results have some relevance.	There is little to no similar research. Conclusions about desirable benefits require more direct study.	There is some similar research to indicate that the intended application may have desirable benefits. ○ Methods are similar but may vary in a key area (scale, data type). ○ Context may differ. ○ Results have relevance to the benefit.	There is much similar research to support the conclusion that this application will have desirable benefits. ○ Methods are similar. ○ Context is similar. ○ Results are similar to what is desired to achieve the benefit.	Directly relatable research that demonstrates how the desired benefits can be achieved.

Table 4-4 Rubric for assessing the likelihood of achieving the expected benefits

Chapter 5: Results – Gap/Opportunity Analysis

The purpose of the gap/opportunity analysis is to address conceptual feasibility. It situates the problem within a broader management context and identifies methodological limitations. A solution is identified and discussed that is theoretically capable of addressing these limitations.

5.1 Gap

5.1.1 Context – Managing for Forest Biodiversity

The impetus for this research was the forest biodiversity cumulative effects assessment (FBCEA) procedure within the cumulative effects framework. However, the FBCEA procedure is in a state of change and it is more relevant to situate the research within the broader context of forest biodiversity assessment. To understand the context of this research it is important to reiterate what is meant by forest biodiversity and how it is measured (see discussion in section 3.3 for more detail).

In BC a common approach is to assess forest biodiversity from a 'historic range and variability' (HRV) theoretical perspective. Indeed, this approach is commonly adopted by many forestry professionals (e.g. Oregon [Wimberly et al., 2000], Yellowstone [Tinker et al., 2003], Quebec [Cyr et al., 2009]). HRV theory assumes that forest conditions vary spatially and temporally in response to natural disturbances, and within this historic range of conditions ecosystems are self-sustaining and resilient (Keane et al., 2009). Management from an HRV perspective assumes that if forests are managed within this broad historical envelope of possible ecosystem conditions, it is more likely that all native species and ecological processes will be maintained (BC Ministry of Environment, 1995; Keane et al., 2009; Landres et al., 1999). Given the insurmountable task of quantifying all aspects of forest biodiversity, to use HRV effectively variables must be: measurable across a specific temporal and spatial extent; representative of broader ecological processes; and applicable to the management context (Keane et al., 2009). Measuring coarse structural attributes as a surrogate for species and genetic diversity is seen as a more pragmatic and cost-effective approach to measure biodiversity than focusing on individual species or residual structure (BC Ministry of Environment, 1995; Franklin, 2001; LeMay et al., 2008). For example, forest age and landscape pattern can be measured on a broader scale more readily than measuring the amount of standing dead trees within stands (Delong, 2011; Wimberly et al., 2000). This ecological concept is at the heart of the foremost document for biodiversity management in BC (Biodiversity Guidebook) (BC Ministry of Environment, 1995) and is used throughout North America to guide ecosystem management, species conservation and landscape restoration (Bollenbacher et al., 2014; Cyr et al., 2009; Tinker et al., 2003; Wimberly et al., 2000). In this context, **forest biodiversity** is measured by the variability in broad habitat indicators such as seral stage and patch size across a range of ecosystems and landscapes; connectivity of ecosystems and; interior habitat conditions (BC Ministry of Environment, 1995). These habitat indicators are used as a surrogate for the fine-scale structural attributes (e.g. snags, downed wood, and coarse woody debris) that support the natural diversity of species and ecosystem processes.

Forest Biodiversity	Refers to diversity of habitat structure such as seral stage, amount and distribution. Habitat diversity is used as a surrogate for species and genetic diversity. This approach is based on the ecological HRV concept that natural disturbance regimes create forests of different age and pattern that contain the structural attributes that species rely on.

In a cumulative effects assessment context, the deviation of current conditions (e.g. the amount and distribution of old seral forests) from the benchmark HRV estimates can be used to gauge potential negative effects on forest biodiversity. Methods for quantifying HRV vary. For example, fire frequency and severity can be quantified from charcoal deposits and historical vegetation conditions can be measured using pollen deposits or repeat photography (Keane et al., 2009). In BC, HRV conditions focus on seral stage and are derived from original Biodiversity Guidebook (BGB) estimates and updated where possible with more recent research (Wong et al., 2004). Early, old and mature seral stages are associated with a range of forest stand structural attributes (e.g. snags, downed wood, and coarse woody debris) that support native species populations and community assemblages (BC Ministry of Environment, 1995; Canadian Council of Forest Ministers, 2007; Forest Practices Board, 2012; Lewis, 2016; Yearsley & Parminter, 1998). The age structure of forests is an important outcome of the natural disturbance regime (e.g. amount and distribution) (Landres et al., 1999; Yearsley & Parminter, 1998). The BGB used the Biogeoclimatic (BGC) classification system to categorize BGC subzones into 'natural disturbance types' (NDT) that reflect differences in the frequency and intensity of stand replacing events (BC Ministry of Environment, 1995; Lewis, 2016). For each natural disturbance type, first a stand-replacing disturbance return interval is estimated based on the frequency and intensity of disturbance. A negative exponential model is then used to calculate an expected mean amount of old, mature and early seral forest by BGC subzone, assuming constant disturbance rate and randomly located events. A distribution around the mean can then be calculated to reflect a "range of possible disturbance return intervals and greater periodicity in the frequency and variability in amount of area affected by disturbance annually" (Lewis, 2016, p. 11).

Current forest conditions in BC are measured using the vegetation resource inventory (VRI). VRI is an age-based inventory derived from the manual interpretation of aerial photography (Sandvoss et al., 2005). Manual interpreters follow a standardized procedure to delineate relatively homogeneous polygons in terms of landcover (FLNRO, 2015). Polygons, which represent forest stands, are assigned various forest attributes such as vertical complexity and age (FLNRO, 2015; Sandvoss et al., 2005).

5.1.2 Limitations

This discussion of limitations focuses on the BC context and the constraints associated with VRI data, assessment of forest structure and applicability to cumulative effects assessment. However, the challenges associated with establishing baseline conditions in forest structure are not exclusive to BC. Forest planning and restoration efforts in regions throughout North America use HRV baseline estimates as a guide (e.g.: Bollenbacher et al., 2014; Cyr et al., 2009; Demeo et al., 2018; Hessburg et al., 2013). Quantification of historical conditions requires "temporally deep, spatially explicit historical data, which is rarely available and often difficult to obtain" (Keane et al., 2009). The best sources of baseline data are spatial chronosequences or multi-temporal digital maps of forest structure (Keane et al., 2009). Yet these sources often lack the necessary temporal and spatial coverage and are not an adequate inventory of forest structure (Morgan & Gergel, 2013; Keane et al., 2006, 2009). A variety of models have been used to quantify HRV instead, but these are difficult and complex to use (Didion et al., 2007; Hessburg et al., 2013; Keane et al., 2009). The limitations described below reflect the broader issue of defining HRV with enough detail and at the appropriate scale for forest management.

First, the analysis of baseline conditions and long-term trends is a fundamental component of cumulative effects assessment (Noble, 2010, 2015b; Whitelaw & McCarthy, 2016), yet VRI data lacks the temporal range to establish baseline conditions and assess trends beyond 2003 (Sandvoss et al., 2005). This temporal scale is relatively short in comparison to the timeframe it takes for some forest structural attributes to accrue (Clark et al., 1998; Reilly et al., 2015). Therefore the current conditions cannot fully be understood in the context of individual and aggregated impacts of multiple actions on the landscape over time and space; an integral component of cumulative effects assessment (Gunn & Noble, 2011; Noble, 2015a, 2015b). Instead any assessment of forest biodiversity must rely on comparisons between current conditions, arbitrary ecological benchmarks and hypothetical 'natural' conditions derived from an HRV conceptual perspective to determine the nature and significance of cumulative change. The HRV concept that underlies the forest management in BC and elsewhere has many faults and limitations but is accepted as a viable benchmark due to its relative lack of uncertainty compared to forward looking projections (Keane et al., 2009; Wong et al., 2004). These hypothetical estimates based on broad natural disturbance types is a good proxy in place of missing information; however it is not sufficient to capture the complexity of reality (Wong et al., 2004). Without assessing current conditions relative to actual past conditions, there is no indication of rate and direction of change, and whether the current regime has led to improved or diminished forest biodiversity (Dubé, 2003; Hegmann et al., 1999). This is a significant omission as rate, size and temporal correlation of habitat disturbances, together with the rate and longevity of forest patches are central aspects of biodiversity (Bunnel & Dunsworth, 2009; Innes & Koch, 1998; Perera et al., 2004).

Second, VRI data lacks quantification in important stand level structural elements that may remain following partial disturbance or even severe disturbance (D. Lewis, personal communication, 2016; Sandvoss et al., 2005). This limitation stems from the age-based estimates of VRI (Keane et al., 2009). Age is notoriously problematic in VRI beyond about 100-150 years as it is based on the co-dominant forest canopy (D. Lewis, personal communication, 2018; Steventon, 1997). It misses older trees that survive previous disturbances and is only a measure of the age of that cohort of trees and not the time since the last stand-replacing disturbance (D. Lewis, personal communication, 2018; Steventon, 1997). Using age as a surrogate for forest stand-level structural attributes assumes that forest polygons of similar age contain similar structural attributes. The reality is that forest stands that have been affected by partial disturbances (e.g. wildfires, insect attacks and partial cutting that remove or alter forest canopy within a stand) have varying levels of residual structure (Turner et al., 2013). Some attributes in VRI could be used to modify age-based estimates, but lack completeness and consistency. Data on disturbance history for example can be used to 'net-down' age and associated residual structure (Lewis, 2016). However, interpretation of disturbance history relies on multiple data sources that can be inconsistent, incomplete, and/or out of date, in terms of specifying residual structure (Lewis, 2016). Harvest data in particular are reliant on forest licensees to update info on harvested areas, which is often incomplete (e.g. data of understory planted in partial harvest but no data on overstory) (Lewis, 2016). In addition, the effects of different types of partial disturbances on forest structure, composition and complexity are not correctly accounted for (D. Lewis, personal communication, 2016). For example, consider two 50 year-old pine stands with 40% tree mortality. In the first stand, tree mortality was a result of mountain pine beetle and not salvaged. Natural regrowth and succession took place after disturbance. In the second stand, 40% of trees were harvested and removed and the block was manually replanted. The residual structure of these two stands would differ (e.g. coarse woody debris, snags, undergrowth) but if age is used as a surrogate, these differences may not be correctly captured.

Lastly, manual VRI interpretation must sometimes rely on subjective decision-making by the interpreter. For example, the VRI-based approach relies on a set of arbitrary rules to differ between forest and non-forest in interface areas, such as grassland interface, or the subalpine/alpine interface (Sandvoss et al., 2005). As well, forest patches of homogenous seral stage are delineated by amalgamating similarly-aged polygons (e.g. 0-20, 21-40). This is problematic where a mosaic of forest stands have ages that span these arbitrary cut-offs (e.g. adjacent patches of 19, 26 and 31 yr. old forests that have similar attributes are separated based on age) (Sandvoss et al., 2005).

5.2 An Opportunity

There is an opportunity to improve the historic baseline and quantification of forest structure to utilize in biodiversity assessment by addressing the limitations described above, specifically by:

- correctly classifying partial disturbances and associated residual structure with more consistency and objectivity;
- capture stand-level structure and heterogeneity more effectively and less subjectively than existing data sets;
- distinguishing similar forest 'patches' more objectively than using arbitrary age-based rules; and
- establishing more concrete baseline conditions to improve temporal range.

5.2.1 Alternative Approaches

A multi-temporal analysis of historical aerial photography is capable of filling the gap in baseline data and trend analysis, which is a limitation of existing datasets utilized in forest biodiversity assessment. Employing an object-based image analysis (OBIA) approach as a means of conducting this analysis has the potential to fulfill the other stated limitations: subjective decision-making and lacking forest structural information.

5.2.1.1.1 *Multi-temporal analysis of historical aerial photography*

Establishing a baseline from which to assess change/trends on the landbase is essential for quality CEA (BC Ministry of Environment, 1995; Forest Practices Board, 2011; Franklin, 2001; Hegmann et al., 1999). An appropriate accessible means of fulfilling the data information gaps in the cumulative effects assessment of forest biodiversity is the vastly underutilized provincial and federal archives of historical aerial photography (Morgan et al., 2010). Aerial photography is the “longest available, temporally continuous and spatially complete record of detailed, objective ecological and historical information” (Morgan et al., 2010). Aerial photographs offer significant contributions to forest management in the form of quantitative data, and repetitive and synoptic coverage of vegetation cover and condition dating back to the 1920’s in some regions (Franklin, 2001; Morgan et al., 2010). This information is important for assessing vegetation condition and landcover over time, monitoring landscape and ecosystem change and estimating the historic range of variability within a system (Landres et al., 1999). Manually interpreted aerial imagery is an indispensable source of information for resource management and is not likely to be discarded (Lillesand et al., 2008). Yet, there are several challenges associated with historical aerial photography: individual photos have limited spatial coverage and therefore more time is required to process larger areas; difficulty in standardizing image contrast and rectification; the quality of photographs is dependent on many factors (e.g. weather), and; limited or inconsistent metadata (Morgan et al., 2010). However the high spatial resolution, stereoscopic views, reduced atmospheric interference (lower altitude), and large temporal spans make historical aerial photography an invaluable and essential resource for forest biodiversity assessment (Morgan et al., 2010).

A multi-temporal approach is necessary to identify long-term trends in rate and direction of change in forest structure (Gillanders et al., 2008). Multi-temporal data are collected at the same area over multiple time periods (Lillesand et al., 2008). A multi-temporal analysis for trend analysis of landscape change requires data from at least three points in time (Brown et al., 2000; Bulmer et al., 2011; Danby & Hik, 2007; Gillanders et al., 2008; Grossmann & Mladenoff, 2007; Kennedy et al., 2009; Morgan et al., 2010). Historical aerial photography that has the temporal coverage to fulfill this requirement can be used to assess trends in forest structure.

5.2.1.1.2 *Object-Based Image Analysis – a hybrid approach*

Image analysis is used here to broadly refer to the systematic conversion of the raw radiometric data in aerial photographs into meaningful and suitable information (Bock et al., 2005). There are two overarching image analysis methods: manual and automated. *Manual interpretation* relies on the expert judgement of trained interpreters to methodically delineate and classify polygons 'by hand'. Interpreters draw on their own experience and knowledge, using a 'convergence of evidence' approach to identify relatively homogenous polygons based on numerous characteristics simultaneously: tone, colour, size, shape, texture, pattern, shadow, site and context (Morgan et al., 2010). Manual interpretation is the traditional approach to image analysis, and despite the advent of advanced technology, is still widely used due to its effectiveness and accuracy (Lillesand et al., 2008; Morgan et al., 2010; Wulder, 1998). A key advantage of manual methods is the unique ability of human perception to process contextual information in an image (Morgan & Gergel, 2013; Morgan et al., 2010; Wulder et al., 2008). Interpreters are able to incorporate local (i.e. relationship between image regions) and global (e.g. time and location of the image) contextual information at their discretion into the classification process (Benz et al., 2004). However, the advantage of manual interpreters being able to apply expert judgment in arbitrary contexts also manifests as a main weakness: inconsistent results among interpreters (Thompson et al., 2007). Spectral characteristics and other objective measurements are not always fully evaluated and decisions in complex situations are ultimately up to the discretion of the interpreter. The individuality of each interpreter means that manual analysis results are not fully repeatable (Morgan & Gergel, 2013). Even with only one interpreter, the accuracy of this method is directly related to the experience of the interpreter and, even with high levels of experience, can yield inconsistent and inaccurate results (Thompson et al., 2007). Furthermore, manual interpretation can be very resource intensive; it requires extensively trained individuals, and analysis, especially of large areas, is labour intensive (Lillesand et al., 2008, p. 31).

Automated image analysis techniques operate on the underlying measurable data in an image. An image is essentially a grid of pixels, each with a unique radiometric/spectral response. While manual methods consider the image as a whole, automated methods rely on a statistical analysis of the radiometric data within an image to classify an image on a pixel-by-pixel basis and thus are able to identify nuanced differences throughout the landscape (Lillesand et al., 2008). Automated methods include: *spectral pattern* recognition, which uses pixel-by-pixel spectral information to classify an image; *spatial pattern recognition*, where the characteristics of the immediate surrounding pixels, such as texture, shape, pixel proximity and directionality, are considered in the classification process; and *temporal pattern recognition* where the change in a pixel over time is used to aid in feature identification (Lillesand et al., 2008). An example of spectral pattern recognition is an unsupervised classification. This method creates a number of ‘classes’ based on the range of radiometric values within an image. Each individual pixel is then assigned to a class with the most statistically similar radiometric response.

Automated methods rely on the statistical evaluation of data and therefore are well-suited to inject objectivity and repeatability into forest classification procedures that rely on subjective and inconsistent decision-making (Morgan & Gergel, 2010, 2013; Wulder et al., 2008). Compared to manual methods, a common criticism is that traditional pixel-based approaches inadequately incorporate contextual information in the interpretation procedure (Blaschke et al., 2008; Desclée et al., 2006; Hay et al., 2003). While some algorithms process contextual information to some extent (e.g. edge detection), they lack the ‘scene understanding’ that comes from human perception (Blaschke, 2010).

Object-based image analysis (OBIA) is a hybrid-approach that combines the statistical analysis of automated methods and contextual understanding of manual interpretation. OBIA contains three main functional processes: image segmentation, deriving analytical information about the segments (object-based metrics), and classification (Lillesand et al., 2008).

Segmentation is an iterative process of grouping pixels together into relatively homogenous regions that represent relevant ecological features (Blaschke, 2010; Bock et al., 2005; Hay et al., 2003; Morgan & Gergel, 2010, 2013). Initial segmentation is mainly data driven, using low-level information such as pixel values to generate ‘image object primitives’ according to the statistical similarity in pixel values (Benz et al., 2004; Blaschke, 2010). As pixels are consecutively merged into progressively larger objects, additional spectral information is calculated (e.g. mean reflectance), a spatial dimension is added (e.g. shape, distances, areas, topologies), and a hierarchical network of image objects is built where each object knows its neighbors, sub-objects and super-objects (Blaschke, 2010). This extensive set of quantitative ‘object-based metrics’ can be used to classify objects according to specific forest and terrain characteristics, such as crown-cover, canopy layers or dead tree/snag abundance (Hessburg et al., 1999) using techniques such as classification and regression tree analysis (Morgan & Gergel, 2013), cluster analysis (Morgan & Gergel, 2013), or nearest neighbour/fuzzy classifiers (Pringle et al., 2009).

OBIA is well suited to forest structure classification: it produces high quality GIS-ready information in an efficient, time and cost saving approach (Benz et al., 2004); it is able to incorporate existing vector-databases during all steps of the classification process, enabling it to take advantage of existing datasets at the CEF’s disposal[3] (Bock et al., 2005), and; it is capable of effectively analyzing historical black and white aerial photography, with some research producing classification accuracies greater than 80% (Halounová, 2004). The ability to produce this type of information is indispensable to natural resource managers who must make decisions such as how much of a resource to allocate and whether to allow or restrict certain activities. These methods permit abstract concepts like forest biodiversity to be quantified with more concrete surrogate measures of forest structure and be visualized alongside existing datasets related to existing and proposed resource activities, natural disturbances and legislated forest values (e.g. old growth management areas). This information facilitates more transparent and justifiable decisions. Furthermore, the ability to calculate and incorporate ecologically relevant metrics similar to what a manual interpreter would use (e.g. shape, tone, size, texture and contextual relationships with neighbouring objects) in an automated procedure makes OBIA a potent tool in ecological analysis (Blaschke, 2010; Hay et al., 2003; Laliberte et al., 2004;

[3] Vector datasets have an advantage over raster datasets such as aerial images as they are already processed into usable information and no further data conversion is needed.

Morgan & Gergel, 2010, 2013). Ecological classification is enhanced with OBIA methods (Dorren et al., 2003) due to "meaningful statistic and texture calculation, an increased uncorrelated feature space using shape (e.g. length, number of edges) and topological features (e.g. neighbor, super-object), and the close relation between real-world objects and image objects" (Benz et al., 2004, p. 240). The inherent multi-scale approach creates a hierarchical network of image objects that enables precise analysis of the substructures of a specific region (Benz et al., 2004), and; the statistical analysis of spectral signatures (characteristic of automated methods) can be supplemented with the quantification of spatial and contextual information to distinguish ecologically meaningful structures that do not necessarily have distinct spectral features (Bock et al., 2005).

5.2.2 A Solution

Morgan & Gergel (2010; 2013) analyzed panchromatic aerial photographs of a watershed in Clayoquot Sound, BC from 1937-38 using a unique OBIA protocol. They used the multi-resolution segmentation procedure in Definiens as the basis for analysis (Benz et al., 2004; Definiens, 2012). Based on the object-based metrics (OBM) that are derived automatically for segmentation results, Morgan & Gergel compared manual and OBIA methods of delineating forest polygons (2013), classified objects according to VRI forest classifications schemes using a Classification and Regression Tree (CART) analysis (2013) and quantified spatial heterogeneity using factor and cluster analysis methods (2010). From this point on, the protocol will be referred to as **Historic Aerial Photograph Heterogeneity Analysis (HAPHA)**. HAPHA has several characteristics that position it to address the limitations in existing inventory data (e.g. VRI) for cumulative effects assessment of forest biodiversity:

- Objective and efficient assessment of historical aerial photography in a reproducible manner to establish historical baseline conditions;
- Quantification of ecologically relevant metrics (OBM and heterogeneity) that may provide unique insights into forest structure ; and,
- Ability to establish trends in forest structure over time by utilizing historic datasets, contextual information and ancillary data to capture cumulative change from natural and anthropogenic disturbance.

A brief overview of HAPHA will be given here to highlight its potential relevance to the cumulative effects assessment of forest biodiversity. The discussion will focus on the main image analysis tasks: segmentation, classification and heterogeneity analysis. For a more detailed description of the HAPHA process and settings, refer to Morgan & Gergel (2010; 2013). The potential benefits of HAPHA to forest biodiversity assessment are examined in section 7.2.

5.2.2.1.1 *Segmentation*

HAPHA uses the multi-resolution segmentation process in Definiens. Definiens, formerly eCognition, is the pioneering software for object-based image analysis (OBIA) and is still the most flexible and comprehensive object-oriented system for image classification (Benz et al., 2004; Bock et al., 2005; Definiens, 2012). The multi-resolution segmentation process is a bottom-up pairwise region-merging technique that creates ‘objects’ that are internally homogenous (Benz et al., 2004; Definiens, 2012; Morgan & Gergel, 2010, 2013). It is an iterative process: initial segmentation acts on individual pixel ‘objects’ and iteratively aggregates adjacent ‘objects’ creating intermediate object states with increasing differentiation of classification. The objects are extracted at different resolutions of the photo, representing different features/processes that occur at different scales (Benz et al., 2004).

Input layers provide the building blocks for the segmentation process. The delineation, characterization and differentiation of meaningful image objects (i.e. representing real world features) relies on the ecologically relevant information contained in these layers (Benz et al., 2004). Morgan & Gergel (2010; 2013) used 8 different input layers derived from tone, texture, and terrain data. Tonal data are the primary data source and refers to the aerial photographs. Texture and terrain data are auxiliary layers that have aided classification and analysis of forest parameters (Franklin et al., 2000; Morgan & Gergel, 2013; Wulder & Boudewyn, 2000). Texture in a photograph refers to the quantification of the spatial variation in image tone that contains valuable information about the diverse arrangement of forest structure horizontally and vertically (Franklin et al., 2000; Wulder & Boudewyn, 2000). Unique variations in image tone can be used to stratify stands and increase the accuracy of forest classification and modelling of biophysical attributes (Bock et al., 2005; Franklin et al., 2000; Halounová, 2004; St-Onge & Cavayas, 1997). Topography is related to vegetation pattern, structure and composition (Torontow & King, 2011). Incorporating topography into ecosystem and landscape analysis using elevation and terrain derivatives has demonstrated applicability (Dorren et al., 2003; MacMillan et al., 2007) and ecological relevance (e.g. elevation and aspect influence solar energy and water regimes, and topographic wetness indices are used to describe patterns of soil moisture, that are both linked to variation of vegetation patterns) (Gergel & Turner, 2002; Landres et al., 1999; McPherson & DeStefano, 2003; Morgan & Gergel, 2010, 2013). The final layers selected by Morgan & Gergel (2010; 2013) were chosen according to results of a correlation analysis.

The multi-resolution segmentation (or multi-scale) approach has been used successfully in ecological, forestry, and landscape ecology applications (Baatz & Schäpe, 2000; Benz et al., 2004; Bock et al., 2005; Burnett & Blaschke, 2003; Grossmann & Mladenoff, 2007; Kalma, McVicar, & McCabe, 2008; Morgan & Gergel, 2010; Mui, He, & Weng, 2015; Sheeren et al., 2009). Multi-resolution segmentation: can easily incorporate ancillary (thematic) data, and by assigning weights, this data can have varying degrees of influence on the resulting objects; has various factors that can be manipulated to create objects at different scales and to reflect objects of interest (scale, shape, compactness), and; creates more meaningful objects (Benz et al., 2004). Morgan & Gergel (2013) compared their segmentation results to manual interpretation. They found that segmentation objects can be created that are similar in size, number and quality to manually delineated polygons created according to VRI standards (Morgan & Gergel, 2013). These polygons, which represent medium scale forest stands, can then be broken down into progressively smaller sub-objects to calculate within-object heterogeneity (Morgan & Gergel, 2010).

5.2.2.1.2 *Classification*

Morgan & Gergel (2013) used 30 OBM to classify objects into forest classes according to the VRI classification scheme (see Appendix A:). Classification and Regression Tree (CART) analysis was used with the Gini-splitting (tree-fitting) algorithm to create a series of binary splits to divide entities into homogenous groups using the best distinguishing variables. Accuracies between classes varied, but when provincial VRI mapping standards for overlap accuracy was considered accuracies fell within or exceeded acceptable thresholds (82-87%). Not all classes achieved high classification accuracies and more research is needed to determine the applicability of this approach. However, the initial success of this approach has important implications for assessing forest structure and the potential relevance to cumulative effects assessment. These automated methods are a more objective and efficient alternative for utilizing the extensive historical photography archives than manual interpretation. This improves the feasibility of using historical photography for establishing baseline conditions

5.2.2.1.3 *Heterogeneity*

The most unique aspect of this approach is the quantification of heterogeneity. Heterogeneity is broadly defined as the degree of spatial variability of some property within a system (Li & Reynolds, 1995). Heterogeneity is thought to be the ultimate source of biodiversity (Pickett, 2003), influencing species diversity, resilience and ecosystem function, and making it very relevant for sustainable forest management (Lindenmayer et al., 2006). In addition, changes in heterogeneity over time in response to human activity can be used to gauge the cumulative effects of these activities on ecological function and complexity (Turner et al., 2003).

Morgan & Gergel (2010) quantify heterogeneity using the statistical variability in numerous ecologically relevant object-based metrics derived from the input data sets and contextual data (object/patch border characteristics) derived through the segmentation procedure. This quantitative approach offers unique advantages over traditional approaches to heterogeneity assessment that rely on arbitrary categorical classifications, and the proportion of habitat type or number of classes used in the classification scheme (Morgan & Gergel, 2010). This method also has the capacity to account for within object heterogeneity thanks to the inherent multi-scale approach and hierarchical spatial-semantic network of objects created within OBIA (Morgan & Gergel, 2010).

This approach is consistent and relies on statistical variability within the data to generate an almost limitless range of scales from various sources of remotely sensed data (as opposed to the single scale present in VRI data) (Morgan & Gergel, 2010). Morgan & Gergel (2010) also demonstrate the potential to use this approach regardless of landscape variability; ecologically, biophysically and topographically. The potential utility of the heterogeneity analysis is as a more reliable and objective metric for residual forest structure than using forest age as a surrogate. This is explored in more detail in section 7.2 (Potential Benefits).

5.3 Discussion – Conceptual Validation

The results of the gap/opportunity analysis indicate that an OBIA analysis that incorporates historical imagery might be capable of assessing changes in forest structure due to landscape change and would be beneficial from the perspective of cumulative effects assessment (Table 5-1). Specifically, a multi-temporal view of forest conditions would provide better insights into how forest conditions have responded to stressors and legal designations (Franklin, 2001; Morgan et al., 2010; Gillanders et al., 2008). However, extracting information from historical aerial photographs can be difficult, costly and time consuming (Morgan et al., 2010; Pringle et al., 2009). The greatest foreseeable challenge is the logistics of converting the photos into useable, GIS-compatible information. The gap/opportunity analysis found that an OBIA approach has the potential to mitigate challenges with historical imagery and make this task more cost-effective. Object-based image analysis (OBIA) is a hybrid-approach that combines the objective statistical analysis of automated methods and contextual understanding of manual interpretation. An object-based, multi-resolution segmentation approach combined with image enhancement techniques may be better equipped to deal with the variability in historic photos (Flanders et al., 2003; Halounová, 2004). Also, the semi-automated nature of OBIA means that it is repeatable, i.e. the rules and settings learned in one area can be saved for use in other areas, and can be modified based on local constraints (Flanders et al., 2003). Thereby, OBIA could also contribute to the financial feasibility of the protocol by increasing the speed, consistency, and efficiency of converting photos to GIS-products (Wulder et al., 2008).

Gap/Opportunity Analysis	
Gap	
1. What are the management/decision-making objectives? (Context)	The overarching objective is to manage forests to sustain long-term benefits for a diverse set of users.
2. What are the key limitations in meeting these objectives? (Limitations)	Limitations to forest biodiversity assessment in BC stem from the use of VRI data and HRV based benchmark conditions. This is not a criticism of this approach. The current approach makes use of available information using the best methods available. o Subjective delineation of forest stands and estimates of forest structure; o Lack of long-term data to establish baseline conditions and trends; o Reliant on VRI-derived age estimates as a surrogate for structural complexity within stands.
Opportunity	
3. What methods and/or data might reasonably be expected to address the limitations facing management? (Alternative Approaches)	Historical aerial photographs have a greater temporal range, thus an opportunity exists to estimate historical forest conditions (e.g. stand composition and landscape pattern) and better assess trends in forest biodiversity over time in relation to management decisions and cumulative effects. The best methods for assessing historical aerial photography are: o Multi-temporal approach o OBIA
4. What techniques are best suited to generating the information that is needed? (Potential Solution)	The research by Morgan & Gergel (2010; 2013) was identified as having the greatest potential in establishing baseline conditions in forest structure. Particularly promising are the unique quantification of heterogeneity, objective and reproducible analysis of historic photos, and use of contextual information. Initial results show that the methods can be accurate and consistent across landscapes.

Table 5-1- Gap/Opportunity Analysis Results:

HAPHA uses the same underlying OBIA procedure to generate unique, quantitative definitions of heterogeneity (Morgan & Gergel, 2010) and to classify forest polygons according to BC forest and terrain schemes (Morgan & Gergel, 2013). High classification accuracies (Morgan & Gergel, 2013) and the potential relevance of historical heterogeneity to estimate residual forest structure and help overcome tonal variability of historic photos is promising (Blaschke et al., 2001; Blaschke et al., 2008; Morgan & Gergel, 2010, 2013; Turner et al., 2003; Turner et al., 2013). Conceptually the potential value of this approach directly aligns with cumulative effects assessment, particularly at a strategic level of planning: evaluating the effectiveness of legal objectives, assessing trends, and informing resource management decisions (Lewis, 2016). A multi-temporal analysis using historical photos can supply important baseline information from which to assess trends. This information can be used to assess the adequacy of existing legal designations, forest practices and other resource management activities (including environmental assessment) for meeting biodiversity objectives (BC Ministry of Environment, 1995; Forest Practices Board, 2011; Franklin, 2001; Hegmann et al., 1999).

5.3.1 Limitations, Assumptions, Uncertainty

First and foremost are the uncertainties and known difficulties with historical imagery. Error is intrinsic when comparing photos from different dates and times of day that were possibly taken at different scales and by different sensors (Flanders et al., 2003). Historic photos especially are notoriously variable adding an additional level of uncertainty (Lillesand et al., 2008). Assuming aerial coverage would be sufficient, each photo would have to be inspected to determine the quality of image beforehand. Additional complications could arise when orthorectifying historic photos. There are really no opportunities to collect ground truth points for historic photos unless there are permanent or lasting features (e.g. geological formations). If the area lacks distinguishable points of reference (e.g. no roads/structures and just trees) then this task could be difficult and introduce more uncertainty into the process (PCI Geomatics, 2011). Historic photos could also be missing metadata (e.g. focal length, flying height) that could reduce the accuracy of orthorectification (Morgan et al., 2010).

OBIA methods were selected as a means of overcoming variability in historical imagery as well as for more objective and repeatable results. A common criticism of the OBIA approach is the level of expertise required to properly select OBIA parameters (Blaschke et al., 2008; Hay et al., 2005). The ideal user needs to have a significant knowledge of the objects of interest, including the spatial and spectral behaviour of the objects and the underlying processes, to choose the best parameters to identify and classify the objects (Flanders et al., 2003; Morgan & Gergel, 2010). Once parameters are established, OBIA is designed to capture expert knowledge and how it was applied so that it can be efficiently applied elsewhere (Blaschke et al., 2000). However, deciding on transferability of a protocol to a new area is also a matter of analyst judgement. The assumption is that an ideal user exists. An aspect of feasibility that will need to be carefully considered is the appropriate expertise to develop this tool and then building the capacity to use this tool (e.g. existing qualified users, or logistics of training new users).

Chapter 6: Results - Pilot Study Design

The purpose of the pilot study design is to assess the practical feasibility of testing HAPHA. The pilot study design has two components: the research design and the multi-criteria evaluation. The research design lays out the considerations for the pilot study: design, variables to consider, number of samples required and power to detect effects. The research design was necessary to guide the multi-criteria evaluation of potential study sites. The MCE identified study sites that might meet the data requirements of the proposed research design, and thus the ability to conduct a pilot study that would assess the usefulness of HAPHA with some degree of confidence. This was essential for assessing the practical feasibility of HAPHA. The research design was also intentionally preliminary, with the intent that it can be used as a reference for further research.

6.1 Research Design

The research design is the template for collection and analysis of data in the pilot studies (Bhatta, 2013). A research design determines the questions to study, the most relevant data and the methodological approaches suitable for data collection and analysis. Meticulous construction of the research design ensures the research questions are answered with confidence in a timely and cost efficient manner.

The purpose of the research design in this feasibility assessment is to identify key focus areas for future testing/calibrating of HAPHA. Purposely, this research design is not fully developed and will need to be calibrated by a statistician prior to implementation. The intent is that identifying key elements of a sound research design for this purpose will generate a realistic expectation of the requirements for implementation of the pilot studies (and potential provincial implementation). This helps to inform the cost-benefit analysis as well as lay the groundwork for future research.

This section begins by outlining the ‘performance objectives’: the practical questions dictating the suitability of HAPHA to its intended purpose. Data relevant to these questions is then discussed in the variables section. Finally, the analytical design and sampling design are discussed in relation to the performance objectives, concepts of power and the nature of the data. The sampling design is concerned with how data are to be observed and the analytical design is how collected data are to be analyzed.

An underlying theme in this section is the concept of statistical power. Power refers to the probability of detecting an ‘effect’, i.e. a correlation or a change in the response variable, as statistically significant when there is in fact an effect (LeMay & Robinson, 2004; Yanai et al., 2003). Several important aspects of the research design affect power: the sampling design (experimental unit, sampling scheme, and/or number of samples); the variability of the response variable(s); the magnitude of the change being measured (effect size); and the nature of the test (i.e. significance level and whether the alternative hypothesis is one-sided or two-sided) (LeMay & Robinson, 2004; Yanai et al., 2003). Balancing these factors is necessary to achieve the appropriate amount of power; too little power and the experiment will fail to detect significant differences in treatment means, too much power and the experiment will detect differences of no practical importance (LeMay & Robinson, 2004). High statistical power may not be a reality in the pilot study. The details of the statistical analysis Nevertheless, with careful consideration of the design components discussed in this section it may be possible to maximize power, and thus confidence, regarding the association between biodiversity and cumulative effects, and in change detection (Montello & Sutton, 2013; Yanai et al., 2003). The effect size, or the size of the relationship expressed as a proportion of the noise in the data, must be given careful consideration. If a meaningful effect size can be determined, the research design can be adjusted to have adequate power to detect that effect.

6.1.1 Performance Objectives

The proposed image analysis protocol (HAPHA) has been specifically chosen for its potential to address gaps in an HRV-based approach to forest biodiversity assessment (see Chapter 1: for more detail):

- subjective delineation of forest stands and estimates of forest structure;
- lack of long-term data to establish baseline conditions and trends;
- reliant on VRI-derived age estimates as a surrogate for structural complexity within stands.

The ability to address these gaps can be gauged according to two overarching *performance objectives*:

1. *Delineate and classify relatively homogenous forest cover polygons.*

An automated or semi-automated protocol capable of delineating relatively homogenous forest stands (e.g. cover type, seral stage) would be an efficient and cost-effective means of interpreting historical aerial photographs to identify long-term trends and rate and direction of change. Adequate stand delineation and classification will need to be consistent (i.e. *content* within and between photo landscapes and photo years) and accurate. A quantitative accuracy assessment of the results will be imperative.

2. *Estimate structural characteristics of forest polygons.*

Second, automated analysis of aerial photography has the advantage of generating object-based metrics (OBM) that relay information about each polygon, its relationship to its neighbouring polygons and the hierarchical context. If these metrics can be used to estimate continuous stand-level structural attributes (e.g. snags, coarse woody debris) of forest stands, this would add more confidence in the assessment of forest biodiversity than the HRV-based approach of using age as a surrogate. Particularly, OBM may be able to tell us more about the difference in residual stand structure as a result of different partial disturbances that are not accurately reflected in VRI forest inventory information (Lewis, 2016). To use OBM as a predictor of structural attributes, a robust and reliable relationship must first be established.

6.1.2 Variables

This discussion of variables is not exhaustive and should only be used as a starting point. They are identified based on theory, common sense and availability of data.

The primary objective is to gain a more accurate understanding of the state of forest biodiversity by measuring forest structure, using objective and repeatable methods to examine historical aerial photography. Therefore, the two primary variables are object-based metrics (OBM) and forest structural attributes. Forest structural attributes will be the primary response variables indicating the state of forest habitat biodiversity. Any measurable attributes that can be obtained from field-collected plot data that capture variability in stand structural composition (e.g. snags, large standing live trees and downed wood) have the potential to be useful. A number of variables (e.g. tree size distribution, snags, coarse woody debris, canopy openness, leaf area index) are important habitat indicators in structural complexity indices, are easily and efficiently measured, and have been successfully used in previous forest modelling of individual attributes and in multivariate redundancy analysis (RDA) structural complexity modelling (Torontow & King, 2011).

The primary explanatory variables will be the object-based metrics (OBM) and associated heterogeneity elements generated using HAPHA (Table 7-9). In theory, OBM capture important quantitative data on relationships and patterns that are related to forest structural attributes. Establishing the relationship between OBM and forest structural attributes balances the empirical approach with a “parallel theoretical effort to relate spectral properties to biophysical properties” (Hansen et al., 2001b). A single forest structure index, such as heterogeneity, might be most effective as forest structure parameters are often plagued with multicollinearity and influence remotely sensed attributes (Kasischke et al., 2004).

Understanding changes to forest structure in the context of cumulative effects assessment is a fundamental component of this research. One of the main gaps in the current assessment protocol is that seral stage is used as a surrogate for forest structure and the impact of different partial disturbances on forest structure is not accurately captured (Lewis, 2016). Incorporating data on disturbance history is therefore essential. Disturbance history can be split into three treatment levels: disturbance type, severity and time since disturbance. The combination of these levels will simplify the multitude of possible disturbance scenarios (e.g. fire, insect, wind-throw, variable-retention strategies, clear-cut, and shelterwood) and allow comparisons across sites and studies (Thom & Seidl, 2015). An additional factor to consider in the case of disturbance history is the operator (Senyk & Craigdale, 1997). However, it may prove difficult to obtain adequate operator data for historical managed disturbances.

Additional confounding variables (variables expected to have an effect on the response variable) should be empirically controlled by identifying and measuring the values of these factors and incorporating them into the regression analysis (Montello & Sutton, 2013). There are boundless potential confounding variables (e.g. microclimate, soil properties, snow pack, edge effects, natural regeneration, site preparation (silviculture), livestock grazing) (Graham, 2003; LeMay & Robinson, 2004). Therefore, factors that are relatively easy to measure and have a coarse ability to capture change in structural attributes should be prioritized (Spence & Volney, 2008). Two factors that stand out are BEC classifications and seral stage.

The biogeoclimatic ecosystem classification (BEC) system is an established system within BC that groups ecosystems by vegetation, soil and topography (BC Ministry of Environment, 1995; FLNRO, 2018). **Biogeoclimatic zones** encapsulate the natural variability expected to affect forest structural biodiversity, and is in fact the basis for base-line estimates within the CEF's biodiversity procedure (Lewis, 2016). Using the BEC system as a means to control for variability is advantageous; relevant data (i.e. maps and GIS products[Forest Services BC, 2018]) and supporting information (e.g. field guides [Forest Services BC, 2018a]) are readily available, making the testing of HAPHA more cost effective and efficient (FLNRO, 2018). Though valuable, the BEC system must be used with caution. The BEC system was developed in the 1970s and despite ongoing refinement and adaptation, it has never been adequately modified to account for a changing climate, does not embrace complexity science and is based on outdated notions of a linear, climax ecosystem in equilibrium (Haeussler, 2011). Furthermore, there is a dwindling supply of experts who are able to comprehend the complex approach to ecosystem classification used by BEC founders (Haeussler, 2011). Nonetheless, the BEC system will likely be sufficient to identify potential study sites.

Seral stage of forest stands is an important factor related to the natural variability in residual structure such as, coarse woody debris, snag abundance and large standing live trees

(Hansen et al., 2001b; Venier et al., 2014). Controlling for seral stage will allow for a statistical comparison of OBM between forest stands of varying age and also between polygons of similar age and different disturbance history. This will help differentiate between the residual forest structures of stands that have been subjected to different cumulative effects.

Variable	Justification
Forest structural attributes	Structural attributes refer to the within stand characteristics that reflect key difference in forest habitat that species rely on. These are the features that we are trying to infer using composite measures such as disturbance history, geographic location as well as age. *Example: Downed wood, snags, coarse woody debris, standing dead wood*
OBM & Heterogeneity elements	Automatically derived OBM have the potential to assess forest habitat biodiversity more objectively than using age as a surrogate. *Example: Sub-object variability, average spectral reflectance, shape complexity*
Disturbance Type	Expected to vary in residual structure (e.g. standing and downed dead wood) following disturbance (Turner et al., 2003; Venier et al., 2014). *Example: two treatment levels - natural disturbance and anthropogenic disturbance.*
Disturbance Severity	This is a common factor used in experimental designs to categorize varying partial harvest strategies (Huggard, 2002, 2005; Jull, Stevenson, Eastham, & Sanborn, 2001; Klenner, 2004; Spence & Volney, 2008; Yanai et al., 2003). *Example: Canopy loss - undisturbed or (0%), low or (5-30%), med or (31-60%), high or (61-95%), stand-replacing or (100%)].*
Time Since Disturbance	Time since disturbance will affect the development of structural attributes of a stand and must be accounted for. This may only be useful for partial disturbances; otherwise seral stage will capture age. *Example: continuous age or estimated intervals*
BEC Classification System	Encapsulate natural variability expected to affect forest structural biodiversity, existing dataset and associated research and a hierarchy of ecosystem classification *Example: BEC Subzones or Variants*
Seral Stage	Seral stages can be reasonably expected to minimize the variability in forest structure within experimental units. This will reduce the noise in the data and enable more confidence in a comparison between residual structure (measured in plots) and object-based metrics, and the difference in these response variables between treatments (disturbances). *Example: early seral, mid-seral, and late (mature and old)*
Photo Year	The difference in tonal measurements between more recent colour photo years may only include a small amount of variation and may be treated as a random effect. However, the difference between historical panchromatic photos and colour photos will be more substantial and the influence on OBM may be better suited to being treated as a fixed effect.

Table 6-1: Variables to consider in analysis

Accounting for the variability between photos will also be essential. Difference in spectral data for each photo will vary in response to a number of factors e.g. time of day, time of year, type of camera, focal length, altitude, weather (atmospheric interference) (Lillesand et al., 2008). Of particular importance is the difference in quality between historical panchromatic (black and white) photos and more recent colour photos. Colour photos have more spectral data and tonal variability than panchromatic photos, and will therefore influence the calculation of OBM (which include tonal and textural input values). A careful analysis of how OBM is influenced by different photos (photo year or film roll) will be necessary for establishing long-term trends in forest biodiversity using HAPHA.

Variable	Justification
Forest structural attributes	Structural attributes refer to the within stand characteristics that reflect key difference in forest habitat that species rely on. These are the features that we are trying to infer using composite measures such as disturbance history, geographic location as well as age. *Example: Downed wood, snags, coarse woody debris, standing dead wood*
OBM & Heterogeneity elements	Automatically derived OBM have the potential to assess forest habitat biodiversity more objectively than using age as a surrogate. *Example: Sub-object variability, average spectral reflectance, shape complexity*
Disturbance Type	Expected to vary in residual structure (e.g. standing and downed dead wood) following disturbance (Turner et al., 2003; Venier et al., 2014). *Example: two treatment levels - natural disturbance and anthropogenic disturbance.*
Disturbance Severity	This is a common factor used in experimental designs to categorize varying partial harvest strategies (Huggard, 2002, 2005; Jull, Stevenson, Eastham, & Sanborn, 2001; Klenner, 2004; Spence & Volney, 2008; Yanai et al., 2003). *Example: Canopy loss - undisturbed or (0%), low or (5-30%), med or (31-60%), high or (61-95%), stand replacing or (100%)]*.
Time Since Disturbance	Time since disturbance will affect the development of structural attributes of a stand and must be accounted for. This may only be useful for partial disturbances; otherwise, seral stage will capture age. *Example: continuous age or estimated intervals*
BEC Classification System	Encapsulate natural variability expected to affect forest structural biodiversity, existing dataset and associated research and a hierarchy of ecosystem classification *Example: BEC Subzones or Variants*
Seral Stage	Seral stages can be reasonably expected to minimize the variability in forest structure within experimental units. This will reduce the noise in the data and enable more confidence in a comparison between residual structure (measured in plots) and object-based metrics, and the difference in these response variables between treatments (disturbances). *Example: early seral, mid-seral, and late (mature and old)*
Photo Year	The difference in tonal measurements between more recent colour photo years may only include a small amount of variation and may be treated as a random effect. However, the difference between historical panchromatic photos and colour photos will be more substantial and the influence on OBM may be better suited to being treated as a fixed effect.

Table 6-2: Variables to consider in analysis

6.1.3 Analytical Design

The success of HAPHA is assessed by its capacity to meet the performance objectives. Fulfillment of these performance objectives is contingent on the presumed relationship between remote sensing metrics and actual forest attributes. The analytical design section discusses appropriate methods for assessing the existence and strength of these underlying relationships given the nature of the data (Bhatta, 2013).

Both of the performance objectives assume a relationship between forest attributes (e.g. cover type, structural attributes) and remotely sense attributes (e.g. object based metrics). The ideal conditions for testing this relationship with the maximum amount of power would be a fully-replicated, full-factorial experiment, where a comprehensive list of confounding variables are known and controlled for. This would permit examination of the effect of each factor on the response variable, as well as the effects of interactions between factors on the response variable. There would be a large sample size of independent homogenous experimental units randomly selected to represent a range of structural conditions. Forest plots established within these experimental units would have been established pre-treatment and optimized for the explicit purpose of testing HAPHA: identifying cover type for accuracy assessment and all relevant structural attributes for regression analysis. However, the exploratory nature of the pilot studies, and the post-hoc nature of assessing historical photos necessitate the analytical design adhere to a normative method of scientific procedure (Franklin, 2001).

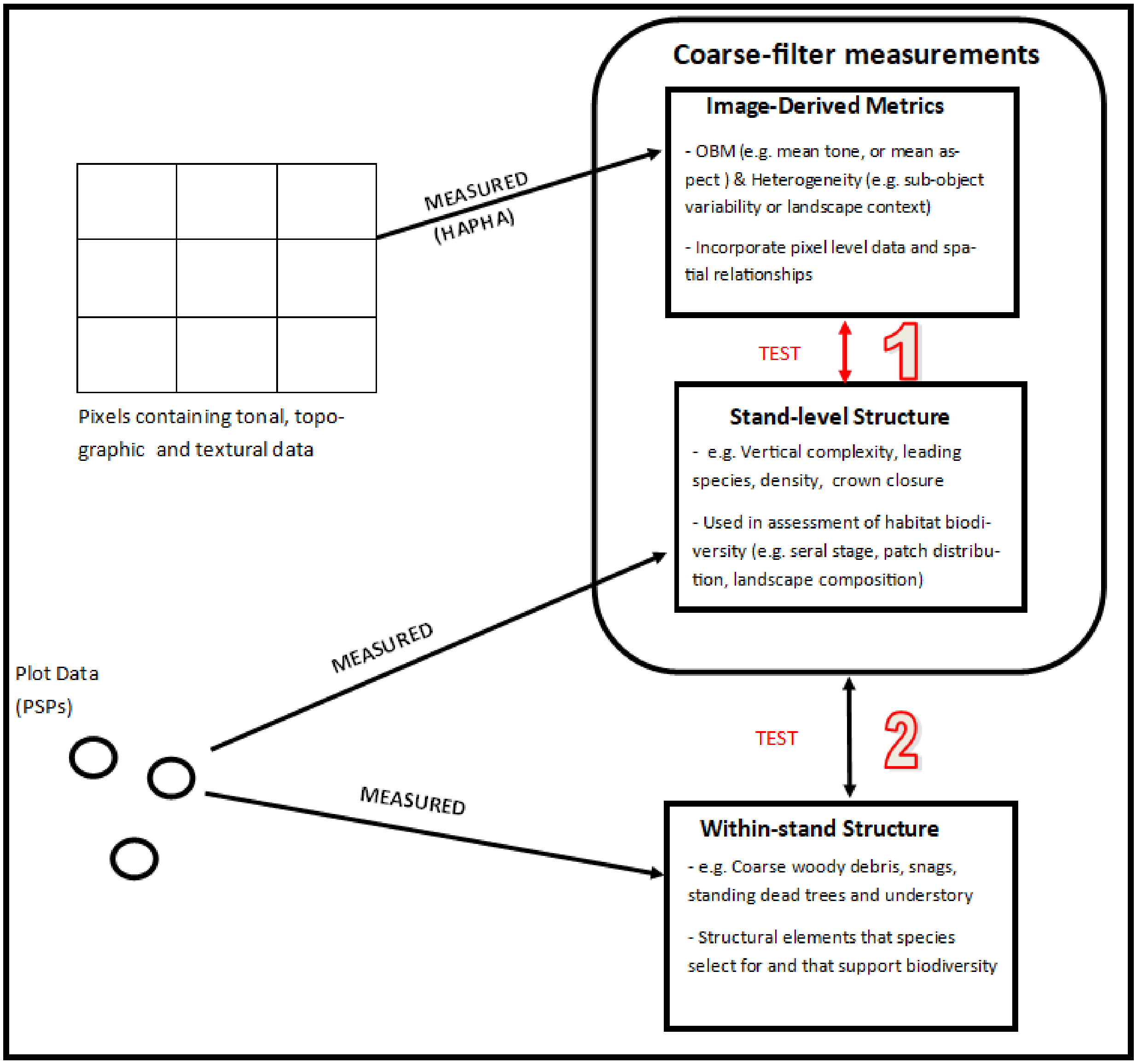

Figure 6-1: Schematic of analytical design
HAPHA is being used to derive metrics from the underlying data in the image. The feasibility of HAPHA depends on the relationship between image-based metrics (OBM / heterogeneity) and forest structure. This relationship will be tested in two ways using plot measurements of forest structure and manual interpretation. (1) The ability to delineate stands and classify them according to stand-level attributes. This will be verified using plot data and manual interpretation in a comparative analysis. Assuming OBM/heterogeneity are acceptable coarse metrics, the pilot study will (2) evaluate if there is a relationship between the image-derived metrics and within-stand structure using plot data. The desired outcome is a reasonably strong relationship that justifies using HAPHA as a better indicator of residual structure and biodiversity.

An observational study, or quasi-experiment, is a normative method that collects and analyzes data from different site conditions without actively pre-defining the conditions (Zhao et al., 2014). This design is highly accessible requiring only remote sensing infrastructure components (for analysis), a remote sensing image and some field data (Franklin, 2001). While cause and effect cannot be determined, the purpose is to explore the ‘normal’ relationship between remote sensing metrics and forest characteristics that can be used cautiously to assess performance objectives and to generate new insights that can guide further research and new applications (Franklin, 2001; Hansen et al., 2001a, 2001b; Montello & Sutton, 2013). The proposed analytical design (Figure 6-1) consists of two tests for assessing the performance objectives: comparative analysis (test 1) and regression analysis (test 2).

6.1.3.1.1 *First Performance Objective: Comparative Analysis*

The first performance objective is the ability to delineate and classify forest polygons in an objective and consistent manner. Forest polygons derived using HAPHA must be subjected to a valid quantitative accuracy assessment before the results can be used in a decision-making context (Congalton & Green, 2009). Polygon delineation must be assessed for consistency with CEF objectives (e.g. in size, shape, and content), while classification will need to be verified for accuracy (according to important/relevant attributes such as forest cover or species). The comparative accuracy assessment method employed by Morgan and Gergel (2013) is recommended as a guideline for these two tasks.

Morgan & Gergel (2013) used manual interpretation as reference data to assess the consistency and accuracy of object-based results. To do this, a qualified manual interpreter delineated forest polygons for each photo. These polygons were then input into Definiens to calculate OBM. The OBM for manually interpreted images were then compared to the OBM for automatically segmented photos. The overall conclusions of similarity between the two methods were based on the number of photos (landscapes) that did not show a statistical difference in the OBM.

For classification accuracy, standard confusion matrices within photos and across all photos were constructed using the manual classification results (see Morgan & Gergel, 2013 for more detail). What is important to note is that their method circumvented the inability to collect ground truth data for historical photos while acknowledging the necessity of comparative accuracy assessments (Morgan & Gergel, 2013). This method will need to be calibrated further to accommodate the unique situational requirements of HAPHA (e.g. the effect of photos from different years on OBM and incorporation of ground truth data).

6.1.3.1.2 *Second Performance Objective: Regression Analysis*

The second performance objective is that OBM (explanatory variables) be used to model forest structural attributes (response variables). In order to isolate and test the relationship between forest structure and OBM, additional sources of variability (e.g. photo year, seral stage) must be controlled. However, even in a manipulated forest experiment it is difficult to identify and control all sources of variability in a complex ecological system (LeMay & Robinson, 2004). Considerations for testing this relationship reliably are laid out below. The adequacy and details of these considerations will need to be carefully considered by a statistician prior to any further implementation. This is strictly a preliminary discussion.

1. There are a number of potentially relevant forest structural attributes (response variables), just as there are numerous image-derived metrics (OBM) (predictor variables). Multivariate representation of forest structure can be an effective way of assessing complex characteristics of forests, such as biodiversity (Pasher & King, 2010; Vázquez de la Cueva, 2008).
2. Collinearity is a common problem in ecological data and likely exists in both the set of potential response variables and the set of predictor variables (Elith et al., 2012; Fisher et

al., 2018; Graham, 2003; Steel et al., 2013). This must be properly dealt with to ensure accurate model parametrization, adequate statistical power and inclusion of relevant variables (Graham, 2003).

3. The assumption that observations are independent may not be met due to spatial and / or ecological processes in a forest environment (LeMay & Robinson, 2004; Steel et al., 2013). This will be especially relevant for the pilot studies due to the non-manipulative nature of the research design (Lepš & Šmilauer, 2003; Zhao et al., 2013).

The relationship of interest is the 'fixed effect' between forest structure and the measured image-based variables (OBM). However given, the potential non-independence of observations it is important to incorporate variables related to the spatial/ecological context and treat these variables as 'random effects' (Fang & Bailey, 2001; Yang & Huang, 2011). Therefore, a mixed-effects approach would be justified. A mixed-effects regression approach would enable better quantification of these sources of variation, and thus yield more reliable models (Bolker et al., 2009; Lussetti et al., 2019; Meng et al., 2007; Steel et al., 2013; Yang & Huang, 2011). A true mixed-effects regression approach is not currently possible when there are multiple response variables. Therefore, one potential method that deserves consideration is redundancy analysis (RDA) with stratified permutations to account for so-called "random effects". Redundancy analysis is a multivariate statistical technique that permits analysis of multiple response variables and predictor variables simultaneously (Pasher & King, 2010; Torontow & King, 2011; Vázquez de la Cueva, 2008). It is a constrained ordination approach that aims to reduce 'noise' by organizing high dimensionality data along one or more simplified gradient (Torontow, 2010; Vázquez de la Cueva, 2008). Stratified (or restricted) permutations can be used to consider random effects with essentially equivalent results to mixed-effects regression models (Felde et al., 2016; Lepš & Šmilauer, 2003; Oksanen et al., 2015; Šebelíková et al., 2016).

6.1.4 Sampling Design

Sampling indicates the analysis of a subset of a population to make inferences to the whole population (Bhatta, 2013). The sampling design affects the variability in the response variable, which ultimately affects the power to detect effects (Yanai et al., 2003). As a component of the feasibility assessment, the pilot study will consider the appropriate sampling scheme, sampling unit and number of samples as a means of gaining a preliminary estimate of costs.

6.1.4.1.1 *Sampling Unit*

Forest stands of medium operational scale (10 – 20 ha) as the experimental unit (as opposed to plots of trees) ensures greater confidence in inferences about populations of stands at broader spatial scales (Yanai et al., 2003). This range corresponds with the size of VRI derived polygons and the size of experimental units used in similar research (Huggard, 2002; Morgan & Gergel, 2013; Spence & Volney, 2008). The scale should be flexible to accommodate the variability in size and shape caused by different origin (natural disturbance or harvest) and environmental factors (steep terrain/valley, riparian/alpine), but be within a certain range to ensure consistency and comparison between stands.

An important consideration when defining the sampling unit is homogeneity. To control extraneous variability and isolate the relationships of interest, sampling units must be relatively homogenous. Homogeneity can be subjective, especially in complex, inherently heterogeneous systems. Therefore, *relative* homogeneity is important for HAPHA. Relative homogeneity can be qualitatively defined according to specific variables or quantitatively defined in that the variability within objects is less than the variability between objects (Definiens, 2012). This quantitative definition is in fact the basis for object creation within Definiens.

6.1.4.1.2 *Sampling Scheme*

A stratified sampling scheme would help to control for variability of different ecosystems and reduce error variance in order to draw inferences to the broader population of BC forests (Montello & Sutton, 2013). A stratified sampling scheme groups potential samples together into 'strata' according to a relevant variable that is statistically related to the response variable (Montello & Sutton, 2013). The BEC classification system could be used as a primary means of stratification. BEC schemes are internally homogenous in terms of geographic factors that affect forest structure (e.g. elevation, soil, climate, climax species) and differ in important ways between strata. By ensuring equal representation of each unique stratum (in terms of the number of cases from each stratification class), stratified random sampling can reduce sampling error (Montello & Sutton, 2013, p. 172).

6.1.4.1.3 *Sample Size*

Sample size refers to the number of replicates that should be included in the analysis. Replication is when two or more experimental units receive identical conditions. Replication is important to account for random variation and isolate the relationship of interest. The variables described above (Section 6.1.2) are used to define what constitutes a replicate.

Power analysis could be used to determine the appropriate sample size for the pilot study a priori given the nature of the data, analytical design and desired power (Yanai et al., 2003). However, key variables are not known, i.e. the variability in the response variable and the expected effect size. Nevertheless, the *rule of thumb* is that the more samples of each particular case (replicate), the more precise the estimation and the higher the power of the hypothesis testing (LeMay & Robinson, 2004). However, in a trial pilot study, a small sample of cases is often recommended to reduce initial costs (Montello & Sutton, 2013).

Morgan & Gergel (2013) generated 547 polygons from a total of eight photos for classification. Depending on the classifications scheme (e.g. vertical complexity vs. leading species) the number of samples of each class ranged from 1 (for rare classes) to 210 (for the predominant classes). When including overlap accuracy, overall class accuracies met or exceeded provincial overlap accuracy standards. Predominance of rare classes [4] and of certain classification schemes reduced overall accuracies and thus Morgan & Gergel (2013) note that a study with more samples would yield better results. Nevertheless, an exploratory study of this size was still sufficient to demonstrate with confidence the potential application of HAPHA.

An important consideration for determining sample size is the effect size (i.e. correlation between OBM and structural attributes) needed for the protocol to be useful for management objectives. If a large effect size is suspected, then a large sample size is less crucial. A sensitivity analysis may be helpful in determining the number of samples that balances cost & effort with adequate confidence.

6.2 Multi-Criteria Evaluation

The multi-criteria evaluation (MCE) identifies potential study areas with adequate data to assess the performance objectives identified in the research design (s.4.3.1 0 Analysis was done using a mix of spatial and attribute queries and overlay analysis in ArcMap using data from

[4] Over half of all classes examined were rare (</= 10% of objects) and subsequently had lower overall accuracy. The classification of leading species was the major source of reduced accuracy across the broader landscape.

DataBC (DataBC, 2018). The first criterion for potential study areas was to take advantage of existing research sites / field plots that have collected data on past disturbance and forest structure. The second criterion was to differentiate between natural and anthropogenic disturbance types. Potential study areas meeting these criteria were stratified according to BEC subzone variants. An outline of the study area was then created in ArcMap and used to explore photo availability for the site in the provincial and federal databases. Two potential study areas are suggested here: Opax/Isobel site for anthropogenic disturbance and Arrowstone Park for natural disturbance. These sites are within the same BEC variants, have existing field data, have consistent aerial photo coverage and have distinct disturbance histories. Both sites have had a retrospective analysis done that would help identify and control for seral stage in the pilot studies. This section first discusses the GIS data and workflow used to identify these sites. Following that is a brief description of each site, including data and photo availability.

6.2.1 GIS Data

Potential variables are discussed in section 6.1.2 of the research design. From these variables, three main criteria were used to identify potential study areas: historic plots or research sites that have collected ground-based data on forest structure; multi-temporal photo coverage; and varied disturbance type. Datasets for the MCE were identified using the BC Data Catalogue from DataBC (DataBC, 2018). All data was publically available. Access to private datasets may provide better information for selecting study areas. Nonetheless, the publically available datasets are sufficient for a first approximation. A pragmatic description of the datasets is included below.

Variable	Dataset
Forest structural attributes	*Permanent sample plots* *Research Installations*
Object-based metrics & Heterogeneity elements	*Photos*
Disturbance Type	*Research Installations* *Parks/reserves*
Disturbance Severity	
Time Since Disturbance	
Confounding Variables	*BEC Classification System*

Table 6-3: Proposed variables for pilot studies and associated datasets used in the MCE

6.2.1.1.1 *Structural Attributes*

The second performance objective is to test the relationship between OBM (explanatory variables) and forest structural attributes (response variables). Having field data on forest attributes to verify the assessment of historical photos is more robust than using only manual interpretation as a comparison (Morgan & Gergel, 2013; Vohland et al., 2007). As a post-hoc analysis, taking advantage of an existing research site or established plot is the most feasible option for getting data on past conditions. It will dramatically reduce costs associated with testing HAPHA, (such as doing tree core analysis to reconstruct past condition or collecting data on current conditions). An established silvicultural research plot also makes it possible to study more diverse harvesting conditions than what would be encountered at any one site. Using existing data means that it has not been optimized for this specific purpose. It is however the only possible way of getting plot data for historical photos and is congruent with a normative method of analysis (Franklin, 2001; Zhao et al., 2014).

Two datasets were used for this purpose: research installations and permanent sample plots. Permanent sample plots (PSP) were initially established by the BC government in the 1920s and located subjectively over a range of stand and ecosystem types (FLNRO, 2018; Omule, 2015). After the creation of the Forest Productivity Council in 1986, other PSP programs merged to form the current Provincial PSP Program (BC Forestry, 2018). PSPs are arrayed throughout the province based on BEC, species, age, density and site index (BC Forestry, 2018). For accuracy assessment of historical photos, this dataset is probably the best option. A limited number of PSPs were established before 1950, which may restrict the temporal range of analysis (Figure 6-3). Nonetheless, there is still potential to examine this data and the explosion of PSPs after 1960 still provides a longer temporal range than current VRI data (Figure 6-2). The research installations dataset contains numerous research sites, active and decommissioned, on a variety of resource related research. It was used to identify silvicultural research sites that have collected forest structure data. Some of these sites have done retrospective analysis to determine past conditions and some overlap with historical PSPs.

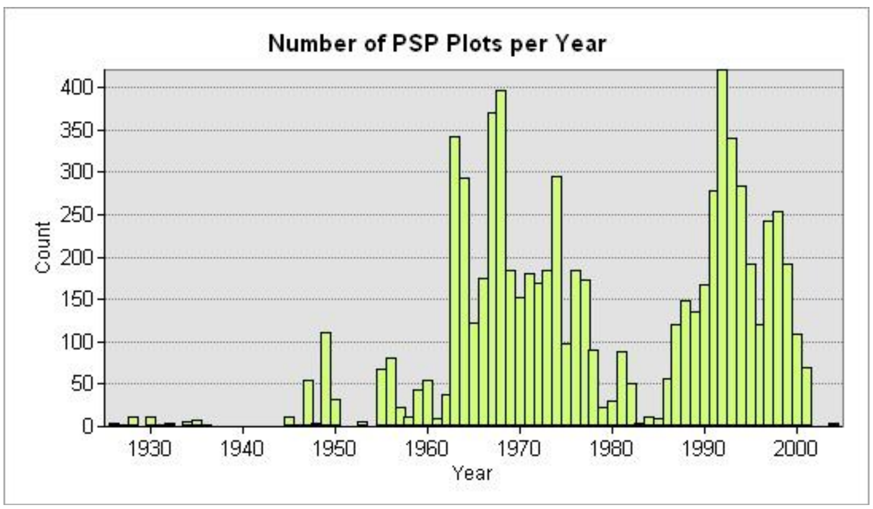

Figure 6-2: Total number of records in the PSP dataset distributed by year.

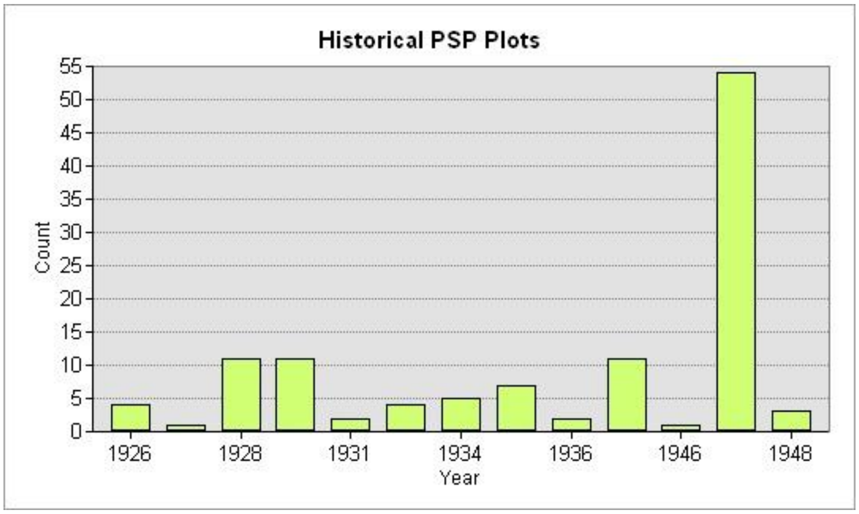

Figure 6-3: Number of PSP plots established before 1950 (according to PSP dataset).

6.2.1.1.2 *Disturbance*

Disturbance type was simplified as anthropogenic and naturally disturbed regions. It is generally acknowledged that anthropogenic disturbances, such as forestry, impact important habitat features (e.g. dense canopy, large snags, and coarse woody debris) differently than a naturally disturbed landscape (Turner et al., 2003; Turner et al., 2013). Within these broad categories disturbance type and residual structure is markedly varied. Attempting to control for all disturbance scenarios would be infeasible. The initial pilot study is meant explore how OBM and heterogeneity differ between these broad types of disturbance and how these metrics change over time in response to disturbance.

Anthropogenic disturbances were identified using the *research installations* dataset. Silvicultural research installations were identified so that there was specific data on the treatments applied, consistency in the operator that applied the treatments, and a more diverse set of conditions in a confined area.

Naturally disturbed areas with minimal anthropogenic disturbance were identified using the BC *parks, ecological reserves and protected areas* dataset and the *old growth management areas* dataset. These designations are intended to preserve forested ecosystems that are representative of a natural/ecologically important state (BC Parks, 2018; Forest Practices Board, 2012). These datasets were a logical coarse filter for identifying forests with minimal anthropogenic disturbance.

6.2.1.1.3 *Confounding Variables*

BEC subzone variants were used to stratify potential study areas due to their assumed coarse ability to capture natural variability. Accounting for the natural variability in forest structure between sites will enable a clearer comparison between disturbance types. BEC subzones are defined according mostly to vegetation climax, which reflects climate, soil and topography. Variants reflect small changes in vegetation that may occur within a subzone due to climatic variation. By using BEC as a means of stratifying potential study areas, variability in the response variables caused by confounding variables will ideally be minimized. However, quantification of confounding variables using data from existing research sites/PSPs would be beneficial.

Figure 6-4 is a bar graph showing the number of parks and research installations within each BEC subzones. These areas have the potential to be study areas for further investigation of HAPHA. Particularly the CWH subzone which has the greatest concentration of parks and research installations.

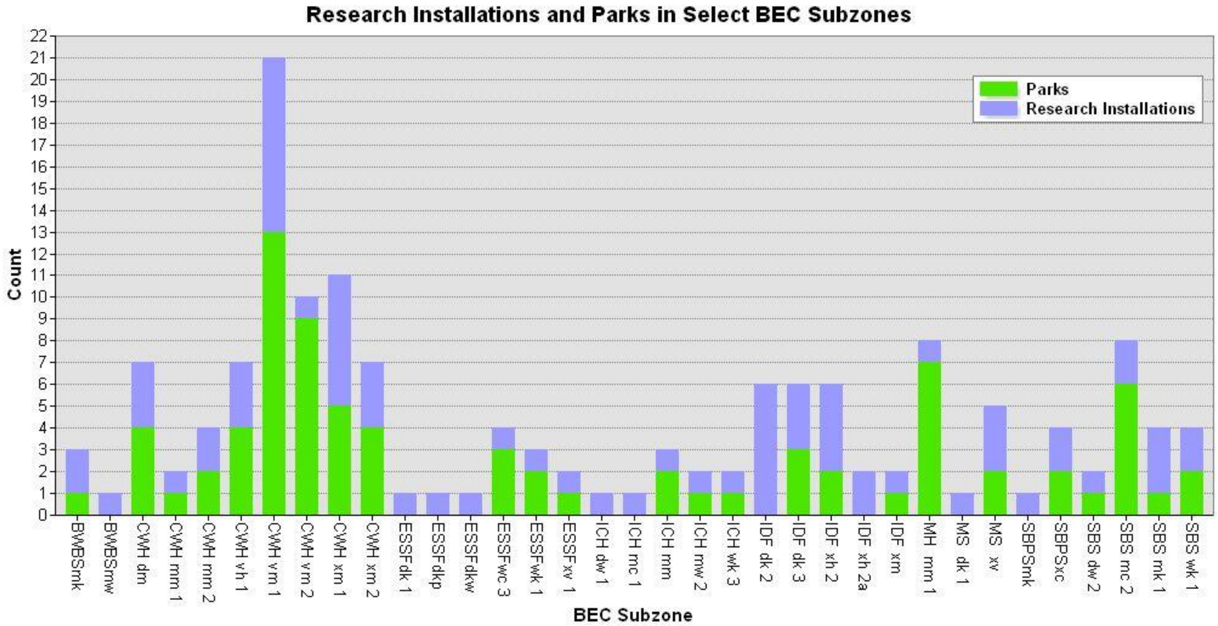

Figure 6-4: Number of research installations and PSPs in each unique BEC Subzone variant.

6.2.1.1.4 *Air Photos*

BC has extensive air photo coverage dating from approximately the 1930s – present. These photos are available in large scale (1:10,000 to 1:25,000), medium scale (1:31,680 to 1:40,000) and small scale (1:50,000 to 1:70,000). Photos are mostly black and white but colour photos are available after 1975. Photos dating between 1936-1962 are mostly medium scale photos. Figure 6-5 explains how scale and photo type are related to spatial resolution and level of vegetation identification (Wulder et al., 2004).

Table 1. Ranges of spatial resolution associated with different instruments or photographic scales and corresponding levels of expected plant recognition.

Type of instrument or photographic scale	Approximate range of spatial resolution (meters)	General level of plant discrimination
Low-resolution satellite images	1000 (AVHRR) 500 (MODIS)	Broad land-cover patterns (regional to global mapping)
Medium-resolution satellite images	30 (Landsat) 20 (SPOT-4 multispectral) 10 (SPOT-4 panchromatic)	Separation of extensive masses of evergreen versus deciduous forests (stand-level characteristics)
High-resolution satellite images (e.g., IKONOS)	> 1 (panchromatic) > 4 (multispectral)	Recognition of large individual trees and broad vegetative types
Airborne multispectral scanners	> 0.3	Initial identification of large individual trees and stand-level characteristics
Airborne video	> 0.04	Identification of individual trees and large shrubs
Digital frame camera	> 0.04	Identification of individual trees and large shrubs
1:25,000 to 1:100,000	0.31 to 1.24[a]	Recognition of large individual trees and broad vegetative types
1:10,000 to 1:25,000	0.12 to 0.31	Direct identification of major cover types and species occurring in pure stands
1:2500 to 1:10,000	0.026 to 0.12	Identification of individual trees and large shrubs
1:500 to 1:2500	0.001 to 0.026	Identification of individual range plants and grassland types

AVHRR, Advanced Very High Resolution Radiometer; MODIS, Moderate Resolution Imaging Spectroradiometer; SPOT-4, Systeme Pour l'Observation de la Terre.

a. Based on a typical aerial film and camera configuration using a 150-millimeter lens.

Source: Wulder (1998).

Figure 6-5: Scale of remote sensing images and the relevance to natural resource management (Wulder et al., 2004).

Flight line information is available online to aid in identifying which photos will be needed to cover the study area. The provincial collection can be checked online as well as using Google Earth based tools. The federal collection can also be checked online.

Collection	Tools	Usage
Provincial	○ Base Map Online Store	Search for photos using an area of interest or the name of a location and the photos for a given area are returned.
	○ Historical Index Map Viewer (Google Earth) ○ Air Photo Viewer (Google Earth)	PDF files of flight lines are provided as .kmz files for Google Earth. They are organized by map sheet and year.
Federal (National Air Photo Library)	○ National Earth Observation Data Framework Catalogue	Search for photos using an area of interest or the name of a location and the photos for a given area are returned

Table 6-4: Image resources and tools.

6.2.2 GIS Workflow

The GIS workflow is presented here to demonstrate how potential study areas could be selected. It must be acknowledged that the selection of data and search criteria are arbitrary. The intent is that this general workflow could be followed, but that with better access to data more robust search criteria could be developed. The final selection of sites could also be streamlined (instead of manually searching potential sites online for existing research). Nonetheless, the two potential study areas identified using this approach have legitimate potential.

1. Identify silvicultural research sites.

- There were a vast number of research installations to begin with (2345). To focus the search for silvicultural research sites, the RI dataset was intersected with the PSP dataset. This will by no means be inclusive of all potential sites but is a crude measure to reduce the number of research sites to search through. The rationale was that an area that has both PSPs and research installations has greater potential to be a host of data than either in isolation. A more robust way of selecting research sites could be substituted here. For now, this method was successful in reducing the number of sites and identifying potential study areas.
    a. Overlay Research Installations (RI) with permanent sample plots (PSPs) → (output: RI_PSP) (47 of 2345)

2. Identify the unique BEC subzone variants that contain the research installation/PSP intersection.

- The BEC system is being used to stratify potential study areas. To narrow down the search for naturally disturbed areas, BEC subzones that contain the identified research installations were extracted (unique BEC). They were then dissolved to create a single record for each BEC subzone.

a. Intersect RI_PSP with BEC → (output: BEC_RI_Intersect)

b. Create a list of unique BEC subzone variants using ArcPy that can be used in an SQL query

```
>>> def unique_values(table,field):
...     with arcpy.da.SearchCursor(table, [field]) as cursor:
...             return sorted({row[0] for row in cursor})
...
>>> list = unique_values(r'I:\MCEData\BEC_RI_Intersect.shp' , 'BGC_LABEL')
>>> print """' OR "BGC_LABEL" = '""".join(list)
"BGC_LABEL" = 'BWBSmk' OR "BGC_LABEL" = 'BWBSmw' OR
"BGC_LABEL" = 'CWH dm' OR "BGC_LABEL" = 'CWHmm 1' OR
"BGC_LABEL" = 'CWH mm 2' OR "BGC_LABEL" = 'CWH vh 1' OR
"BGC_LABEL" = 'CWH vm 1' OR "BGC_LABEL" = 'CWH vm 2' OR
"BGC_LABEL" = 'CWH xm 1' OR "BGC_LABEL" = 'CWH xm 2' OR
"BGC_LABEL" = 'ESSFdk 1' OR "BGC_LABEL" = 'ESSFdkp' OR
"BGC_LABEL" = 'ESSFdkw' OR "BGC_LABEL" = 'ESSFwc 3' OR
"BGC_LABEL" = 'ESSFwk 1' OR "BGC_LABEL" = 'ESSFxv 1' OR
"BGC_LABEL" = 'ICH dw 1' OR "BGC_LABEL" = 'ICH mc 1' OR
"BGC_LABEL" = 'ICH mm' OR "BGC_LABEL" = 'ICH mw 2' OR
"BGC_LABEL" = 'ICH wk 3' OR "BGC_LABEL" = 'IDF dk2' OR
"BGC_LABEL" = 'IDF dk 3' OR "BGC_LABEL" = 'IDF xh 2' OR
"BGC_LABEL" = 'IDF xh 2a' OR "BGC_LABEL" = 'IDF xm' OR
"BGC_LABEL" = 'MH mm 1' OR "BGC_LABEL" = 'MS dk 1' OR
"BGC_LABEL" = 'MS xv' OR "BGC_LABEL" = 'SBISmk' OR
"BGC_LABEL" = 'SBPSxc' OR "BGC_LABEL" = 'BGC_LA dw 2' OR
"BGC_LABEL" = 'SBS mc 2' OR "BGC_LABEL" = 'SER' OR
"BGC_LABEL" = 'SBSwk 1'
```

Figure 6-6: ArcPy code used to extract unique BEC subzones.

c. Select BEC subzones using the ArcPy generated list (Unique BEC Subzones) → (output: Unique_BEC)

d. Dissolve feature → (output: Unique_BEC) (34 unique zones)

3. Select parks/reserves that intersect with unique BEC subzone variants → (output: Parks_unique) (505 of 928)

4. Using only the above selection of parks/reserves, intersect with PSPs → (output: Parks_PSP) (44 of 928)

- Parks that intersected with the unique BEC subzones were selected. To reduce this number to a more manageable search these parks were intersected with permanent sample plots. The rationale being that there is a greater chance of finding historical structural data where PSP plots exist.

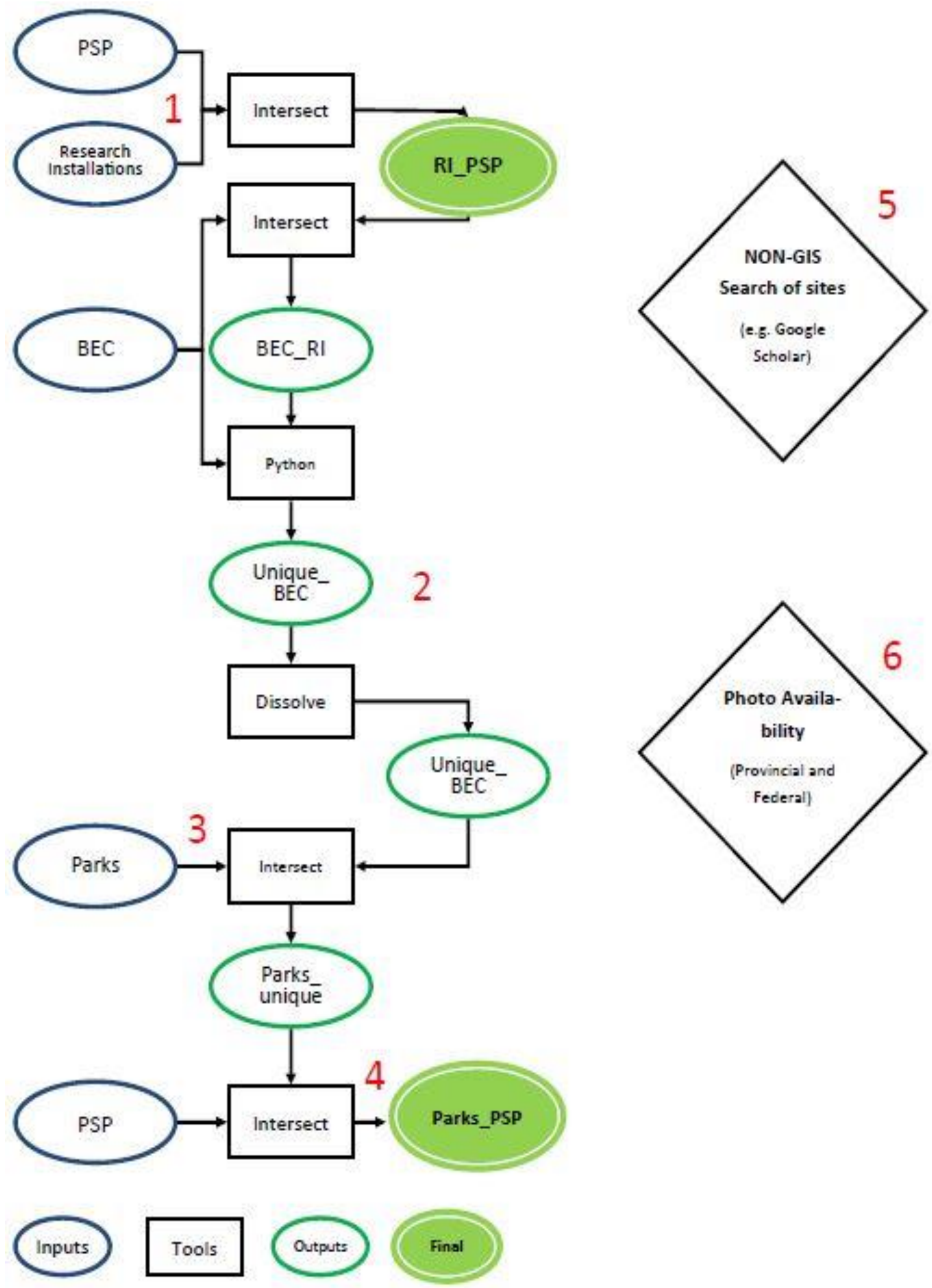

Figure 6-7: GIS workflow followed for the multi-criteria evaluation of potential study sites.

5. Non GIS – look at potential sites online for existing data

- This part of the workflow included searching parks and research installations for existing data and to identify primary activities in these areas. With the right dataset, this stage could be streamlined. With the datasets available, this was a necessary step. This search was primarily conducted using Google, Google Scholar and the UBC Library Catalogue.

6. Examine photo availability

- Photo availability for potential study areas was determined last. Once the Non-GIS search confirmed potential study areas, a shapefile was created of the potential study area. The shapefile was then uploaded onto the provincial and national websites to identify photos for the area. The shapefile was also converted into a .kmz file and loaded into google earth. This was used to search for historical photos using the Historical Index Map Viewer, which is a georeferenced PDF collection of air photo flight-lines.

6.2.3 Potential Study Areas

There were 47 research installations and 44 parks that were identified using the GIS workflow. Knowledge of a research installation with potential value was used to narrow the manual search of parks to the IDF subzone (D. Lewis, personal communication, 2016).

BEC Code	Description	Study Area
IDF	Interior Douglas-fir. This BEC zone dominates the low- to mid-elevation landscape of south-central interior BC. It has a continental climate and the landcover is dominated by open to closed mature forests of Douglas-fir. The zone has historically been subject to frequent ground fires.	Isobel/Opax, Arrowstone
IDF (xh2)	This is the very dry, hot subzone of the IDF zone. Ponderosa pine is more common in these subzones.	Isobel/Opax, Arrowstone
IDF (dk2)	The dry, cool subzone variation of IDF. Trembling aspen is more prevalent in these subzones.	Isobel/Opax

Table 6-5: BEC Subzone Variants in potential study area.

The search revealed that there are two potential study areas within the IDF subzone that have distinct natural and anthropogenic disturbances: Isobel/Opax Silvicultural Research sites and Arrowstone Provincial Park (Figure 6-8).

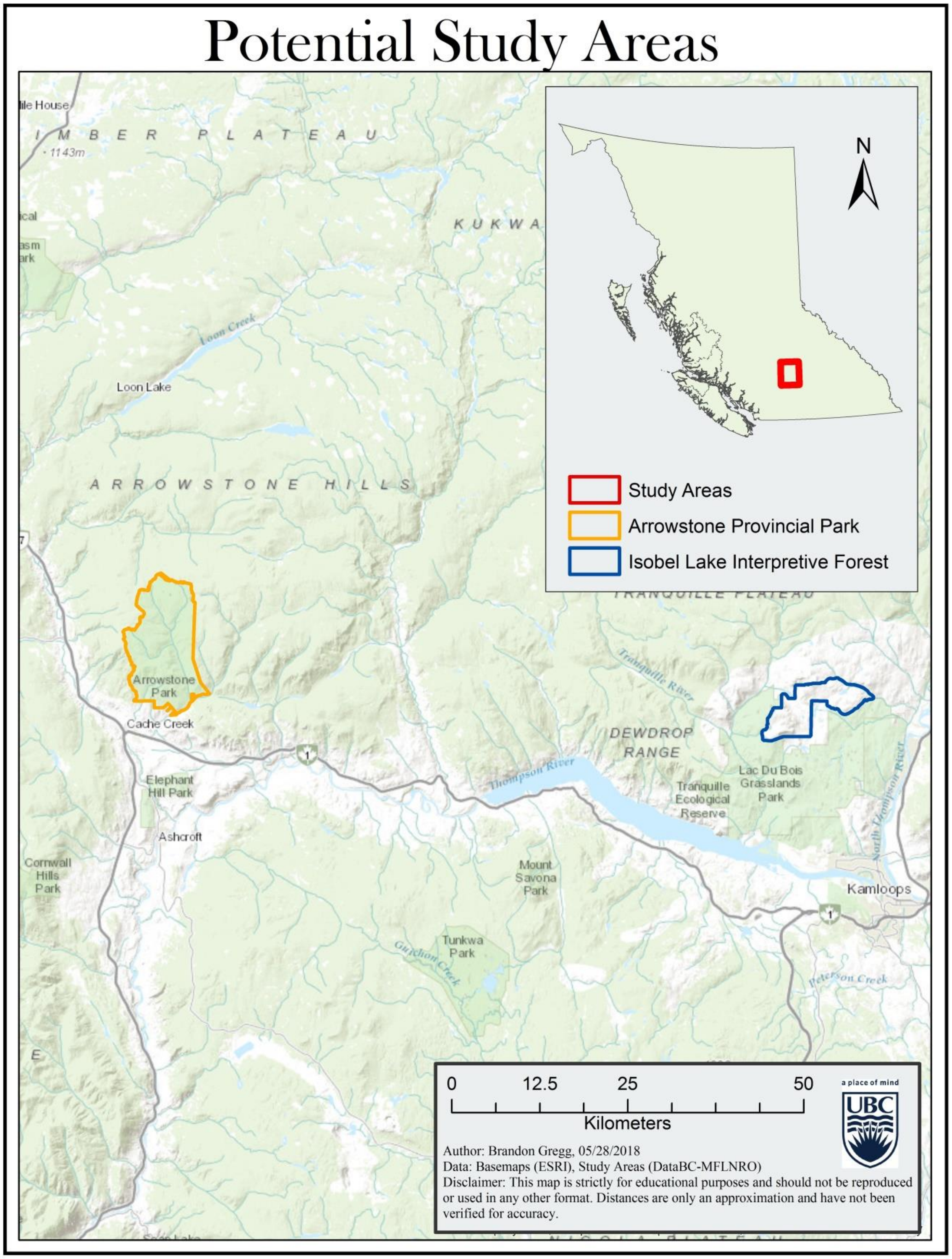

Figure 6-8: Proposed study areas.
(World Topographic Basemap Sources: Esri, DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, and the GIS User Community)

6.2.3.1.1 *Anthropogenic Disturbance*

The Opax Mountain and Isobel Lake silvicultural research projects are located approximately 20km northwest of Kamloops, BC (Figure 6-9). The study area covers two variants of the Interior Douglas-fir (IDF) BEC subzone. The IDF subzone is characterized as dry forests at lower elevations, with a natural disturbance regime of frequent, low intensity stand maintaining fires. These two complimentary research projects examine the impact that different partial-cut silvicultural prescriptions have on Interior Douglas-fir overstory and understory conditions using a replicated experimental design at an operational scale. Researchers at these sites have examined natural disturbances, stand structure, microclimate, soils, tree regeneration, vegetation and wildlife species (Vyse et al., 1997; Klenner, 2004; Klenner et al., 2008; Klenner & Arsenault, 2006; Arsenault, 2012). The complex composition of IDF forests and the concentration of diverse silvicultural prescriptions create the opportunity to test the delineation/classification procedure of HAPHA. The research on disturbance history and data on stand structure presents the opportunity to examine the relationship between different partial disturbances and OBM/heterogeneity. The harvest treatments have been applied fairly recently (1993-1994 and 2004/2005) and therefore stand structure has not fully developed (succession, natural disturbance, harvest). However a retrospective analysis on historical natural disturbances using tree ring analysis was done; historical harvesting activities are known; recent harvests have been implemented in an experimental design, and; there are aerial images for the study site at multiple dates pre- and post-disturbance (Huggard, 2005; Klenner & Arsenault, 2006). The extensive collection of data presents great potential to establish baseline conditions and compare how OBM and heterogeneity metrics respond to different anthropogenic partial disturbances in a cost-effective way.

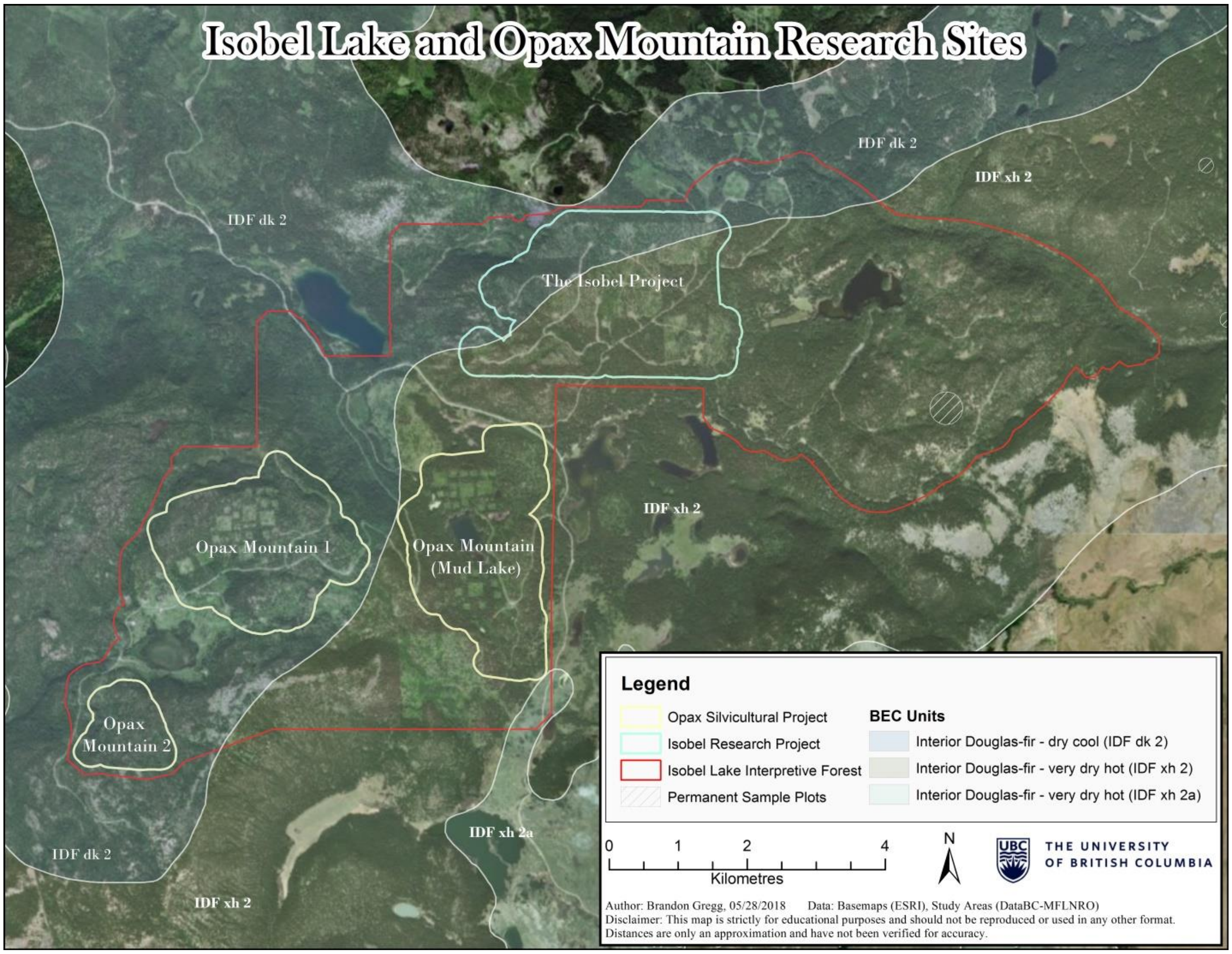

Figure 6-9: Isobel Lake and Opax Mountain proposed study areas.
(ESRI World Imagery Basemap Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

6.2.3.1.2 *Opax Mountain Silvicultural Systems Project*

The Opax Mountain Silvicultural Systems Project is split into two study areas approximately 150 ha each within the IDFxh2 and IDFdk2 variants (see Table 6-5) of the Interior Douglas-fir Biogeoclimatic Subzone (Huggard, 2005). Historical forestry activities include selective logging during settlement between 1900-1920 and more extensive logging in 1956-1957 (Huggard, 2005). Historical conditions beyond these dates were assessed through a retrospective analysis that examined: fire severity, pattern and return interval for the past 300 years; insect outbreaks over past 300 years; windthrow post-harvest and relationship with beetle outbreak and stand structure.

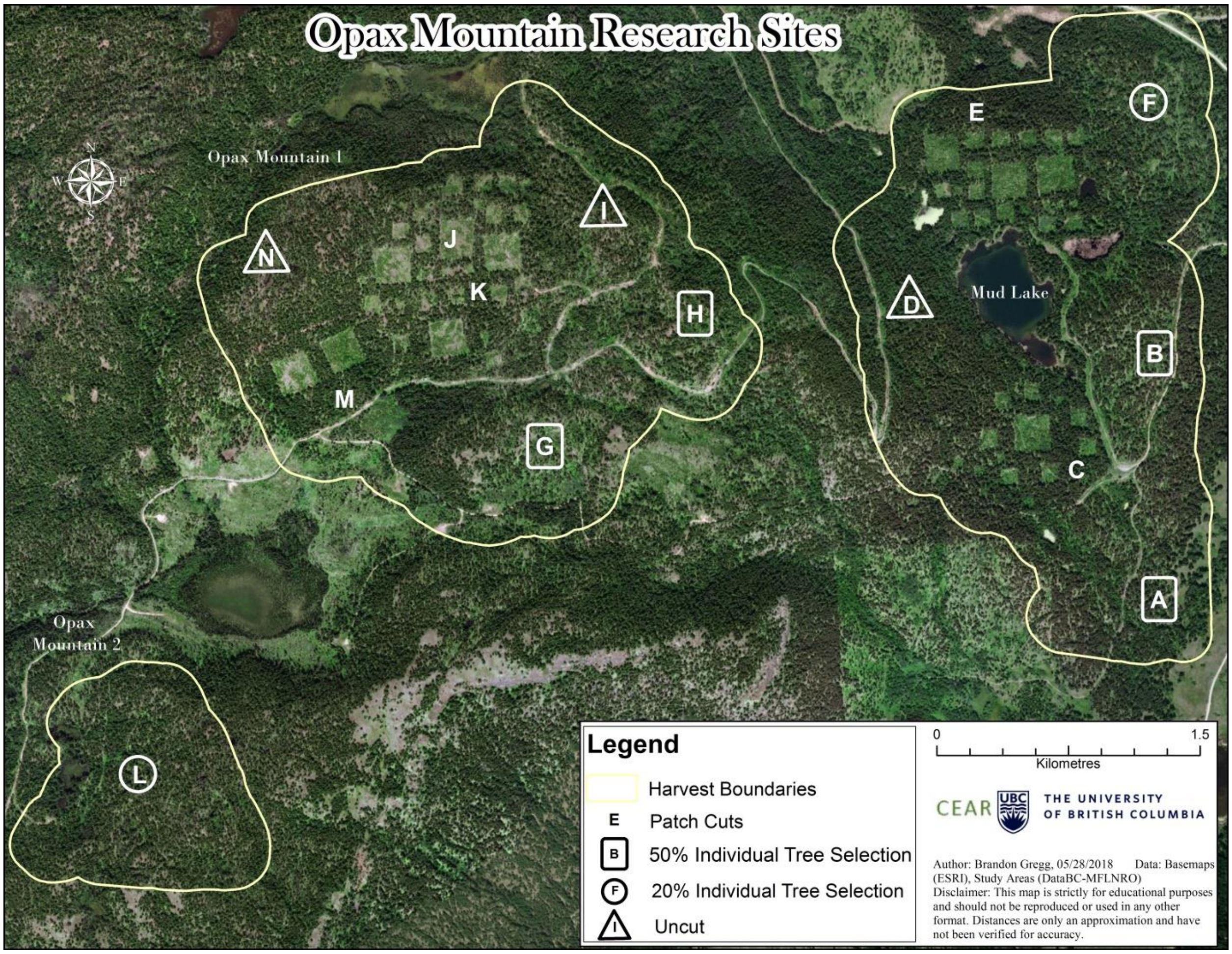

Figure 6-10: Opax Mountain proposed study area.
(ESRI World Imagery Basemap Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

The purpose of the project is to evaluate the consequences of harvest intensity and pattern on dry Douglas-fir forests (Huggard, 2005). Each study area consists of 6 operational-scale harvest treatments of about 25ha each that were harvested in the winter of 1993-1994: Uncut control; 20% merchantable volume removal using uniform partial cutting; 20% area removal using small patch cuts (0.1, 0.4, and 1.4 ha); 50% uniform removal; 50% removal with patch cuts; and, 50% uniform removal over 70% of the block, with the remaining 30% as uncut reserves (Huggard, 2005). Within the primary treatment blocks additional conditions were applied to look at prescribed burning, mechanical site preparation, livestock exclusion, manipulating the abundance of coarse woody debris, tree planting and tree seed additions (Klenner & Arsenault, 2006). Forest conditions pre- and post-treatment were recorded in permanent sample plots.

The diverse research at the Opax site has created data that can be used to measure the response variables of interest, and also control for the myriad of confounding variables. A number of studies have been done, including retrospective analyses to quantify historic natural disturbances, the evaluation of diverse ecosystem responses to experimental harvesting and site preparation treatments, and stand modelling to anticipate the likely long-term consequences of treatments (Vyse et al.,1997). Data includes: growth and yield, stand development, fire regime, insects, windthrow, soil temperatures, soil moisture, snow depth and duration, soil chemistry, decomposition, advanced regeneration, seed fall, planted seedlings, natural regeneration, seedling bank age structure, vascular plants, lichens and bryophytes, soil seedbanks, fungi, habitat elements, birds, mammals, salamanders, invertebrates and stand dynamics simulations (Vyse et al.,1997).

6.2.3.1.3 *Isobel Project*

The Isobel project covers an area of approximately 215ha adjacent to the Opax project. There are 12 treatment units evenly divided between the IDFxh2 and IDFdk2 variants ranging in size from 12.8ha-23.3ha (Klenner, 2004). Harvest treatments were applied in 2002-2003 at three levels of harvesting intensity: 0% (control), 50–60% and 75–80% merchantable volume removal. Each overstory management treatment was replicated four times across the site, with two replicates in each half of the study area (mesic and xeric) (Klenner & Arsenault, 2006). Site preparation, conifer planting, and livestock management treatments were applied in a split-plot design within the primary treatment units (Klenner & Arsenault, 2006).

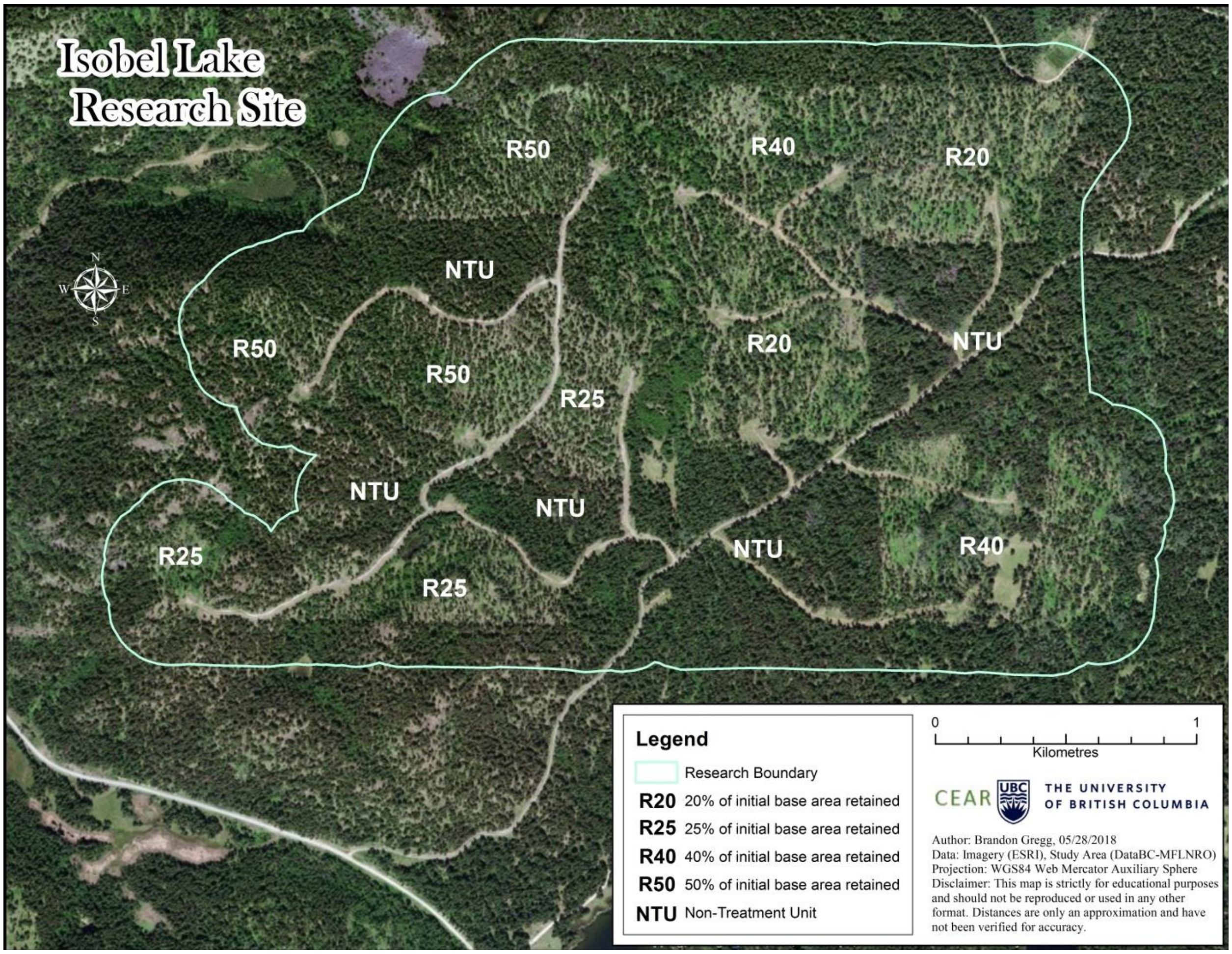

Figure 6-11: Isobel Lake proposed study area.
(ESRI World Imagery Basemap Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

The main objective of the Isobel project was to examine the efficacy of various silvicultural prescriptions to maintain prolonged open canopy conditions in dry Douglas-fir forests in a cost- effective manner, while maintaining a balance of timber, forage and ecological values (Klenner, 2004). An extensive collection of permanent sample plots (PSP's) were established across the study area to establish pre-disturbance conditions and monitor post-treatment (overstory removal and site disturbance) change in a diverse set of indicators related to conifer regeneration, understory grass, forb and shrubs, fuel loading and soil and vegetation nutrients (e.g. fine fuel, coarse woody debris, forest floor, tree growth, nutrients, trees, biomass, mineral soil, organic material, light conditions).

Photo availability for the Opax/Isobel Site was extensive; photos from 24 different years, not including any recent orthophotos (for full list of film rolls see 0B). A selection of photos from different points in time, including the oldest available photos, are presented here to show the potential for a multi-temporal analysis (Table 6-6).

Year	Scale	Type	Source
1951-52	1:70,000	Film- black & white	Federal
1959	1:15000 – 1:40000	Film- black & white	Provincial
1981	1:40,000	Film- black & white	Provincial
1987	1:70000 1:15000	Film- black & white Film - colour	Provincial
1988	1:15000	Film – colour	Provincial
1990	1:15000	Film – colour	Provincial
1996	1:5000	Film - colour	Provincial
2011	1:20,000	Digital – colour	Provincial

Table 6-6: Selection of available photos for the Opax/Isobel Study area

6.2.3.1.4 *Natural Disturbance*

Arrowstone Provincial Park is approximately 90km west of the Opax-Isobel Site and Northeast of Cache Creek in the Thompson River Basin. The park was established as a wilderness area (ecological reserve) in 1996 to protect one of the largest undisturbed valleys in the dry southern interior (BC Parks, 2018a). The 6,153 ha park contains the IDFxh2 and IDFdk2 variants of the Interior Douglas-fir Biogeoclimatic Subzone (that the Opax-Isobel Site contains) and has large stands of old growth Douglas-fir. Within the IDFdk2 variant there are PSPs that were established in 1977. There has also been research in the park on the spatio-temporal pattern of fire history (Arsenault, 2012). Fire history, forest structure and vegetation were assessed in 90 plots distributed in different parts of the watershed (Arsenault, 2012). A fire chronology was constructed from 143 fire scar samples and spanned a period from 1585 to 2006. Additional

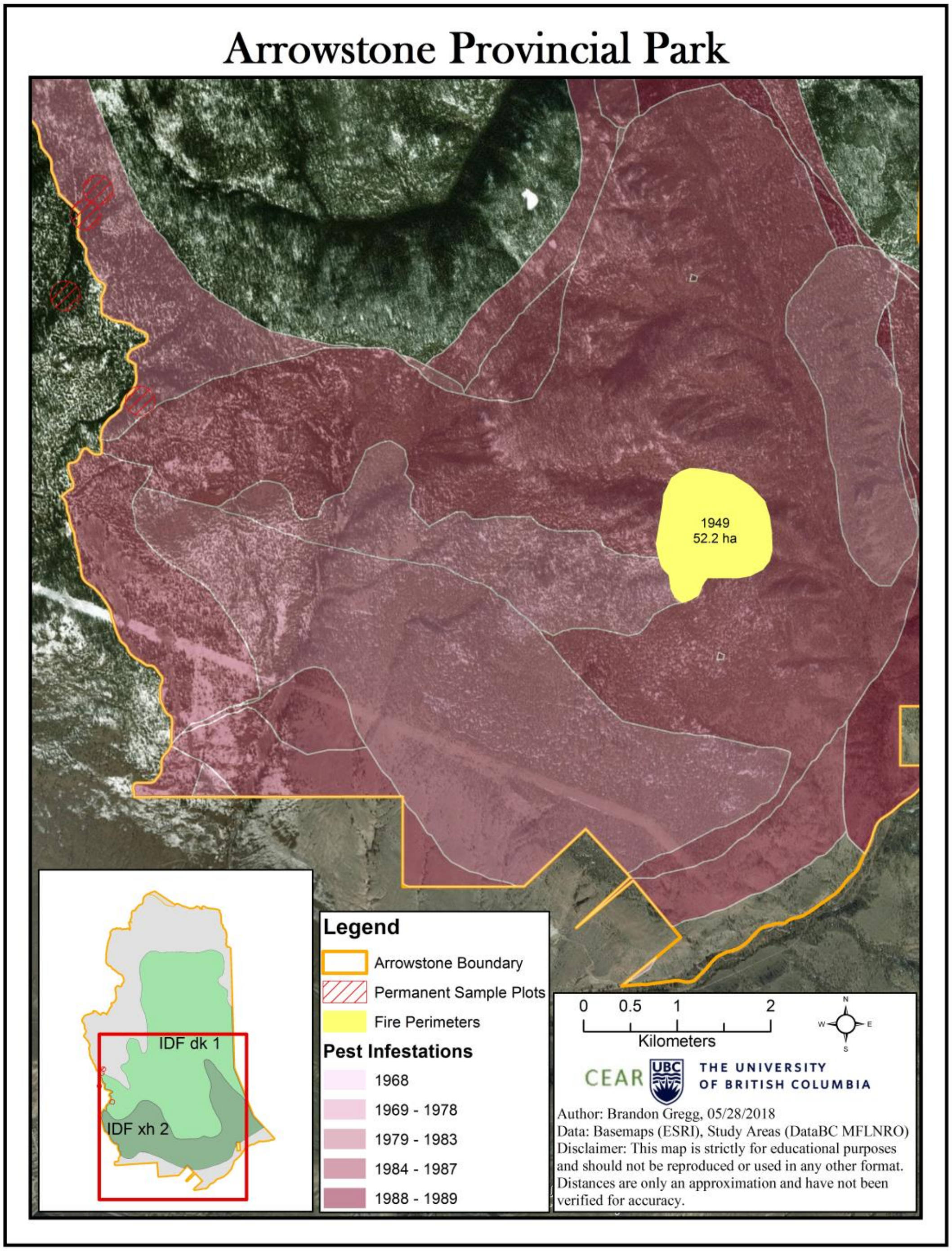

Figure 6-12: Arrowstone Provincial Park proposed study area
(depicting natural disturbance regime and PSP locations)(ESRI World Imagery Basemap Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

cores were collected from this valley and nearby Hat Creek to construct a long chronology from 1312 to 2006. A survey silvicultural report for the Arrowstone Forest from 1932 is also available which may add some value (Hodgins, 1932).

Arrowstone has potential as a study area because: it is within the same BEC variant as Opax-Isobel; there has been very little human disturbance, including very little fire suppression; field data has been collected for the area, and; research has shown that episodic catastrophic fire and insect disturbances have played a major role in shaping the structure and composition of these forests (Arsenault, 2012). There are photos dating back as far as 1948 with fairly regular coverage of the area to present (for full list of film rolls see 0). A selection of photos from different points in time that coincide with Isobel/Opax photos, including the oldest available photos, are presented here to show the potential for a multi-temporal analysis (Table 6-7).

Year	Scale	Type	Source
1948	1:35,000	Film- black & white	Provincial
1950	1:35,000	Film- black & white	Provincial
1951	1:70,000	Film- black & white	Federal
1959	1:30,000	Film- black & white	Provincial
1981	1:40,000	Film- black & white	Provincial
1987	1:70,000	Film- black & white	Provincial
1992	1:10,000 1:15,000 1:30,000	Film- black & white Film - colour Film- black & white	Provincial
1997	1:40,000	Film- black & white	Provincial
2011	1:20,000	Digital - colour	Provincial

Table 6-7: Selection of available photos for Arrowstone.

6.3 Discussion - An Accessible Pilot Study Design

The pilot study design consists of a research design and a GIS-based multi-criteria evaluation (MCE) of potential study sites. The research design outlines the performances objectives for the pilot study and identifies the most relevant data and methodological approaches suitable for data collection and analysis. The performance objectives are the practical questions related to the success of the protocol. The first performance objective requires that HAPHA be capable of delineation and classification of relatively homogenous forest stands according to forest structure, such as vertical complexity and cover type (Congalton & Green, 2009; D. Lewis, personal communication, 2016). The second performance objective is to establish a reliable relationship between heterogeneity metrics/OBM and residual forest structure that is more objective than using seral stage as a surrogate (LeMay & Robinson, 2004; Graham, 2003). The likelihood of achieving these performance objectives is assessed in section 7.2. The purpose of this section is to determine the necessary requirements for testing the performance objectives and determining if there are study areas with sufficient data to do so. A normative method of analysis (i.e. variables and conditions are not manipulated) was selected as the best means of assessing the performance objectives for two primary reasons: assessing historical photography means that experimental conditions cannot be predefined, and; this design method is less resource intensive and suitable for an exploratory analysis (Franklin, 2001; Hansen et al., 2001a, 2001b; Montello & Sutton, 2013; Zhao et al., 2014). The proposed analytical design consists of a comparative accuracy assessment of segmentation results using manual interpretation as a reference; and a multi-variate mixed-effects regression approach to model the relationship between OBM/heterogeneity and forest structure. The proposed sampling design is a stratified sampling scheme based on the BEC classification system. The primary sampling units will be forest stands of medium operational scale (10-20 ha) within a landscape (photo) of approximately $12km^2$. This could result in upwards of 500 sampling units (i.e. delineated forest stands) (Morgan & Gergel, 2013). Following Morgan & Gergel's (2013) example, manual interpretation can be used as reference data in this exploratory stage. Manual interpretation and a comparative assessment would only be necessary for the pilot studies as a quality check.

Incorporating existing plot data/research data will add an additional level of certainty to the accuracy assessment (LeMay & Robinson, 2004). Plot data will be necessary to explore the relationship between OBM/heterogeneity and residual forest structure that can only be estimated with manual interpretation methods (LeMay & Robinson, 2004). A mixed-effects regression method is well-suited to the complexity of a forest ecosystem, where the consideration of both fixed and random effects can help to reduce noise and thereby facilitate detecting any true effects. (Mellin et al., 2012; Meng et al., 2007). Given the multi-variate nature of this assessment, a redundancy analysis (RDA) with stratified permutations is recommended. The details of this assessment will require further attention by a statistician.

The intent of the research design is to be accessible and cost-effective by taking advantage of existing data resources. A definitive cause and effect relationship would not be established, but the purpose is to explore the relationship that exists between variables and the confidence that can be gained in the procedure using existing data (Bhatta, 2013). The MCE establishes that there are datasets that could potentially be used to support the proposed research design. The *permanent sample plot* dataset and the *research installations* dataset were used to indicate areas that may contain historical plot data. These data are critical for examining the relationship between OBM/heterogeneity and forest structure in historic photos (LeMay & Robinson, 2004). The primary treatment considered was disturbance history, which is broadly divided into anthropogenic and natural disturbance to permit more general inferences about the effects of disturbance type on forest structure (Thom & Seidl, 2015; Bhatta, 2013). The *research installation* dataset was used to identify silvicultural research sites to represent anthropogenic disturbances. *Parks/ecological reserve* and *old growth management area*[5] datasets were used to identify naturally disturbed regions. Potential study areas were then stratified according to the *BEC* system. Based on these key variables, two study areas were identified using the GIS-based multi-criteria evaluation: Opax/Isobel Silvicultural Research sites and Arrowstone Provincial Park. They each have a distinct disturbance history of either anthropogenic or natural origin, historical field-data and consistent aerial photo coverage. The suitability of the data to statistical analysis has not been verified and the research design will need to be carefully calibrated prior to the pilot studies to ensure the maximum amount of confidence in the results. The MCE is meant as a demonstration / guideline of the rationale for identifying study areas and the process described in this thesis could be amended to incorporate more appropriate datasets. For example, the BEC classification system is identified as an important variable to control for the natural variability in forest structure. Despite uncertainties pointed out by Haeussler (2011) BEC was accepted as a suitable means of identifying study areas. However, updated notions of ecosystem classification could be used in place of this variable (e.g. DeLong (2011) presents alternatives to the Natural Disturbance Type regions first presented in the Biodiversity Guidebook). Nonetheless, the identification of potential study sites demonstrates the practical feasibility of the pilot studies. The discussion of critical analytical components in the research design should be used to focus future testing of HAPHA and has also helped to estimate costs.

6.3.1 Limitations, Assumptions, Uncertainty

A major assumption underlying HAPHA, and forest biodiversity assessment in general, is that coarse structural attributes (mostly age) serve as reliable indicators of forest biodiversity (D.

[5] The *old growth management area* dataset was not incorporate in the GIS workflow but was used as supplementary information when viewing potential sites.

Lewis, personal communication, 2016). Using remote sensing data and GIS tools to assess forest biodiversity restricts the focus of analysis to certain forest components (e.g. old and mature forest) that are associated with forest species (Dorren et al., 2003; Franklin, 2001; Khorram et al., 2012). However, these components themselves aren't necessarily as important to forest species as the biological legacies within. Managing for coarse components and measuring residual structure indirectly is really the only feasible way of providing estimates on a large scale; the cost of measuring forest structure directly would be astronomical (Zhao et al., 2014). Using surrogate measures will always entail some degree of uncertainty. A desired outcome of HAPHA is to minimize uncertainty by identifying indicators that capture the various levels of residual structure better than age. For managing cumulative effects, being able to quantify the differences in residual structure across a variably disturbed landscape and understand what that means for forest biodiversity is increasingly important (D. Lewis, personal communication, 2016). The exact implications of doing this must be carefully examined.

The research design and selection of variables for the multi-criteria analysis were intentionally preliminary and meant to focus further development. For example, seral stage was identified as a key parameter to include in the pilot studies as a control variable (Vohland et al., 2007). However, forest age can be difficult to assess directly, even in the field, and the suitability of this factor will need to be assessed further (Franklin, 2001). The use of the BEC system to control for confounding variables and the simplification of disturbance treatments as anthropogenic and natural are also assumptions regarding the relationship between forest structure and these variables. Proceeding from the uncertainties with variable selection in the research design, the multi-criteria evaluation (MCE) also makes assumptions. The MCE was meant to demonstrate how potential areas could be identified. Methods for selecting study areas were based on the research design, but no statistical analysis was done on the data and the accuracy/completeness of datasets was not verified. Primarily, the completeness and quality of plot data indicated in the PSP and research installation datasets will need to be verified. The PSP dataset specifically was noted by this author to be incomplete as it did not include all of the PSP locations that were reported by the Isobel research team (Klenner, 2004). An additional uncertainty is obtaining the data from researchers.

An underlying theme in the research design is statistical power. A component of the feasibility assessment is to be able to gain adequate confidence using existing data or with little additional effort/cost. The effect, or statistical relationship, of interest is between image-derived metrics and forest structure. The strength of this relationship (effect size) affects confidence in the results and usefulness of the procedure. A number of factors impact effect size, including number of samples and variability between sites, could reduce the strength of association. Stratifying sites using BEC, the proposed number of photos and using a mixed-effects regression model are components of the research design meant to control for variability and strategies to improve power. Whether these will be effective is uncertain. Even in a manipulated forest experiment it is difficult to identify and control all sources of variability in a complex ecological system (LeMay & Robinson, 2004). To this end, the identified study areas will need to be examined more carefully. For example a sensitivity analysis could help determine the value of additional samples for improved power. Additionally, if more appropriate datasets are found, there is the option to use a modified MCE to identify more ‘data rich’ study areas. Analysis could also be modified to identify and better control for variability. For example, a blended “mixed model” / CART analysis approach may be capable of determining if variability in the factors of interest are attributable to photo variation (which is a potential source of noise) (J. Pither, personal communication, 2018).

Chapter 7: Results – Cost/Benefit Analysis

The purpose of the cost/benefit analysis is to enable a more informed decision regarding investment in the pilot studies. This component of the GFAF builds off of the gap/opportunity analysis and pilot study design sections by providing a more tangible assessment of HAPHA. Costs of testing the pilot studies are estimated using expert judgement. These costs are derived from the analysis of one pilot study (Opax/Isobel or Arrowstone) but can easily be extrapolated to both sites. Only the costs of the pilot studies are estimated because these results will be necessary to plan any further implementation. Benefits are assessed using a comparative analysis of relatable research and assigned a likelihood using a unique rubric. This is a more objective assessment of potential benefits than the conceptual discussion in the gap/opportunity analysis. While inherently uncertain, this is an important exploratory step to ensure that benefits are adequately assessed from a methodological perspective.

7.1 Costs - Pilot Studies

An informal request for a rough estimate of costs and time associated with testing HAPHA was sent to four engineering/consulting sources and one academic source. These are firms that had worked with the Centre for Environmental Assessment Research at UBC and they knew that the request was for research purposes. The academic source is within UBC. The consulting firms treated the request in the same manner as they would if a client had asked for an estimate. These are personnel authorized to provide information or data in the ordinary course of their employment. The results are reported collectively (ranges) and not individually. Two of the sources were intimately familiar with Morgan & Gergel's work (2010; 2013). Professional experience included working with VRI data and orthophoto interpretation, experience in image analysis and processing including object-based image analysis, VRI manual interpretation, and remote sensing research. The request included a table with a description of each step and sub-task with a column to provide estimates (0C). Tasks were split up into 4 major steps: Data Preparation, Image analysis, Classification and Calculating Heterogeneity Metrics. Each major step was then subdivided into main sub-tasks. The assumptions behind estimates were that:

- Analysis is based off of **12 medium scale aerial photographs** (~12-20km²) (4 photos from 3 different points in time) – This would cover **one study area**
- Photos would be provided – costs of photos do not need to be included in estimates.

Estimates focused on time for each task and were provided either as hours or in days based on 8 hour work days. Time is a more useful metric as cost can be easily calculated from these estimates based on different hourly rates. Time is also more relevant to the research context. The minimum and maximum combined estimates were calculated by summing the lowest and largest individual estimates for each sub-task. At first glance estimates have a considerable range. However for each step there was one estimate that was either much larger or much lower than the average response. To more accurately represent the average response the 'average range' column has removed the outliers that did not correspond with other responses. Essentially, this column is the 'mode'. The average range in days was calculated by dividing hours by 8 and rounding up. Estimated cost was based on a common or standard consultant rate of $100/hr, although in practice this could be higher or lower depending on the firm.

Table 7-1 breaks down the average estimates for each step and the overall estimates for completion of the entire pilot study. The smallest combined estimate for steps 1-4 (the least amount of time attributed to each task) was 89.5 hours, or just over 11 days. The largest combined estimate for steps 1-4 (the most amount of time attributed to each task) was 910 hours;

about 114 days or almost 6 months (based on 8 hour work days and 5 day work weeks). Excluding the extreme estimates, the average range was 130 – 214 hours, or approximately 13-28 days. This would equate to about 3-6 work weeks. At a rate of 100/hr this would cost between $13,000 and $21,400 for a single study area.

These estimates are largely based on a team of experts being able to divide up tasks amongst themselves. Any one individual completing these tasks would likely take considerably longer, if they even possessed all the skills to complete all tasks. It is more feasible that at least some of these tasks would need to be contracted out. In fact, while some sources did provide an estimate for every task, no one task received an estimate from every source. This reflects the specialized nature of this work and the diverse tasks involved. For some tasks, particularly task 4 (calculating heterogeneity elements), estimates are highly dependent on the skills and resources of the person(s) undertaking that task. Therefore, in considering these estimates accounting for the higher end of estimates is recommended. While there was general agreement around the 3-4 week range, the largest estimates (at least for the statistical analysis) come from reliable sources and should not be ignored. In an academic setting one could expect consistently higher estimates, especially if the researcher was looking to publish.

Step	Min. Combined Estimate (hrs)	Max Combined Estimate (hrs)	Average Range (hrs)	Average Range (days)	Estimated Cost ($)
1. Data Preparation	12.5	64	40-46	5-6	$4,000-$4,600
2. Image Analysis	39	114	39-56	5-7	$3,900-$5,600
3. Classification	23	132	36-52	5-7	$3,600-$5,200
4. Calculate heterogeneity metrics	15	600	15-60	2-8	$1,500-$6,000
Total	89.5	910	130-214	17-28	$13,000-$21,400

Table 7-1: Total cost estimates for each step.

The estimates for each sub-step are summarized in Tables Table 7-2 to Table 7-5. These tables show the minimum and maximum estimates given for each sub-step. The average range column has removed outliers to more accurately reflect the average response (most similar to 'mode').

Step			Min. Estimate	Max Estimate	Average Range
1. Data Preparation	*Scan Photos*		0.5	8	4-8
	Image enhancement/correction		1	8	4-8
	Orthorectification		3	16	4-16
	Create Auxiliary Layers	Texture Layers	5	12	8-12
		Terrain Layers	3	16	12-16

Table 7-2: Cost estimates broken down by sub-step for task 1.

The data preparation estimates (Table 7-2) had the most agreement between sources. On average, total time was estimated between 40 and 46 hours. Creating auxiliary layers, especially the terrain layers, was identified as being particularly resource intensive. Orthorectification was similar in time and one source pointed out the potential for this to take considerable longer if there was no points of reference. One source noted that the 'scan photos' sub-task could be further divided into 'project setup' and 'scanning'. This was an 8 hour estimate with 6 hours allotted to project set-up with an actual scan time of approximately 10 minutes per photo (12 photos/120 minutes). Another allotted a cost of $100 to contract out this task.

Step		Min. Estimate	Max Estimate	Average Range
2. Image Analysis	*Segmentation*	12	60	12-20
	Manual Interpretation	15	30	15-16
	Comparison of polygons and objects	12	24	12-24

Table 7-3: Cost estimates broken down by sub-task for step 2.

Step 2 (Table 7-3) had one major outlier for the segmentation sub-task at 60 hours. This likely reflects the time consuming task of setting up the workspace in Definiens and iteratively working out parameter settings. Without this outlier, total estimates varied between 39-56 hours. Average time allotted to each sub-task is relatively equal.

Step		Min. Estimate	Max Estimate	Average Range
3. Classification	*Automated: CART*	7	80	7-32
	Manually	12	40	12-40
	Comparative analysis	4	12	4-12

Table 7-4: Cost estimates broken down by sub-task for step 3.

Three out of five sources estimated between 36-52 hours for all of step 3 (Table 7-4). The large 80 hour estimate for CART classification was calculated based on 19km^2 total area (4 sites x 16 km^2 x 3 time series) and a classification rate of 2km^2 an hour. This is only an average as the source noted that the setup for CART analysis is lengthy, but processing time would not be and making modifications to apply the ruleset to new areas would be efficient.

Step		Min. Estimate	Max Estimate	Average Range
4. Calculate heterogeneity metrics	*Factor Analysis*	4	24	4-24
	Cluster Analysis	4	16	4-16
	Calculate 3 measures to represent overall importance of clustered factors	3	4	3-4
	Exploratory regression analysis	4	16	4-16

Table 7-5: Cost estimates broken down by sub-task for step 4.

Step 4 (Table 7-5) has the most uncertainty and the most discrepancy in estimates. Estimates ranged from as low as 15 total hours to 3-4 months. The estimate of 3-4 months was given as a total time for step 4 (not broken up by sub-task) and was provided with the caveat that the analyst is experienced. Even with this estimate removed, the average range was still between

15 and 60 hours, the largest range of all steps. In addition to this variability this step also had the least amount of estimates, which alludes to the specialized nature of this task.

7.1.1 Other Costs

It is assumed, at least for the pilot studies, that existing field work will be "piggy-backed" to help save costs. To get an idea of what kind of cost savings this would bring one source provided an estimate for field work based on TEM-level (terrestrial ecosystem mapping) data collection standards. The estimate was based on 24 survey sites and included travel to and from the field and data management. This work was budgeted between $26,500 and $32,000 with a stipulation for the accessibility of the field site.

If hard copies of photos are accessible at no cost through the Ministry of Forest, Lands and Natural Resource Operations then this will cut down on costs. If photos need to be purchased Table 7-6 provides an overview of costs. The costs of scanning and orthorectifying photos could also be eliminated if there are already orthophotos for an area, and depending on the temporal scale that is desired.

Type	Source	Cost per photo
Raw TIFF scan or rolls prefixed with BC/BCB/BCC/BCD (	Base Map Online Store (BC)	$18.50
Orthophotos (scales: 5k, 10k, 20k) (Digital)	Base Map Online Store (BC)	$200
Post 1940 Monochrome Contact Print (Hard-copy)	National Air Photo Library	$14.99
Pre 1940 Monochrome Contact Print (Hard-copy)	National Air Photo Library	$37.50
8 bit Monochrome, 300dpi (Digital)	National Air Photo Library	$24.99
8 bit Monochrome, 600dpi - 1200dpi (Digital)	National Air Photo Library	$32.49
24 bit Colour, 600dpi - 1200dpi (Digital)	National Air Photo Library	$37.49

Table 7-6: Costs of photos from provincial and federal sources.

7.2 Potential Benefits

The focus of the benefits analysis at this stage of the feasibility assessment (as a preliminary investigation) was on effectiveness benefits. Effectiveness benefits are realized when new information is generated that fills gaps and leads to more informed decision-making (opposed to efficiency benefits, which improve the performance of existing tasks). In this context the desired benefits are unique and more reliable information products that generate new perspectives on forest structure and help to manage cumulative effects. These information products address the gaps in a HRV-based assessment of forest biodiversity identified in section 5.1.2 . Three overarching potential effectiveness benefits were identified in the Opportunities section of the feasibility assessment (section 5.2 :

- Objective and efficient assessment of historical aerial photography in a reproducible manner to establish historical baseline conditions;
- Quantification of ecologically relevant metrics (OBM and heterogeneity) that may enable more reliable measurements of forest structure; and,
- Ability to establish trends in forest structure over time in relation to cumulative impacts with the aid of contextual information and ancillary data (e.g. silvicultural practices, resource development, management regimes).

As a preliminary, cost-effective means of judging the merit of the proposed approach and justifying the pilot studies, a 'likelihood rating' was assigned to each benefit based on a comparative assessment of relatable research using a unique set of evaluative criteria (Table 4-3) and a likelihood rubric (Table 4-4). The evaluative criteria reflect three fundamental elements of remote sensing applications: context, methods and results. In essence, the evaluative criteria are used to compare the results of applications using similar methodology in a similar context. The evaluative criteria acknowledge that the successful conversion of data (historical photographs) to information for pragmatic purposes (effectiveness benefits), is dependent on the design and execution of the methodology (Meera et al., 2004; Wang et al., 2005). The likelihood rubric is a standardized means of expressing the level of confidence in achieving the desired benefits based on this comparative analysis.

HAPHA is summarized according to the 3 evaluative criteria in Table 7-7. Case studies that were similar to the context (objectives and study area) and methods (analysis procedures, data type and scale) of HAPHA were considered for inclusion in the comparative analysis (Table 7-8). **Methods** were the first search criteria. Case studies that examined historical aerial photography and employed an object-based image analysis approach were identified. A few exceptions were permitted where Landsat Data was used because of the lack of examples of OBIA analysis of historical imagery. Potential case studies were then refined by **context**. A forestry context with an objective to examine topics such as disturbance impacts, habitat suitability and landscape composition was given prerogative, while strictly urban and agricultural applications were disregarded. A broad range of study areas and forest types was permitted to reflect the diversity of the BC landscape. Too restrictive a focus would have impractically reduced the number of comparative cases. An analysis of the **results** of the compared research is woven into the discussion of potential benefits in this section. A more detailed summary of each individual paper can be found in Appendix C.

Evaluative Criteria for Proposed Protocol	
Context	A procedure to improve the assessment of forest structure in a mixed-disturbance and diversely forested land-base.
Methods	o Analysis of historical aerial photography with an object-based image analysis protocol using Definiens' multi-resolution segmentation procedure. This procedure would take advantage of existing datasets and be comparable to more contemporary photos. o Forest classification similar to VRI classification standards using CART modelling. o The unique method of heterogeneity quantification defined by Morgan and Gergel (2010) will also be explored. o Data type: historical, black and white, aerial photographs o Scale: Medium (~1:35,000) o Analysis: Multi-resolution segmentation (Definiens) and CART analysis
Results	Establish a baseline for landscape heterogeneity that would better assess the impact of partial disturbances and the change in forest structure as a result of cumulative effects.

Table 7-7: Brief summary of HAPHA according to the evaluative criteria.

The most important articles providing the strongest support for this approach are Morgan & Gergel (2010; 2013), given that their methods are the basis for HAPHA and the context is directly relevant: historical photos of an unharvested watershed on Vancouver Island in BC. The distinctiveness of their approach and the unique way in which it can be applied in cumulative effects assessment means that there was not any directly comparable research (i.e. no cases of OBIA methods being used to assess cumulative effects using historical imagery). As a result, the comparative analysis focused on the technical achievement of the two 'performance objectives' outlined in section 6.1.1 . The performance objectives are the practical questions dictating the suitability of HAPHA to its intended purpose: delineate and classify relatively homogenous forest cover polygons and estimate structural characteristics of forest polygons. Achieving these performance objectives is the minimal requirement of HAPHA. In addition, the comparative analysis looked at how technical features of HAPHA might support the assessment of cumulative effects.

Research	Context	Method
Improved Landsat-based forest mapping in steep mountainous terrain using object-based classification (Dorren et al., 2003)	*Objectives*: topographic correction to improve accuracy of forest stand type mapping *Study Area*: Steep mountainous Montafon region in Austria.	*Data* Type: LandsatTM5scene and IRS-1C (Indian Remote Sensing Satellite) *Scale*: Landsat TM scene: 30mx30m; IRS-1C (6mx6m); Extent of approximately 35x35km *Analysis*: eCognition, multi-resolution segmentation and decision tree classification
Preliminary evaluation of eCognition object-based software for cut block delineation and feature extraction (Flanders et al., 2003)	*Objective*: Test object-based image analysis using eCognition software to classify forest cut blocks. *Study Area*: Extensively logged area near Revelstoke, BC.	*Data type*: Landsat enhanced thematic mapper plus (ETM+) *Scale*: 30m resolution *Analysis*: eCognition multi-resolution segmentation and fuzzy logic membership classification and stability
Quantifying Historical Changes in Habitat Availability for Endangered Species: Use of Pixel- and Object-Based Remote Sensing (Pringle et al., 2009)	*Objective*: Determine medium to long-term trends in suitable habitat for the broad-headed snake over 3 time periods. *Study area:* Plateau sites north of Sydney in New South Wales, Australia.	*Data*: 8 panchromatic, black and white aerial photographs from 1941 and 1971 and Quickbird images from 2006 *Scale*: 1:14,550 in 1941, 1:23,270 in 1944, 1:79,540 in 1971; Quickbird: 0.6m resolution. *Analysis*: OBIA: Multi-resolution segmentation method in eCognition into 3 hierarchical spatial levels; Classified using 'nearest neighbour' and 'fuzzy' methods.

Research	Context	Method
Quantifying historic landscape heterogeneity from aerial photographs using object-based analysis (Morgan & Gergel, 2010)	*Objective*: Quantify spatial landscape heterogeneity in historical aerial photographs using an object-based approach. *Study area*: Unharvested Kennedy Lake watershed in Clayoquot Sound, BC.	*Data Type*: Panchromatic Historic aerial photographs captured in 1937–1938 Four photographs of each landscape type (riparian and upland), were randomly selected from the photographs. *Scale*: Spatial extent of approximately 12 km2; resolution resampled to 0.5m; 1:19,000. *Analysis*: Multi-resolution segmentation process in Definiens; Factor and cluster analysis on object-based metrics to find elements of heterogeneity.
Open woodland and savanna decline in a mixed-disturbance landscape (1938 to 1998) in the Northwest Wisconsin (USA) Sand Plain (Grossmann & Mladenoff, 2007)	*Objective*: To illustrate how a landscape mosaic changes in association with a mixed natural-anthropogenic disturbance history. *Study area*: The study was done on the sand glacial outwash plain of Northwest Wisconsin and Sand Plain (NWSP). Mixed-disturbance area.	*Data type*: Historic airphotos (1938, 1960, 1980, 1998) *Scale*: Nine 4x4km landscape study blocks; 0.5m resolution; MMU of 30mx30m; 1938 (1:36,000), 1960 (1:20,000), 1980 (1:40,000), 1998 (1:15,840). *Analysis*: Three disturbance scenarios were assessed: prescribed fires, wildfires, and industrial forestry. Two-level segmentation and nearest neighbour algorithm classification in Definiens. This data was aggregated to make 'transition maps' of rate of transition between landcover types.
The Automatic Classification Of B&W Aerial Photos (Halounová, 2004)	*Objective*: Find solutions for automatic information extraction from B&W aerial orthophotographs. *Study Area*: Mixed-use area in Czechoslovakia	*Data Type:* Black and white aerial orthophotos. *Scale*: 1:23,000 *Analysis*: Image enhancement phase followed by multi-resolution segmentation, and nearest neighbour classifier in eCognition.
Automated analysis of aerial photographs and potential for historic forest mapping (Morgan & Gergel, 2013)	*Objective:* Processing historical aerial photos and extracting useful information. *Study Area:* Unharvested Kennedy Lake watershed in in Clayoquot Sound, BC	*Data type:* Eight stereo-pairs of panchromatic vertical aerial photographs taken in 1937–1938 *Scale:* 1:19,000 *Analysis:* Multi-resolution segmentation process in eCognition. CART analysis to classify the objects.
Land-use history and topographic gradients as driving factors of subalpine Larix decidua forests (Garbarino et al., 2013)	*Objective:* Investigate the anthropogenic disturbance regime and its impact on landscape composition using historical data to inform management strategies. *Study Area:* Western Central Italian Alps. Historically, the land was used for grazing, charcoal production and pitch extraction, mowing, stone removal, burning and thinning.	*Data type:* Aerial photographs from 1954, 2000 and 1961, 2003; Historical grazing data (1901-2010); Stand structure data from field plots; Topographic variables from 10-m DEM; Anthropogenic variables from thematic maps *Scale:*13,000 ha; 1-m resolution; MMU of 9m2 *Analysis:* Automated segmentation with manual correction using eCognition; Fragstats analysis and transition matrix to assess change; Redundancy analysis; Multivariate statistical analyses.
An object-oriented approach to assessing changes in tree cover in the Colorado Front Range 1938–1999 (Platt & Schoennagel, 2009)	*Objective:* To evaluate the premise that fire suppression policies has resulted in denser forests than were present historically. *Study Area:* Montane zone of the northern Front Range of Colorado.	*Data type:* 39 image pairs between 1938 or 1940 historical images and modern orthophotos (1999); 10m DEM *Scale:* 1:20,000 *Analysis:* 2-level segmentation and classification using eCognition.
Object-oriented classification of repeat aerial photography for	*Objective:* Study pinyon-juniper woodland expansion, using panchromatic aerial photography collected during two time periods,	*Data type:* Panchromatic aerial photographs from 1966 and USGs Digital orthophotos for year 1995. *Scale:* The study site covered an area of 25km2; 1m spatial resolution

Research	Context	Method
quantifying woodland expansion in central Nevada (Pillai et al., 2005)	thirty years apart. *Study Area:* Southern part of Simpson Park Range in the Central Nevada Great Basin.	*Analysis:* Two-level segmentation and fuzzy classification using eCognition.
Employing Measures of Heterogeneity and an Object-Based Approach to Extrapolate Tree Species Distribution Data (Jones et al., 2014)	*Objective:* Assessed the use of an object-based approach to extrapolate tree species *Study Area:* Gulf Islands National Park Reserve (GINPR) and its surrounding lands in the SGI archipelago, in southwest BC. Anthropogenic activities pose an ever-growing threat, making it one of the most ecologically at-risk regions in Canada. Forested lands in the SGI are dominated by Douglas-fir and secondarily by red alder.	*Data type:* Hyperspectral/LiDAR-Derived Tree Species Data, Landsat-5 TM scene, Tree species dominance – (11 possible species), Heterogeneity (tree species richness, Simpson's index of diversity, tree species evenness) *Scale:* Landsat – spatial resolution of $30m^2$, 1050 km $extent^2$, Segment size ranged from 0.54–2.7 ha, averaging 1.23 ha *Analysis:* Three measures of heterogeneity (i.e., richness, evenness and diversity); Segmentation in eCognition; Classification: A regression tree was constructed to predict each measure of heterogeneity (i.e., richness, diversity, and evenness), wherein segment-level geometric properties and/or statistical summaries of Landsat data were the independent predictor variables.

Table 7-8: Summary of the compared research based on context and methods

7.2.1.1.1 *Segmentation/Classification*

The performance objective to 'delineate and classify relatively homogenous forest cover polygons' can be broken down into two distinct activities: first segmentation and then classification. Although separate activities, they are inextricably linked and both rely on the same underlying data. Segmentation determines the scale and content of forest polygons, which directly affects the classification outcome. While acknowledging this interrelation, each activity is examined separately for ease of discussion.

HAPHA uses the **multi-resolution segmentation** procedure in Definiens. Existing research clearly supports the potential for this procedure to delineate relevant forest objects from historical aerial images. The multi-resolution segmentation procedure has been used to delineate objects at scales of individual trees and groups of trees (Pillai et al., 2005), to forest patches of varying sizes: 0.02ha-3ha (Morgan & Gergel, 2010, 2013), 6ha-24ha (Platt & Schoennagel, 2009) using only the tonal information from the photos and textural derivatives, aided by elevation and terrain derivatives as inputs. Researchers used an informed trial and error method to define the parameters for the segmentation procedure to produce segments that corresponded with some existing form of manually derived forest inventory standard (e.g. Common Vegetation Units of the USDA Forest Service [Platt & Schoennagel, 2009] and VRI Standards of British Columbia [Morgan & Gergel, 2013]). Agreeability was commonly determined based on qualitative visual validation and an assessment of average object size. In addition, a quantitative assessment of a variety of object-based metrics showed that segments representing forest stands were indistinguishable from manually delineated polygons at several scales for most metrics (Morgan & Gergel, 2013). Overall, segmentation results were unanimously found to be relevant and accurate.

Classification of resulting segments achieved high relative accuracy when compared to pixel-based methods (Pillai et al., 2005; Pringle et al., 2009; Dorren et al., 2003; Flanders et al., 2003), manual methods (Morgan & Gergel, 2010; Platt & Schoennagel, 2009), and based on field plot data (Garbarino et al., 2013; Pringle et al., 2009). Objects of interest and classification detail differed between studies, ranging from basic classifications such as vegetative cover (shrub and woodland) vs. exposed rock (Pringle et al. 2009) and tree vs. non-tree (Platt & Schoennagel, 2009), to broad categorization of forest type (e.g. dense coniferous, open coniferous, broadleaved, mixed (Dorren et al., 2003)) and to even more detailed forest classification schemes including species (Morgan & Gergel, 2013) and forest age (Halounová, 2004). At the very least, classification results were found to be indistinguishable from other methods (e.g. Halounová, 2004). In one case, a pixel-based approach produced slightly higher accuracies; however local foresters found that the OBIA results were in better agreement with the field situation (Dorren et al., 2003). This area had a large variation in mixture, age and tree distribution as a result of frequent disturbances. The pixel-based method produced large homogenous areas mostly determined by altitude while the OBIA method produced a strong variation in forest stand types (Dorren et al., 2003). The researchers concluded that the slightly higher accuracies of the pixel-based method were likely a result of misrepresentation of rare classes in ground truth polygons and the way that clasification errrors were represented (Dorren et al., 2003).

The method of classification for HAPHA is a CART modelling procedure. Morgan & Gergel (2013) classified segments into 5 classification schemes (leading species, vertical complexity, site productivity, site position, and surface expression) using OBM as predictor variables. Accuracies between classes varied, but when provincial VRI mapping standards for overlap accuracy was considered accuracies fell within or exceeded acceptable thresholds (82-87%). Overlap accuracy is a more appropriate metric given the gradual transition of forest classes rather than exclusive classes with abrupt boundaries (Lillesand et al., 2008). Classification methods, target classes and validation methods of other supporting research varied. Halounová (2004) used a nearest neighbour classifier to define classes of forest according to age and broad type (coniferous and deciduous), along with urban and agricultural features. High accuracy was achieved (averaging 80%) despite misclassification of urban areas bringing down the average. Platt & Schoennagel (2009) used fuzzy membership functions within Definiens to create a fine level of classification (individual trees) within 4 coarse classes: dark forest, edge forest, interior forest and isolated trees. These coarse classes were designed to make the procedure robust to variation in illumination across the image (Platt & Schoennagel, 2009). Using Spearman's rho correlation to assess accuracy of OBIA methods with manual methods, they demonstrated an 88% correlation. Pillai, Weisberg, & Lingua (2005) also used fuzzy membership functions and produced overall accuracies of 89-94% between photo years for classifications of individual trees ($20m^2$). Similarly, Pringle et al. (2009) used nearest neighbour and fuzzy methods to classify objects into 3 landcover schemes and achieved overall accuracies >70%. Garbarino et al. (2013) achieved overall accuracies between 69-93% for 6 categories of landcover classes (dense forest, sparse forest, grazed forest, shrubland, meadow and rock).

The difficulties with extracting information from historical black and white aerial photography emanate primarily from the quality of photographs (e.g. minimal tonal information, missing information to correct for atmospheric distortion) and lack of field data to validate observations (Morgan et al., 2010). These issues can be particularly relevant in a complex and diversely forested landscape (multiple species/multiple disturbances/multiple ecosystems). Despite these difficulties, the ability to accurately delineate and classify forest polygons using the proposed approach is clearly supported by existing research where similar approaches have been successfully implemented. A series of classification methods were used in the compared research and therefore must be considered with caution. Nevertheless, desirable accuracy levels were achieved regardless of the method. From this observation it is reasonable to assume that the information in historical photos and the OBM generated through the segmentation procedure is sufficient to classify segments with acceptable detail and accuracy. In addition, as should be expected, the context and purpose of supporting research varies. However, it is argued here that the diversity of forest contexts and associated classification schemes where similar methods have been employed successfully is promising [Europe (Dorren et al., 2003; Garbarino et al., 2013; Halounová, 2004), Australia (Pringle et al., 2009), United States (Grossmann & Mladenoff, 2007; Pillai et al., 2005; Platt & Schoennagel, 2009) and BC (Flanders et al., 2003; Jones et al., 2014; Morgan & Gergel, 2010, 2013)]. This diversity validates the adaptability of the proposed methods and the possible application of HAPHA on a broader scale.

7.2.1.1.2 *Estimating forest structural attributes – object based metrics and heterogeneity elements*

The second performance objective is to estimate continuous stand-level structural attributes (e.g. snags, coarse woody debris) of forest stands. This objective can inherently overlap with the first performance objective which is concerned with classifying stands according to a relatively uniform attribute such as species (Morgan & Gergel, 2013) and age (Halounová, 2004). The difference is distinguishing between otherwise similar stands (e.g. same seral stage) based on within-stand variability. In other words, the desired benefit is that OBM and heterogeneity elements will relay more about the residual structure of partial disturbances that is not found in VRI data and provide an objective alternative to the HRV-based approach of using age as a surrogate.

Morgan & Gergel (2010; 2013) did not have any field data to establish any concrete relationships with these metrics and forest structure – as would be the case with most historical images. In addition, their quantitative description of heterogeneity is a unique approach and it is therefore impossible to say with certainty the strength of the relationship between these metrics and structural attributes. Further investigation is needed, but there is enough evidence to suggest a relationship does exist and to warrant further research. First of all, OBM capture ecologically relevant attributes and heterogeneity is linked to forest structure and disturbance (Blaschke et al., 2001; Blaschke et al., 2008; Morgan & Gergel, 2010, 2013; Turner et al., 2003; Turner et al., 2013). Furthermore, the inclusion of hierarchical relationships, the preservation of within-object variability, and the quantification of ecologically relevant concepts may provide the information needed to differentiate between residual structures (Burnett & Blaschke, 2003; Morgan & Gergel, 2010; Turner et al., 2013).

Object-based metrics combine input data (e.g. spectral, textural, and topographic), size and shape of objects, and contextual information (e.g. relationship with neighbours and relationship with higher/lower-order objects). These metrics are ecologically relevant and can be used to model forest attributes (Morgan et al., 2010). For example: spectral data are linked to biophysical parameters (Lillesand et al., 2008); topography affects disturbance patterns and species assemblages (Dorner et al., 2002; Garbarino et al., 2013); size and shape of forest stands are linked to species biodiversity (Olff & Ritchie, 2002); and landscape context is important for the movement of species (Krauss et al., 2010). Using OBM to estimate forest structure is similar to the convergence of evidence approach used by a manual interpreter. Combined, OBM capture nuanced differences in the landscape that a single perspective may overlook (e.g. Dorren et al., 2003).

In landscape ecology heterogeneity is a defining characteristic of a landscape and is widely recognized as being related to forest structure and ecosystem services at various scales (Carnus et al., 2003; Gergel & Turner, 2002; Lindenmayer et al., 2006; McGarigal et al., 2009; Rich et al., 2010; Turner, 1987; Turner et al., 2003; Turner et al., 2013). Landscape ecologists view spatial heterogeneity from a patch-mosaic perspective and use metrics such as patch proportions, patch shape, patch compaction and patch size to quantify concepts like connectivity, fragmentation, corridors and edge effects (Jones et al., 2014; Li & Reynolds, 1995; Morgan & Gergel, 2010; Gergel & Turner, 2002). The patch-mosaic paradigm and associated metrics have been applied globally to advance our understanding of landscape pattern-process relationships (Cushman & Huettmann, 2010). For example, fragmentation research commonly looks at metrics such as number of patches, mean patch size, patch shape and edge density (Hansen et al., 2001a; Zipkin et al., 2009). Using these metrics, fragmentation has been linked to impacts on caribou

(Hansen et al., 2001a), leaf litter decomposition (Riutta et al., 2012), species richness of bird communities (Zipkin et al., 2009), species biodiversity (Olff & Ritchie, 2002) and green tree-retention (Kranabetter et al., 2013). While the patch-mosaic paradigm has proven robust in many situations, a main weakness is that it does not accurately represent continuous spatial heterogeneity (Cushman & Huettmann, 2010; McGarigal et al., 2009). When a patch is delineated, the information contained in individual pixels is absorbed into a single categorical classification potentially losing valuable ecological information (McGarigal et al., 2009; Morgan & Gergel, 2010). Morgan & Gergel's unique quantification of heterogeneity using an object-based approach preserves within-object heterogeneity while maintaining the patch-mosaic framework (e.g. **object** size and shape) (2010). The combination of OBM and heterogeneity is what makes HAPHA unique and have potential for estimating residual forest structure.

From 62 largely unrelated OBM, Morgan & Gergel (2010) uniquely quantified 16 elements (clusters) of heterogeneity. Table 7-9 is a list of the heterogeneity elements defined by Morgan and Gergel (2010) and related OBM. New characterizations of spatial heterogeneity defined by this approach include sub-object variability (within-object heterogeneity) which describes the variability of pixels within an object and dissimilarity to super-object (homogeneity over broad spatial areas) which indicates the variability of the object compared to the stand or landscape it is within (Morgan & Gergel, 2010). These metrics capture spatial heterogeneity over multiple spatial scales and are potentially related to local diversity of vegetation, landform (such as coarse woody debris) and rare or specialized habitat types (Morgan & Gergel, 2010). Ecologically important concepts such as topography and context have also been quantified and incorporated as heterogeneity elements. Landscape context (quantified using mean difference to neighbours elevation and topographic wetness index) and slope orientation (quantified using the ratio to super-object aspect) are examples of this (Morgan & Gergel, 2010). Morgan & Gergel (2010) contend that quantification of these concepts using continuous spatial data and OBM may provide ecologists with new predictive measures for various species.

Heterogeneity Element (Cluster)	Definition	Ecological relevance
Sub-object variability	Overall variability/ heterogeneity of sub-objects/pixels	Represents within object heterogeneity, or local variability, and may be related to biodiversity
Tone	Average spectral reflectance	Reflectance is related to biophysical characteristics
Proximity to border	Continuous measure of distance to the super-object border.	Habitat conditions vary at forest stand edges as compared to interior forest
Texture variability	The degree of texture variation within the object: smooth versus coarse	Related to variation in crown size, tree species type, canopy closure, and stand structure
Aspect	Object aspect: north/south/east/west	Relates to local solar energy and water regimes which affects vegetation pattern
Compactness	Object shape complexity	Feature recognition, such as geomorphic landforms
Landscape position	Topographic position of the object within the landscape.	Topographic position influences patterns of moisture, natural disturbance and thus, vegetation
Position within super-object	Categorical measure of whether the object is interior or border.	Habitat conditions vary at forest stand edges as compared to interior forest
Object orientation	Object direction derived from object's location within the landscape	May be related to geomorphic landforms, such as crest and swale patterns, or river channels
Slope orientation	The aspect of the object in relation to the landscape	Relates to solar energy and water regimes over coarse scales
Texture content	The texture of neighboring/surrounding objects.	Useful for differentiating stand age or species composition of contrasting, neighboring tree stands
Landscape context	Relates to whether an object is higher/lower in elevation than its neighbors.	Neighboring topography is related to moisture potential, natural disturbance and thus, vegetation
Dissimilarity to super-object	Measure of how different an object's tone/texture is to the tree stand it's located within.	Identifies anomalous habitat features within a stand, and may be indicative of specialized or rare habitat types
Curvature	Relates to the sum of changes in direction of the main line of the object, or sinuosity.	Indicative of specific geomorphic features, such as water channels or mountain ridges
Size	Object size	Forest patch size can be linked to habitat quality
Site	Local topography of the object (micro-topography).	Reflects microclimatic and local moisture conditions, and therefore, local species

Table 7-9: Ecological relevance of heterogeneity clusters as defined by Morgan & Gergel (2010).

OBM and the quantification of heterogeneity integrate multiple spatial scales. This multi-scale perspective may provide information on the residual structure of partially disturbed forest stands that is lacking in an HRV-based approach. For example the heterogeneity element 'dissimilarity to super-object' identifies anomalous habitat features within a stand based on tone and texture. This metric could not only identify partial disturbances and/or rare habitat types, but could facilitate a comparison of the residual structure between disturbances of different origin. Little is known of how the heterogeneity of a naturally created landscape mosaic differs from that of an anthropogenically disturbed landscape (Turner et al., 2003). Using these heterogeneity elements HAPHA is posed to explore an important component of resilience and ecosystem services in a unique way (Timpane-Padgham et al., 2017; Turner et al., 2013).

7.2.1.1.3 *Cumulative effects assessment*

Heterogeneity is a potentially potent metric for assessing cumulative effects. It is linked to ecological services and resilience (Timpane-Padgham et al., 2017; Turner et al., 2013) and is both a product and catalyst of disturbance (Turner et al., 2003). Quantifying spatial heterogeneity as a surrogate for forest structure and using historical heterogeneity as a benchmark from which to assess cumulative effects may have value to forest biodiversity assessment. However, further research will be required to determine the exact value. Regardless, from a technical standpoint HAPHA has several qualities aptly suited to cumulative effects assessment: multi-temporal analysis compatible with multiple data types; broad-application across spatial scales and ecosystems, and; compatibility with thematic data.

- Multi-temporal analysis

A multi-temporal perspective is necessary to establish trends. Consequently, if HAPHA is to assess cumulative effects, it must be able to assess the change in OBM and heterogeneity over time. Morgan & Gergel (2010) did not calculate and compare heterogeneity elements over different time periods. However, several authors did demonstrate how OBIA can be used in a multi-temporal approach to compare historical aerial photography with different data types such as high resolution orthophotos and satellite images. Pringle et al. (2009) assessed change in habitat suitability using black and white photographs from 1941 and 1971 and Quickbird Images from 2006. Grossmann & Mladenoff (2007) assessed changes in the landscape mosaic using aerial photos from 1938, 1960, 1980, and 1998. Garbarino et al. (2013) assessed change in landscape composition using aerial photographs from 1954 or 1961 and 2000 or 2003. Platt & Schoennagel (2009) examined forest density using images from 1938 or 1940 and 1999. Pillai et al. (2005) examined woodland expansion using aerial photos from 1966 and 1995. The resolution of analysis varied between photos and the original scale of each photo deviated by as much as 1:14,550 and 1:79,450 (Pringle et al., 2009). These examples are not definitive evidence that a comparison of OBM and heterogeneity elements across years and data types will be reliable. They do however demonstrate that it is possible.

- Broad application

From a practical standpoint, for heterogeneity to be used as a benchmark value it should be broadly applicable to BC's complex and variable forest landscape. Initial research by Morgan and Gergel (2010) support this assumption. The procedure to calculate heterogeneity is consistent and repeatable and relies on relatively little input other than the photos themselves: tonal information (photos), textural derivatives, elevation data, and terrain derivatives. Via the multi-resolution segmentation procedure a series of OBM are generated from the input data that were then subsequently distilled into heterogeneity metrics by Morgan & Gergel (2010). Morgan and Gergel (2010) found that their definition of heterogeneity was applicable across multiple spatial scales and two distinct landscape types (riparian and upland). They also note that their elements of heterogeneity are similar to those derived from manual interpretation and landscape ecology. In addition Morgan & Gergel (2013) found that segmentation and manual delineation results are statistically indistinguishable in key ways. These findings indicate the potential for this procedure to establish baseline conditions on a broad scale. Yet, across the landscape there will likely be instances where new/different heterogeneity elements will be relevant to specific questions related to structural complexity, vegetation composition, and disturbance dynamics (Morgan & Gergel, 2010). Further research is required to identify how the definition of heterogeneity changes between landscapes and which heterogeneity elements are most important for cumulative effects assessment.

- Thematic Data

Thematic data are geographic datasets with information pertaining to a certain theme, such as roads or waterbodies. These datasets are GIS compatible, can be in raster or vector format, and can have both qualitative (e.g. road name) and quantitative (e.g. road length) attributes. In contrast, aerial photographs contain continuous quantitative data (i.e. radiometric response) that must be converted into a relevant format, such as a thematic landcover class. Definiens supports "multisource data fusion" which means that raster and vector data as well as images from different sensors can be incorporated in the workflow (Definiens, 2012). Thematic data can be used in the segmentation procedure as a top-down constraint such as using administrative boundaries or ecological classifications to define upper-level hierarchical objects, or as a mask to identify distinct regions such as roads or water bodies[6]. Numeric attributes of

[6] As an example, Morgan & Gergel (2013) used manually interpreted polygons as a top-down constraint in Definiens to generate OBM. They compared these results to the multi-resolution segmentation results with no constraints to examine the similarity between methods.

thematic data that are not used for object creation can be used as an additional metric to characterize the final objects (similar to texture or elevation), calculate OBM and classify objects. Definiens output (objects) is also easily converted into thematic polygon/vector format facilitating further analysis in a GIS environment (Benz et al., 2004; Definiens, 2012). This is important as GIS is a fundamental tool in CEA (Atkison et al., 2008; Franklin, 2001; LeMay et al., 2008; Phan et al., 2004; Wulder & Boudewyn, 2000).

Incorporating thematic data is important for cumulative effects assessment because it allows the visualization and analysis of spatial relationships (Atkinson & Canter, 2011). For example, Garbarino et al. (2013) used historical and recent aerial photographs to investigate the anthropogenic disturbance regime and its impact on landscape composition. Based on an object-based segmentation and classification procedure to produce landcover classes, they calculated patch/mosaic metrics using Fragstats to (e.g. patch size and density, edge, contagion, connectivity, and diversity). These metrics, which are relatable to the OBM and heterogeneity elements of HAPHA, were used to determine the change in landscape composition over time. Garbarino et al. (2013) then used ancillary thematic data to model the degree of anthropogenic influence on landscape change: historical grazing data, stand structure data from field plots, topographic variables and anthropogenic variables from thematic maps (proximity to features). The results indicate that anthropogenic variables were key determinants in shaping forest and landscape structure, with topography acting as a constraint (Garbarino et al., 2013). This study area lacks the complex disturbance regime often found in BC forests and focused mostly on the impact of grazing and of agricultural abandonment. Nonetheless, this paper demonstrates the potential relationship between OBM and cumulative effects and the value of using thematic data. They concluded that historical ecology can serve as a source of quantitative data on human pressure to inform ecosystem models for prediction of future scenarios of landscape change and species compositional shifts.

In addition to modelling physical processes, thematic data could be used to examine and understand the cumulative effects of management decisions. In Definiens spatial boundaries of management objectives could be used to define 'super-objects', or higher-level objects. The multi-resolution segmentation procedure could then be used to delineate forest stands (sub-objects) within these boundaries. Taking advantage of the hierarchical networks in OBIA, the management objects (e.g. a watershed or old growth management area) could then be characterized based on the qualities of the sub-objects. For example, Platt & Schoennagel (2009) examined the impact that fire suppression policies (super-objects) had on forest density (sub-objects).

7.3 Discussion - Is it worth it?

The potential benefits of this approach are being able to establish baseline conditions from historical imagery, quantify unique ecologically relevant metrics (i.e. heterogeneity) and identify trends in forest structure over time. Altogether the benefit is a unique assessment of forest structure that can be used to guide forest management activities including, but not limited to, cumulative effects assessment of forest biodiversity. Realizing these benefits in this way would be unique and therefore the pilot studies are necessary to validate these assumptions. Nonetheless, the benefits were assigned a likelihood based on a comparative analysis of relatable research in order to provide a justification for conducting the pilot studies (Table 7-10). The comparative analysis focused on the execution of similar methods in a similar context. Despite inherent uncertainty the results indicate that the performance objectives (explained in section 6.1) are achievable, suggesting the benefits could be realized.

Benefit	Associated Activity	Likelihood
Objective and efficient assessment of historical aerial photography in a reproducible manner to establish historical baseline conditions. **Performance Objective #1**	○ Segmentation/ Classification	**Likely** This capability has been demonstrated successfully in diverse contexts. The question that remains will be the scale on which this method can be implemented and how transferrable the method is to other locales.
Quantification of ecologically relevant metrics (OBM and heterogeneity) that may be used to assess forest structure and provide unique insights into the state of forest biodiversity. **Performance Objective #2**	○ Generating object-based metrics (OBM). ○ Calculate heterogeneity elements.	**Somewhat Likely** The OBM and heterogeneity elements are similar to landscape ecology metrics in many ways. These metrics have proven value for assessing ecological processes. They are also uniquely quantified which could help overcome the tonal variability of historic photos and provide a more reliable estimate of forest structure. However a relationship between heterogeneity elements/OBM will need to be statistically explored to quantify the confidence in this approach.
Aid cumulative effects assessment.	○ Change Detection (multi-temporal analysis). ○ Incorporate contextual and ancillary thematic data (e.g. silvicultural practices, resource development, management regimes). ○ Broad application	**Likely** The compared research demonstrated the ability of OBIA analysis to compare photos from different years and detect change (a key component of cumulative effects assessment). In addition, Definiens has the capacity to incorporate ancillary information that could be used to assess change overtime and attribute this change to landscape level factors. Finally, initial research indicates that the unique quantification of heterogeneity may be used across different landscapes and ecosystems, but this needs to be examined further. The remaining questions are the availability of useful thematic data for CEA in BC and the reproducibility of heterogeneity elements on a broader scale.

Table 7-10 : Benefits Rubric Results

Costs were estimated using a bottom-up estimation technique, where the components of each task were broken down and time/cost estimates were provided by experts (Jorgenson, 2004). The estimates are based on an analysis of 12 medium-scale photos and can be extrapolated accordingly based on the final requirements of the pilot study (e.g. doubled for both study areas). The estimates range from approximately 89.5 hours to 910 hours for completion of all steps. On average, there was a general consensus of estimates between 139-214 hours (or 13-28 days). At a cost of $100/hour for a consultant this would be between $13,000 and $21,400.

The costs are rough estimates but are derived from the judgement of reliable and experienced professionals in the fields of geomatics, engineering, remote sensing, and forestry. Despite a general consensus, there were outlier estimates and not all sources were able to provide estimates for every step. From these results it is clear that testing HAPHA will require a diverse set of specialized skills and knowledge. It is possible that the estimates are accurate and will get the desired result. It is also possible that the sources did not fully understand the implications of this research and therefore under- (or over) estimated. Thus it is recommended to consider a buffer above the higher estimates to account for unforeseen costs. Some steps can be budgeted for reliably; for instance the data preparation and manual classification sub-step. The rest of the stages are more exploratory; for instance the selection of parameters for the multi-resolution segmentation procedure. Given the variable estimates associated with the heterogeneity analysis in particular, the pilot study may be best suited towards an academic setting. The ideal end result of the pilot study is a model that can be applied to broad geographic areas at significantly reduced costs in analysis and data (e.g. streamlined procedure, using provincially available orthophotos and no need for manual interpretation). However the costs associated with application of HAPHA following the pilot study are dependent on the results and therefore were not estimated at this time.

The value of HAPHA depends on the potential to more reliably and objectively measure forest structure (e.g. horizontal/vertical complexity and pattern), particularly in relation to both human and natural partial disturbances (D. Lewis, personal communication, 2018). Partial disturbances are a key stressor on the landscape, the effects of which are not well captured by age-based inventories (Keane et al., 2009; Stevens et al., 2016) . Heterogeneity is linked to resilience and ecosystem services and is more directly linked to habitat diversity than age

(Gergel & Turner, 2002; McGarigal et al., 2009; Turner et al., 2013). Heterogeneity may therefore be a more useful metric for setting structural benchmarks than using age-based models. Thus the ability to measure heterogeneity, and compare to historic heterogeneity as a benchmark, would be a valuable tool for forest management. HAPHA could be used to guide forest restoration efforts, conservation priorities and silvicultural practices (e.g. Bolenbacher et al., 2014, Didion et al., 2007, Hessburg et al., 2013). HAPHA can also be perceived as an investment in better cumulative effects assessment, particularly to help examine and compare the strategic factors affecting forest biodiversity objectives. By incorporating a longer temporal range there is the potential to indicate the effects that legal designations and other management activities have had on forest biodiversity (BC Ministry of Environment, 1995; Forest Practices Board, 2011; Franklin, 2001; Hegmann et al., 1999). Establishing trends may reveal important information regarding the direction of change in forest structure and not just the current state (e.g. although current conditions may be poor from an HRV perspective, perhaps the condition has been improving) (Duinker & Greig, 2006; Harriman, 2008; Noble 2010). Given the uncertainties at this stage and the resource intensive task of assessing air photos with limited spatial coverage, full provincial implementation is too difficult to assess. Regardless, HAPHA could have value as a tool in areas of special interest. For example, in areas that have been identified as either being at high risk of losing resilience and ecosystem services, or as a naturally preserved ecosystem. What is learned at these finer scales (i.e. changes in heterogeneity in response to management objectives, forest practices, or legal designations), can then be extrapolated to areas where similar factors are at play (Garbarino et al., 2009). The pilot studies and implementation in other areas could identify factors (i.e. levels of heterogeneity, OBM values, and forest practices) that are critically associated with forest biodiversity and these lessons could help identify areas for further research or for more intensive biodiversity conservation or restoration efforts.

7.3.1 Limitations, Assumptions, Uncertainty

There are two stages of the cost/benefit analysis that are associated with assumptions and uncertainty: selection of appropriate costs and benefits, and estimation techniques. Table 4-2 is a list of potential costs and benefits. Selection of relevant costs and benefits from this list is an assumption that is limited by time, resources and expertise. Intentionally, the selection of costs and benefits was meant to focus on only the most relevant and important factors. However it is possible that key costs or benefits were overlooked. Some factors were also outside the scope of this research. Specifically, the potential costs of testing/ implementation relative to the 'costs' of poorly informed policy decisions (e.g. impacts to biodiversity resulting in costly species recovery programs that would not be necessary if decision makers had the appropriate information) (D. Lewis, personal communication, 2016). Acknowledging these costs will help inform cost-effectiveness and determine if HAPHA is worthwhile. However quantification of these costs is a high-order task (McInnis & Blundell, 1998).

Estimation techniques are also meant to be preliminary and therefore are inherently uncertain. The estimation of costs, by design, is meant to be between 'rough' (within 50-100% of actual value) and 'ball-park' (within 2-3 times actual value) estimates (Katimuneetorn, 2008; Smartsheet, 2018). The sometimes large discrepancies between sources discussed in the above section demonstrate the uncertainty surrounding this protocol. Furthermore, given the exploratory nature of this research it is difficult to account for unforeseen challenges. Some sources did explicitly recognize that these uncertainties were included in their estimates. However it cannot be said whether these estimates will be accurate. Likewise, assigning a likelihood to benefits using a comparative analysis will never be 100% accurate (Asselin & Parkins, 2009; Burdge, 2004). With remote sensing applications each scene is unique and creates a unique set of challenges that is further exacerbated by the difficulties with historical imagery (Flanders et al., 2003; Lillesand et al., 2008; Morgan & Gergel, 2013). Finding comparable cases was difficult given the uniqueness of this approach and a focus on satellite images and high resolution aerial photography in OBIA research (see section 7.2 Some assumptions were made to include relatable research and therefore while the comparative analysis found that the benefits would be worthwhile, the limitations of drawing conclusions based on methodological comparisons must be acknowledged.

Chapter 8: Research Outcomes and Conclusions

This research examines the feasibility of incorporating historical aerial photography in cumulative effects assessment of forest biodiversity. Specifically, it looks at the potential to assess residual forest structure better than the HRV-based approach that uses age as a surrogate. There were two main outcomes of this research: the design of the Geomatics Feasibility Assessment Framework (GFAF) and the use of this framework to identify and evaluate the OBIA protocol designed by Morgan & Gergel (2010; 2013) for its potential to assess forest structure in cumulative effects assessment.

8.1 Research Outcome: Geomatics Feasibility Assessment Framework

The Geomatics Feasibility Assessment Framework (GFAF) was designed to address the initial research questions of this thesis: to evaluate the feasibility of incorporating historical aerial photography in cumulative effects assessment of forest biodiversity. It also addresses the need for a consistent approach to feasibility assessments of geomatics technology by combining common tools found in the literature and defining criteria for their use. The GFAF bounds the concept of feasibility by specific factors that are relevant to the outcome of a geomatics solution: conceptual feasibility and practical feasibility (Figure 4-2). Conceptual and practical feasibility are assessed using the 3 GFAF components that work in a linear direction: gap/opportunity analysis, pilot study design and the cost/benefit analysis (Figure 4-1).

The result is a structured review of feasibility that can be used to determine the merit of investing in a particular geomatics solution. The framework is designed to be flexible to both the institutional context and the type of geomatics solution, as well as to the expertise of the individual/team employing the feasibility analysis. Outside of this research, the GFAF can be used by managers and researchers alike as a standardized means of identifying geomatics solutions and weighing the expected costs and benefits prior to further investment, implementation or research (Meaden, 2013; Obermeyer, 1999). The GFAF framework is particularly valuable in an environment of rapidly advancing technology. Organizations looking to integrate new technology into their procedures or upgrade existing technologies could use the GFAF to evaluate their options and make more informed decisions. In a research context this framework could be particularly useful for funding proposals as it is structured to justify investment in a method based on estimated costs and benefits. Organizations and researchers do conduct feasibility assessments but do not follow any specific guidelines. A more structured and consistent method of feasibility analysis would create more transparency, facilitate comparison between different contexts and produce more confidence in the results (Pickvance, 2005; Katimuneetorn, 2008; Tomlinson, 2007; Wang et al., 2005).

The framework was designed with a specific purpose in mind but with the intent that it be applicable to other contexts and geomatics solutions; not just the OBIA protocol assessed in this research. The approach to feasibility assessments should be consistent, but the application of each component should be customizable (Meaden, 2013; Tomlinson, 2007). Therefore the criteria for each GFAF component are designed to be flexible. The GFAF outlines the tools that will be needed to assess feasibility and the knowledge of how and when to use those tools. Which aspects of feasibility are relevant will depend on the context and priorities of the organization (de Angelis et al., 2004; McInnis & Blundell, 1998). For instance, this research focused on a resource management / research context where the emphasis was on a geomatics solution with potential intangible benefits for improved decision-making. The application of this solution is unique and therefore difficult to quantify (Gillespie, 1994; Worral, 1994; Silva, 1998).

Implementing the pilot studies is resource intensive and requires a diverse set of expertise. Therefore the framework was adjusted to assess the feasibility of the pilot studies with a more abstract discussion of potential benefits. A different context might be a transportation authority that is re-evaluating their GIS-platform. From their existing system they know which GIS functionalities they need to fulfill their information needs. Therefore, the primary question of feasibility is related to time and cost efficiencies rather than intangible benefits. The gap opportunity analysis might identify the costs associated with their current platform (gap) and identify known tools from established platforms (e.g. ArcMap, QGIS and MapInfo) (opportunity). The organization would be able to conduct pilot studies of their routine GIS tasks using the platforms on a trial basis, or with open-source software, and compare the results of each. The cost/benefit analysis would be an objective comparison of the costs associated with each platform (including processing time, possible retraining of employees and transfer of data) and the quality of the final GIS output.

The GFAF is also designed to accommodate the expertise of the person/s performing the analysis. For this research, limited practical experience in this specific context and minimal supporting resources meant that the logistics of completing the pilot studies would have resulted in an unrealistic timeframe (S. Gergel, personal communication, 2016). However, a strong theoretical and working knowledge of geomatics in general made it possible to judge the merits of the approach and lay the ground-work for further investigation. This is important because by definition the technology/methods being explored in a feasibility assessment will be new to the organization. The flexibility of this framework will allow someone with general geomatics knowledge to explore new technology and identify the requirements and concerns that need to be examined by someone with a more advanced working knowledge. A strength of this framework is that by clearly delineating the steps and criteria to reach conclusions, it is more straightforward for others to build off of and compare the results. For example, some organizations are transitioning their geographic datasets to online, open source platforms. GIS professionals within these organizations, who may or may not have had much experience with online mapping, would be able to research possible solutions and identify the best possible option using the GFAF. The GFAF provides a standardized method of reviewing potential platforms, comparing examples from other organizations, and laying the groundwork for more focused development. Someone with the appropriate skills (e.g. a software engineer) could then be hired to develop the final product (i.e. pilot studies and subsequent implementation).

8.1.1.1.1 *Limitations, Assumptions, Uncertainty*

The GFAF was designed with a remote sensing protocol in mind, but with the intent that the criteria are broad enough to encompass GIS and other geomatics solutions. In an attempt to be relevant to a broad range of geomatics solutions, application of the GFAF may overlook some of the more nuanced considerations. The point of the GFAF is to enable a more informed decision prior to investing in a technology. This premise presupposes that the person/organization is not intimately familiar with the technology. Rather it is assumed that they will have a basic understanding of the principles of the technology and will be able to formulate an educated opinion of the technology’s feasibility. Inherently, there may be some information misinterpreted or overlooked. Further research and peer review will help to confirm the choice of criteria and refine their use for specific contexts. A team of experts applying the framework would also help to reduce uncertainties.

8.2 Research Outcome: Feasibility Assessment of the Historic Aerial Photograph Heterogeneity Analysis (HAPHA) Protocol

This research applied the GFAF to identify and evaluate the OBIA protocol (HAPHA) designed by Morgan & Gergel (2010; 2013) for its ability to assess forest structure and establish trends and baseline conditions using historical aerial photography. Each component of the GFAF has distinct outcomes (Table 8-1). Combined, the GFAF summarizes a broad range of information that can be used to make an informed decision regarding investment in HAPHA and as a framework for further research. It identifies the merits of HAPHA and also identifies areas of uncertainty that will require further investigation going forward. The structure and transparency of this approach are such that adjustments can be made to accommodate new information/estimates and draw new conclusions.

GFAF Component	Outcome	Importance
Gap/Opportunity Analysis	- Literature Review	Transparent and structured identification of a geomatics solution. Answers research question #1.
Pilot Study Design	- Research design - Customizable GIS-workflow - Visualization of data (maps, tables, graphs) - Identification of study sites - Identification of relevant data sets	Template for future research / estimate of costs. Demonstrates practical feasibility of testing HAPHA. Provides info for answering research question #2.
Cost/Benefit Analysis	- Estimation of costs - Breakdown of hourly estimates for each sub-task - Comparative analysis of research - Assigned likelihoods	Information to weigh feasibility of testing HAPHA. Provides info for answering research question #2.

Table 8-1: Research outcomes of GFAF components and their relevance to the feasibility assessment.

The gap/opportunity analysis assessed the conceptual feasibility of a geomatics solution capable of overcoming the methodological limitations of VRI data and an HRV-based approach to establish baseline conditions and trends in forest structure (Benz et al., 2004; Bock et al., 2005; Halounová, 2004; Blaschke, 2010; Hay et al., 2003; Laliberte et al., 2004; Morgan & Gergel, 2010, 2013). The gap/opportunity analysis answers the first research question: what is an appropriate geomatics solution for incorporating historical aerial photography to establish trend in forest structure? It is structured to reduce uncertainty and provide justification for linking the proposed geomatics solution to this context.

The logistics of conducting pilot studies were not supported by the expertise of this researcher and available resources. Instead, the GFAF assessed the practical feasibility of proceeding with the pilot studies by laying out the requirements for a suitable pilot study (research design) and identifying study areas that have adequate data to execute the pilot study (multi-criteria evaluation) (Katimuneetorn, 2008; Tomlinson, 2007; Meaden & Aguilar-Manjarrez, 2013). This component had multiple outcomes. First, the research design articulated two ‘performance objectives’ that need to be evaluated to determine the suitability of HAPHA to its intended purpose. The framework to test these objectives with the most confidence (i.e. variables and template for collection and analysis of data) was then carefully outlined. It is acknowledged that the research design is not definitive and will need to be revisited. The intent was to identify key elements to guide further research while also making it possible to estimate the costs of a pilot study.

Second, the multi-criteria evaluation: identified suitable datasets; created a customizable GIS-workflow; identified potential study areas; and produced visual products. These outcomes are essential for assessing the second research question: would this protocol be feasible given associated costs, existing capacity, data needs/availability and expected benefits? Identifying relatable datasets and successfully identifying potential study areas demonstrates the practical feasibility of employing the proposed research design to test HAPHA. Maps, tables and graphs outputs add additional value as visualization tools (De Groot et al., 2010; Wing & Bettinger, 2008). The GIS-workflow used to produce these outcomes is an important product on its own. As is, it can be followed to identify alternative study areas or validate the findings of this research. It can also be used as a template; a clear explanation of the purpose and rationale behind each step in the workflow facilitates modifications that accommodate better datasets or more robust selection criteria.

The cost/benefit analysis delineates expected inputs/investments (costs) and outputs (benefits). Costs were broken down by sub-task and derived from expert judgement. Benefits were derived from a comparative analysis of relatable research using a set of unique evaluative criteria and likelihood rubric. These outcomes are essential tools in a feasibility assessment to determine if a venture is worthwhile (Meaden, 2013). However, comparing costs with potential benefits is not straightforward (Obermeyer, 1999; Meaden, 2013; Katimuneetorn, 2008). The benefits of this approach are intangible: information products that would lead to a better understanding of past conditions and aid decision-making. Costs on the other hand are in monetary terms and based on execution of the pilot studies. Considering if the pilot studies are affordable can be objective and based on budgeting. Deciding if the pilot studies are worthwhile is much more subjective and depends on the valuation of potential benefits (Obermeyer, 1999; Anderson & Al-Thani, 2015). It should also consider what the implications are of ignoring potential benefits. The cost/benefit analysis lays out these factors as objectively as possible so that decision makers can make a more informed decision.

8.3 Conclusions

Forests are a globally important resource that provide a multitude of ecosystem services. Ecosystem services are the benefits that people obtain from ecosystems (Millennium Ecosystem Assessment, 2005; Turner et al., 2013). Environmental services supported by forests include clean water and air, medicine and food, erosion and flood protection, and economic products such as wood, paper and pulp (Drushka, 2003; Fisher et al., 2009; FLNRO, 2016). The overarching goal of resource management is to ensure forests can support long-term benefits for multiple, often competing, users (Environment Canada, 1995; Noss, 1990; United Nations, 1992, 2011).. However forests are complex systems and we do not fully understand the mechanisms that support ecosystem services, making it difficult to set management targets (Puettmann et al., 2009). A common goal has been to manage for biodiversity because it is a key indicator of forest health and is linked to the resiliency and self-organization of species and ecosystems across spatio-temporal scales (Holling, 2001; Peterson, Allen, & Holling, 1998; Carnus et al., 2003). Yet this is still a complicated endeavour as biodiversity is not easily measured. Increasingly, knowledge of natural disturbance dynamics has been used to set management targets and policy (Bollenbacher et al., 2014; DeLong, 2011; Demeo et al., 2018). This has been backed by ecological theory such as the ecological historic range and variability (HRV) concept. HRV theory asserts that natural disturbance regimes create forests of different age and pattern, which contain the structural attributes that species rely on (Keane et al., 2009; Landres et al., 1999). From this perspective, forest biodiversity can be viewed as the variability (e.g. amount and distribution) in habitat structure, such as seral stage, and used as a surrogate for species and genetic biodiversity (Bissonette & Storch, 2003). Deviation of current conditions from the HRV estimates can then be used to calculate risk to forest biodiversity and inform management actions

(Lewis, 2016). A problem with this approach is that most methods of setting HRV benchmark conditions assume stand-replacing disturbances. Resource management activities that attempt to replicate a stand-replacing natural disturbance regime leads to homogenized stands and landscapes (BC Ministry of Environment, 1995). However, many historic disturbances (both anthropogenic and natural) have not been stand-replacing. Disturbances vary in frequency and severity, resulting in more heterogeneous and complex forest structure than an age-based approach would suggest (Cyr et al., 2014; Lindenmayer et al., 2006).

The potential value of HAPHA is a more objective and reliable measure of forest structure than using the age-based estimates of an HRV approach and age-based inventories such as VRI. Specifically, the potential benefits are: establishing baseline conditions through the objective and efficient assessment of historical aerial photography in a reproducible manner; quantification of ecologically relevant metrics (i.e. OBM and heterogeneity) that may provide unique insights into forest structure; and, ability to establish trends over time with the aid of contextual information and ancillary data (e.g. silvicultural practices, resource development, management regimes) (Table 7-10 : Benefits Rubric Results. If the pilot study confirms these benefits, the implications for forest management could be broad. This information could help managers: plan for and mitigate future challenges (including climate change); prioritize restoration and conservation efforts, and; evaluate and revise plans related to silvicultural practices and fire management (Bollenbacher et al., 2014). HAPHA could be particularly useful for cumulative effects assessment of forest biodiversity.

Cumulative effects assessment (CEA) is endorsed as an integral and more holistic approach to effective resource management (Greig & Duinker, 2014; Hegmann & Yarranton, 2011). CEA is especially relevant in British Columbia (BC) where an increase in the quantity and diversity of development activities (e.g. mining and LNG) as well as environmental pressures (e.g. climate change, mountain pine beetle, species decline, and others) results in an increased risk for cumulative effects (Forest Practices Board, 2011; FLNRO, 2016; Rockstrom, 2015; Thom & Seidl, 2015). The data from historical imagery combined with the capabilities of HAPHA could help managers assess how different policies and activities have affected forest structure over time and help connect knowledge about the complex social-ecological-spatial relationships to CEA practice (Hanna et al., 2016). The GFAF analysis suggests that the benefits are achievable, thus exploration of HAPHA would be worthwhile. However, given the unique aspects of HAPHA and the novel way that it would be applied, these preliminary results must be interpreted with caution (McInnis & Blundell, 1998; Rihoux and Ragin, 2009; Asselin & Parkins, 2009; Burdge, 2004). Furthermore, the perceived value of HAPHA is subjective and whether the information HAPHA can produce will be adequate to answer the relevant questions depends on management priorities and institutional capacity (Hanna et al., 2016; Franklin, 2001). This is a concern that underlies CEA in general and is representative of the main issue of feasibility addressed in this research; it is not necessarily the tools for CEA that are lacking, but more importantly a comprehensive system in which to consider cumulative effects (Wulder, 1998; Hegmann & Yarranton, 2011; Gunn & Noble, 2011). A valuable database of historical photography exists but the logistics of accessing this data is a barrier. Pilot studies are necessary to assess if the information in historical photos would indeed be sufficient to measure forest structure and if it can be cost-effectively harnessed (e.g. using existing data). Developing the institutional capacity to harness and implement this information would be the next big question regarding feasibility. Ultimately the decision to invest depends on available resources (e.g.

budget and expertise) and the perceived value of historical photography and HAPHA to manage forest resources and meet legal objectives (Meaden, 2013).

The HAPHA method is not intended to replace an HRV-based approach, but rather to allow an additional capability not available within an age-based inventory (Flanders et al 2003). Incorporating historical aerial photography could provide a more accurate snapshot of past conditions and trends in forest structure than HRV estimates. Even photographs from the more recent past could yield valuable information. Yet, despite its potential value the feasibility of incorporating historical imagery is a multi-faceted issue. A major practical hurdle is that historical images have not been converted to GIS-compatible information and the logistics of converting this data is cumbersome (Morgan et al., 2010; Wulder, 1998). HAPHA has the ability to overcome some of these difficulties and make the information in historical imagery more accessible to forest managers (Morgan & Gergel, 2010).

Accurate and objective information that can directly inform management actions is a valuable asset to natural resource managers who must make decisions regarding resource allocation and whether to allow or restrict certain activities (FLNRO, 2014; Gunn & Noble, 2009). Geospatial tools that are able to quantify concepts like forest biodiversity with more concrete metrics and visualize this information alongside datasets related to existing and proposed resource activities, natural disturbances and legislated forest values (e.g. old growth management areas) are indispensable (Blaschke et al., 2008; de Groot et al., 2010; Didion et al., 2007; Hessburg et al., 2013; Morgan & Gergel, 2010, 2013; Tinker et al., 2003) This information facilitates more transparent and justifiable decisions and provides a feedback mechanism for adaptive management (Franklin, 2001; Lindenmayer et al., 2006; Morgan & Gergel, 2013; Stevens et al., 2016).

8.3.1 Recommendations for future work

The potential value of historical aerial photography seems clear and further investigation into incorporating this valuable resource cumulative effects assessment of forest biodiversity should be pursued. The pilot studies should be implemented to confirm the likelihood of achieving the desired benefits outlined in this research. The results of the pilot studies will indicate the suitability of HAPHA and provide quantitative information for refining cost estimates and predicting the futures institutional capacity required for incorporating the protocol. Prior to conducting the pilot studies it will be necessary to refine the research design and assess data quality in the proposed study areas. A modified MCE that incorporates additional data resources may also be used to identify more data rich study areas. Research data, plot data and important thematic datasets should be investigated for their use. Once pilot studies are completed, the cost/benefits analysis could be adjusted to allow for a more quantitative comparison of potential benefits and costs.

One of the reasons for identifying an OBIA approach is for its potential in transferring the protocol to different sites. This accounts for the sometimes subjective and difficult to replicate results of manual interpreters, as well as the cost of these interpreters. Furthermore, new imagery – including satellite imagery will be obtained going forward. Some of the challenges with historic imagery may not be there with newer imagery – but there may be challenges in comparing over time between different image sets. Further research will need to investigate if HAPHA is transferrable between sites (e.g. different BEC subzones) and photo types with minimal alterations. This is critical to the practical feasibility of HAPHA (particularly ongoing costs and timeliness).

Pending positive results of the pilot study, the logistics of building the institutional capacity within to fine tune the protocol should be examined. The most resource intensive part of HAPHA would be developing and adapting the protocol to CEA. Hiring employees with the expertise to work on developing this tool full-time would be more practical than continuing to rely on consultants. Once the database is built up and HAPHA is fine-tuned the goal should be to minimize on-going costs. Future research would need to consider the costs associated with software, training and qualified personnel. This should include an examination of existing capacity.

Manual forest inventory classification may never be completely replaced by automatic methods. However, OBIA methods that can unlock information from historical photography while simultaneously decreasing processing time and maintaining rigour are very valuable for contemporary forest management and conservation (Morgan & Gergel, 2013). This research would help identify agreement and discrepancies between the measurement of specific attributes by automated and manual methods (Morgan & Gergel, 2013). It would contribute to OBIA research by helping to bridge the gap between software developers and the forest inventory community by identifying the potential and limits to the use of segmentation for stand delineation (Wulder et al., 2008).

Future research could also examine the GFAF for completeness and compatibility with other contexts and geomatics technologies. Experts in business management (feasibility assessments, cost estimation) along with remote sensing, GIS and resource management experts should assess the framework for its value to their specific contexts and to identify any gaps. Experts could also examine how the GFAF can be adjusted for use in different contexts (e.g.

proposals for research funding or for consulting contracts, selecting new software for an organization, or exploring geomatics solutions for information gaps in decision-making).

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Appendices

Appendix A: Procedure settings

The protocol explained below is an amalgamation of Morgan & Gergel (2013) and (2010). From this point on, the protocol will be referred to as the Historic Aerial Photograph Heterogeneity Analysis (HAPHA). The section begins with a brief discussion of the software used. It then describes the main stages in the OBIA procedure: data preparation and image analysis. Data preparation consists of image preprocessing and creating the auxiliary layers that will be used in the image analysis section. The image analysis section describes the two main components of OBIA (segmentation and classification) and the calculation of heterogeneity metrics.

A.1 Software

Only one software platform will be specifically referenced due to its fundamental role in the analysis: the object-based image analysis software Definiens (Definiens,2012). Morgan and Gergel (2010; 2013) used Definiens for the object-based image analysis (OBIA) (creating image objects and generating object-based metrics) which is the basis for the entire procedure. Alternative software options exist, however Definiens, formerly eCognition, is the pioneering software for object-based image analysis (OBIA) (Benz et al., 2004; Definiens, 2012) and is still the most flexible and comprehensive object-oriented system for image classification (Bock et al., 2005). Therefore the discussion will specifically reference the settings and process within Definiens.

Ancillary activities include data preparation (e.g., image enhancement, orthorectification), creation of input layers, statistical analysis and GIS processing (mapping and analysis). Morgan and Gergel (2010; 2013) used various software platforms for these activities: Alta photogrammetry suite was used to orthorectify the photos, ENVI (texture) and ArcGIS (terrain) were used to create input layers, DTREG was used for CART modelling and classification accuracy, and SAS was used for statistical analysis. These tasks are not as specific to their respective software platforms and therefore only a discussion of the process will be included and platform settings will not be explicitly referenced.

Software	Task
Definiens	Segmentation
Alta photogrammetry suite	Orthorectify
ENVI	Texture layers
ArcGIS	Terrain layers
DTREG	Classification
SAS	Statistical analysis

Table A-1: Software used for each task

A.2 Data Preparation

Data preparation refers to the activities that are required to set the data up for analysis. This is an important step to ensure accuracy and relevance of the final output. This task is broken down into the image pre-processing and the creation of the input layers.

Task	Sub-Task	
1. Data Preparation	**Scan Photos**	
	Image enhancement/correction e.g. Auto-dodged	
	Orthorectification ○ Add elevation ○ Resample for uniform spatial resolution	
	Create Auxiliary Layers	*Texture Layers* ○ Calculation of texture layers using co-occurrence matrix (e.g. Entropy, correlation and homogeneity) ○ Correlation analysis of original photos and derived texture layers (Remove redundant layers based on results) ○ Rescale retained layers to same range of tonal values as original photos
		Terrain Layers ○ Generate DEM from TRIM data ○ Generate derivative terrain layers (e.g. aspect, slope) from DEM ○ Generate topographic wetness index layer ○ Correlation analysis of layers ○ Selection of layers based on ecological relevance and between-layer correlations

Table A-2: Task 1 (data preparation) and sub-tasks

Data preparation refers to 3 primary sets of input data: tonal data (photographs), texture data (derived from tone) and terrain data. Tonal data are the primary data source and refers to the aerial photographs. Aerial photographs must be preprocessed to minimize residual error and classification inaccuracies (image enhancement and orthorectification) (Lillesand et al., 2008). Texture and terrain data are auxiliary layers critical for the depth of analysis desired. These layers must be created prior to analysis.

Input Data	Layers	Processing
Tone	Aerial Photos	Scan , image enhancement, orthorectify
Texture	Variance Correlation Entropy Homogeneity	Calculate using co-occurrence matrices of original aerial photograph
Terrain/topography	Elevation (DEM) Aspect Topographic wetness index	Calculate using raster interpolation and raster algebra

Table A-3: Data and processing activities associated with the input data for the multi-resolution segmentation procedure

Aerial photos are available provincially and federally and, depending on the year, available in either hard copy or digital copy. For those that exist in hard copy, the photos will need to be scanned into digital format for further analysis at a resolution that balances clarity and file size. This can be done by the air photo vendor upon request, by the person initiating the research, or by the consultant contracted for analysis.

Aerial photos contain radial topographical distortion (from camera tilts, aircraft movement and natural variation in elevation) and scale variations that must be corrected to enable accurate measurements and quantitative analysis (Lillesand et al., 2008; PCI Geomatics, 2011). Preprocessing operations including correcting geometric distortions, calibrating the data radiometrically and eliminating any noise in the data, are necessary before further manipulation and analysis of the image data is done (Lillesand et al., 2008). Photos from 1963-present exist in digital format and some have been preprocessed. However historical photos (1936-1962) especially will need to be preprocessed. The two overarching categories of preprocessing are image enhancement and orthorectification.

A.3 Image Enhancement

The image data are a grid of pixels with a value relaying the radiometric response for that given area. Image enhancement includes a broad range of techniques used to more effectively display or record the data for visual interpretation and analysis (Lillesand et al., 2008). Image enhancement is meant to increase the distinction between features in an image and remove distortion from systematic and random sources. Two common categories of image enhancement are contrast manipulation and spatial feature manipulation. Morgan & Gergel (2010; 2013) employed a contrast manipulation technique called auto-dodging which equalizes dark and light areas in the photo. Additional image enhancement techniques will depend on the quality of the photos and therefore cannot be suggested at this time.

A.4 Orthorectification

Orthorectification removes the geometric distortions in an aerial photograph caused by camera tilt and topographic relief distortions in order to provide accurate spatial reference (Lillesand et al., 2008). The purpose of orthorectification is to match the image to a constant scale, specifying horizontal and vertical coordinates, so that distances, areas and angles can be correctly measured and photos from different periods in time can be accurately compared (PCI Geomatics, 2011; Danby, 2007). This process ‘geocodes’ the image with a map projection so that it can be integrated with other geographically referenced data.

The orthorectification process requires: spatially referenced data (e.g. topographic maps, TRIM data, orthophotos, vector road and stream data) to orientate the photo to its true position in terms of x,y coordinates, and elevation data (e.g. DEM or TIN), and; camera specific information (e.g. focal length, and changes in altitude, attitude and velocity) to correct for geometric distortion (PCI Geomatics, 2011).

The exact steps will vary slightly depending on the platform and available information (camera calibration data for historical photos may be absent). However the procedure should focus on residual accuracy and compatibility between photos (in terms of uniform spatial resolution and quantitative information). While historical photos will need to be orthorectified, for more recent years orthophotos exist that could be used to process historical photos and reduce the total amount of work.

A.5 Create Auxiliary Layers

There are two categories of auxiliary layers for protocol: texture and terrain. Both categories have ecological relevance and have been shown to aid in classification and analysis of forest parameters (Franklin et al., 2000; Morgan & Gergel, 2013; Wulder & Boudewyn, 2000). The final layers selected by Morgan & Gergel (2010; 2013) were chosen according to results of a correlation analysis. These layers are a good baseline but need not be the only layers included in HAPHA. Additional texture and terrain layers should be explored in the same ways described below.

Texture in a photograph refers to the quantification of the spatial variation in image tone, which contains valuable information about the diverse arrangement of forest structure horizontally and vertically (Franklin et al., 2000; Wulder & Boudewyn, 2000). Unique variations in image tone can be used to stratify stands and increase the accuracy of forest classification and modelling of biophysical attributes (Bock et al., 2005; Franklin et al., 2000; Halounová, 2004; St-Onge & Cavayas, 1997).

Texture layers were calculated using a co-occurrence matrix for all photographs, each with a 3 x 3 pixel processing window. A correlation analysis of the original photographs and the derived texture layers was conducted to identify and eliminate highly redundant layers: correlations less than 43% (abs(r)\0.65). Four layers were retained: entropy (a measure of randomness), variance, homogeneity, and correlation. “Texture layers were then rescaled to the same range of tonal (gray scale) values as the original photograph to ensure equal influence in later analyses” (Morgan & Gergel, 2010).

Topography is related to vegetation pattern, structure and composition (Torontow & King, 2011). Incorporating topography into ecosystem and landscape analysis using elevation and terrain derivatives has demonstrated applicability (Dorren et al., 2003; MacMillan et al., 2007).

Terrain layers were generated from BC TRIM contour data (which was also used to orthorectify the photographs). The first terrain layer created was an elevation layer, which was created by converting TRIM contour lines into a digital elevation model (DEM) using ArcGIS (raster interpolation). The DEM was resampled to match the spatial resolution of the aerial photographs (0.5 m) (a critical step for valid analysis in OBIA (Morgan & Gergel, 2010). ArcGIS was then used to derive various terrain layers (e.g. slope, aspect, hillshade) from the DEM using raster surface algorithms, and to calculate a topographic wetness index (TWI) layer (which represents potential moisture in catchment area). A between-layer correlation analysis was then run on all terrain layers. The original DEM, aspect, and TWI were selected according to low correlation (abs(r) < 0.65) and their ecological relevance (e.g. elevation and aspect influence solar energy and water regimes, and topographic wetness indices are used to describe patterns of soil moisture, which are both linked to variation of vegetation patterns) (Gergel & Turner, 2002; Landres et al., 1999; McPherson & DeStefano, 2003; Morgan & Gergel, 2010, 2013).

A.6 Image Analysis

The image analysis section is split up into 3 categories: segmentation, classification and heterogeneity metrics. Each category describes the process, methods and settings employed by Morgan and Gergel (2010, 2013). As with Morgan and Gergel (2010; 2013), the results of the procedure should be compared with manually interpreted data for quality control. Therefore the image analysis stage will also entail manual classification of photos by a trained interpreter.

Task	Sub-task
2.Image Analysis	**Segmentation** *Goal : produce forest cover polygons similar to VRI standards* *3 factors: input layers and assigned weights; scale parameter; and homogeneity criterion)* *8 input layers: tone (photograph), texture layers (variance, correlation, homogeneity, entropy), topography (elevation, aspect, topographic wetness index))* o Iteratively run segmentation process to determine settings for 3 factors which produce results closest to VRI polygons - Determine appropriate scale parameters based on scale breaks evident in two object metrics: number of objects and minimum object size o Generate object-based metrics for segmented polygons
	Comparison of polygons and objects o Generate object-based metrics for segmented objects o Use VRI polygons to create objects and generate object-based metrics for these objects o Run nonparametric statistical tests: - Wilcoxon signed rank test: local comparisons (paired polygon/objects) , - Wilcoxon rank-sum test: comparison between polygon and object mean values, and - Kolmogorov-Smirnoff tests: landscape-level comparison of the distribution of metrics from each approach
	Manual Interpretation o Use VRI standards to manually delineate polygons of historical aerial photographs

Table A-4: Task 2 (image analysis) and sub-tasks

A.7 Segmentation

HAPHA uses the multi-resolution segmentation process in Definiens which is a bottom-up pairwise region-merging technique that creates ‘objects’ that are internally homogenous (Benz et al., 2004; Definiens, 2012; Morgan & Gergel, 2010, 2013). It is an iterative process: initial segmentation acts on individual pixel ‘objects’ and iteratively aggregates adjacent ‘objects’ creating intermediate object states with increasing differentiation of classification. The segmentation process is circular in nature whereby each segmentation iteration generates new knowledge and information that feeds into the next level of analysis (Benz et al., 2004). The process creates a hierarchical network of objects that know their respective context, neighbourhood and sub-objects (Baatz & Schäpe, 2000). The objects are extracted at different resolutions of the photo, representing different features/processes that occur at different scales (Benz et al., 2004). The result is the spatial aggregation of pixels to image regions as well as a "spatial, semantic network" of image content (Benz et al., 2004).

The segmentation process is governed by 3 primary factors: a set of input layers and associated weights, a homogeneity criterion and a scale parameter. Morgan & Gergel use the same process but with slightly different settings to achieve different goals: produce results visually similar to manual interpretation results (2013) and describing spatial heterogeneity (2010). The image object hierarchy in Definiens enables multiple segmentation outputs to be used simultaneously that will facilitate the unification of these two procedures. The settings used in these two examples can be used as a starting point and a guideline. However, the HAPHA should follow the iterative process of determining the appropriate settings for this purpose to ensure that the two procedures mesh. Attention should be given to the how scale breaks and object size can be linked to ecological processes.

Scale	Object-type	Number of objects	Minimum object size (m2)	Average object size (m2)	Relevant ecological features
280	Sub-object	960	665	10,219	Small clumps of trees (10–50 visible crowns), small stream units and small bogs
500	Primary object	311	2,752	32,107	Medium sized clumps of trees (50–150 visible crowns), and stream reaches
720	Super-objects	165	6,428	59,849	Larger stands of trees (150–300 visible crowns), and small lakes
1200-1650	VRI polygons	541	-------	--------	Medium sized clumps of trees (50–150 visible crowns), and stream reaches

Table A-5: Parameters for HAPHA used by Morgan & Gergel (2010; 2013)
(Scale parameters and corresponding object characteristics [based on 8 photos at scale of ~1:20,000 and 12km])

The input layers provide the foundational data for the segmentation process. The delineation, characterization and differentiation of meaningful image objects (i.e. representing real world features) relies on the ecologically relevant information contained in these layers (Benz et al., 2004). Initial segmentation amalgamates pixels into ‘object primitives’ according to statistically similar input values. The input data are then transformed into a representative statistic for each object by combining the values of each pixel in the object (e.g. mean, standard deviation) (Benz et al., 2004; Definiens, 2012). Additional object-based metrics such as neighbourhood, topologies, length and shape, are also calculated for each object (Benz et al., 2004; Definiens, 2012). Combined, these metrics define and characterize the homogeneity of each object (Benz et al., 2004; Definiens, 2012). The relative importance of each layer in the definition of homogeneity is controlled by assigning weights to each layer.

The homogeneity criterion is a measure of how internally homogeneous or heterogeneous these objects are based on composite calculation of variability in ‘shape’ and ‘colour’ of objects (Baatz & Schäpe, 2000; Definiens, 2012). The ‘colour’ criterion is based on the standard deviation of the input values; input layers are not necessarily limited to tonal values (or colour). The weights assigned to each input layer determine their influence on the calculation of the ‘colour’ criterion and subsequent measure of homogeneity (Baatz & Schäpe, 2000). The shape criterion has two defining properties: compactness and smoothness. The shape criterion is calculated as a deviation from the ‘ideal’ compact and/or smooth shape (the ideal shape is calculated as a ratio between object properties) (Definiens, 2012). The relative importance of ‘colour’ (input layer data) and ‘shape’ in defining homogeneity is controlled by assigning weights to each of the criterion: colour, shape, compactness, smoothness.

The scale parameter is the upper limit of variability allowed within and among a given layer of objects as measured by the homogeneity criterion and influences the size of the objects created (i.e. larger scale = larger objects). The homogeneity criterion is calculated for objects at each iteration in the segmentation process and an underlying optimization procedure identifies the best potential merge of adjacent objects according to the minimal loss of homogeneity (or increase in heterogeneity) (Jiang & Lin, 2010; Karakis et al., 2006). Adjacent objects are consecutively merged until the best potential merge identified by the optimization procedure results in a change to the criterion which would exceed the threshold defined by the scale parameter (Karakis et al., 2006).

The weights assigned to the input layers, homogeneity criterion and scale parameter are the set of constraints which can ensure exact reproducibility of the segmentation process (Benz et al., 2004). Morgan & Gergel (2010; 2013) used 8 different input layers derived from tone, texture and topography. The three data types (tone, texture and topography) were weighted equally in the segmentation procedure (33% each) to ensure equal representation in the creation of objects (Morgan & Gergel, 2010).

The homogeneity criterion consists of colour and shape, which were both weighted equally (0.5) (to ensure equivalent representation of these characteristics in the segmentation output) (Morgan & Gergel, 2010). Shape is broken down into compactness and smoothness, which were also both weighted equally (0.5) to avoid favouring a specific shape type (Morgan & Gergel, 2010).

To determine the appropriate scale parameter, Morgan & Gergel (2010) employed a trial-and-error approach to identify scale breaks in two object metrics produced in the segmentation procedure (minimum object size and number of objects). They identified 3 appropriate scale parameters (280, 500 and 720) which created objects that corresponded to relevant ecological features: sub-objects (small stream units), primary objects (medium-sized forest stands and stream reaches), and super objects (larger tree stands and lakes). The decision to identify and utilize multiple scale parameters acknowledges that no optimal scale exists for any given landscape and that meaningful ecological objects exists at different scales (Morgan & Gergel, 2013).

Alternatively, Morgan & Gergel (2013) determined settings iteratively based on a qualitative comparison between segmented objects and manually delineated polygons. They chose a scale parameter which produced approximately the same number of polygons derived from manual interpretation (corresponding in size and number to "primary objects"). Input layers were still weighted to have equal influence, however they did not include textural derivatives. Tone was favoured in the homogeneity criterion, weighted at 0.7 (out of 1), and shape (weighted 0.3) was also weighted unequally, with compactness weighted at 0.7 and smoothness at 0.3 (Morgan & Gergel, 2013).

A.8 Classification

Object-based metrics (OBM) are derived automatically within Definiens for segmentation results. Morgan & Gergel used these OBM to compare manual and OBIA methods of delineating forest polygons (2013), classify objects according to VRI forest classifications schemes (2013) and to quantify heterogeneity (2010). In both procedures, OBM were calculated according to size and shape of the objects, values of input layers (tone, texture and topography), and context (relationships between neighbours and sub- and super-objects). All border objects were masked out of both procedures to avoid the influence of truncated polygons on the statistics (especially important for shape-related metrics) (Morgan & Gergel, 2010, 2013).

Morgan & Gergel (2013) used 30 OBM to classify objects into forest classes according to the VRI classification scheme. Classification and Regression Tree (CART) analysis was used with the Gini-splitting (tree-fitting) algorithm to create a series of binary splits to divide entities into homogenous groups using the best distinguishing variables. Models were built separately for each class and for each photo pair using 90% of the data, resulting in 40 total models (8 photo pairs x 5 classification schemes). Creating separate models for each photo individually was done to account for the tonal and textural variability among photo landscapes (Morgan & Gergel, 2013). In addition, five models were created using all the combined data from all 8 photo-pairs to assess model accuracy and determine the metrics best able to predict individual classes. CART sizes and accuracies were determined using a minimum cost complexity within a 10 V-fold cross-validation method (Sherrod, 2014). This is a highly accurate method for assessing accuracy and size of the tree without requiring a separate, independent dataset and without reducing the data used to create the tree (Sherrod, 2014).

Task	Sub-task
3.Classification	**Automated: CART** o Use object-based metrics as predictor variables for target VRI classes (assume 5 classes) o Gini-splitting algorithm o build models for individual photo-pair landscapes to account for tonal and textural variability o combine data from all photo-pair landscapes to assess CART model accuracy o Determine tree sizes and accuracies using minimum cost complexity and 10 V-fold cross-validation method
	Manually o Classify according to VRI standards. o Five classification schemes to define polygons and then assign attributes o WANT AGE attribute o For recent photos, use existing VRI data
	Comparative analysis o Comparative classification accuracy using validation data to create confusion matrices

Table A-6: Task 3 (classification and sub-tasks)

A.9 Heterogeneity Metrics

To quantify heterogeneity, Morgan & Gergel (2010) first masked all border objects out of the analysis, and then 202 OBM were calculated related to size, shape, values of input layers, and relationships between neighbours and between sub- and super-objects. Correlated metrics were identified using pair-wise Pearson's correlation coefficients and the simpler and/or more ecologically relevant metric was retained (based on expert knowledge). A factor analysis was then used to reduce the redundancy in the remaining 62 OBM and subsequently grouped into elements of heterogeneity using cluster analysis (Morgan & Gergel, 2010).

A factor analysis with varimax rotation was employed to identify orthogonal axes describing different 'dimensions' of the data over various landscapes. All factors with an eigenvalue greater than 1 were retained for each landscape (latent root criterion). An average of 17 factors were retained for each photo landscape which cumulatively explained 74-78% of the variance within the 62 OBM.

Agglomerative hierarchical cluster analysis using the average linkage method was then used to group the factors together based on their factor pattern (the correlation between all input metrics and the factor). The metrics with high loadings (correlations) for a given factor pattern represent the information summarized for that particular factor. Therefore, clusters or groups were labeled based on the properties of the OBM with the highest consistent loadings within each group of factors. A distance matrix was calculated (1-abs(r) where r is the correlation of the factor patterns) for all of the retained factors. A plot of fusion distances, representing the degree of dissimilarity among clusters as they were fused together, was then used to determine the final 16 heterogeneity elements.

The resulting heterogeneity elements (clustered factors) were then rated by: *Universality* (percentage representation of how often an element was identified over all landscapes); *Strength* (average eigenvalue and percent variance explained by each element), and; *Consistency* (average Pearson's correlation among each element – a measure of how stable the meaning of that element was between landscapes).

Task	Sub-tasks
4.Calculate heterogeneity metrics (Using segmentation results)	**Factor Analysis** (identify independent axes of landscape pattern over various landscapes) o Calculate object-based metrics for objects created in segmentation. o Calculate pair-wise Pearson correlation coefficient for metrics to identify highly correlated metrics and eliminate less ecologically meaningful factors. o Factor analysis of remaining factors using varimax rotation. Use latent root criterion to identify significant factors.
	Cluster Analysis (group related factors together into elements of heterogeneity) o Agglomerative hierarchical clustering to group remaining factors together into elements of heterogeneity. o Average linkage method to group factors based on factor pattern (correlation between all input metrics and factor itself). o Calculate a distance matrix to represent pair-wise measures of dissimilarity among input entities. o Plot of fusion distances to represent degree of dissimilarity among clusters.
	Calculate 3 measures to represent overall importance of clustered factors o *Universality* (percentage representation of how often an element was identified over all landscapes). o *Strength* (average eigenvalue and percent variance explained by each element). o *Consistency* (average Pearson's among each element.
	Exploratory regression analysis (ArcGIS) Are heterogeneity measures: o Associated with structural complexity? - using GIS research plot data (e.g. VRI plots) o Related to different stressors? (managed disturbances vs. natural disturbances) - using GIS ancillary data (disturbance history, management history)

Table A-7: Task 4 (heterogeneity analysis) and sub-tasks

A.10 Comparative Accuracy Assessment

Morgan & Gergel (2013) generated OBM for manually interpreted photos and compared them to the OBM for automatically segmented photos. They compared the OBM characteristics at three scales using nonparametric statistical tests: local comparisons (paired polygons/objects): between polygon and object mean values, and; a landscape-level comparison of the distribution of metrics derived from each approach. At the localized level, a random sample of 15 paired locations was selected from each photo (8 photos in total) (Wilcoxon signed rank test). At the polygon/object level, ranked mean values of the 30 metrics were compared within each photo (Wilcoxon rank-sum test). Finally, the distributions of the 30 metrics were compared for all polygons/objects within each photo (Kolmogorov-Smirnoff test). All tests were conducted at a significance level of 0.05, and if tests did not show statistical differences in means and distributions of the object-based metrics between polygons/objects, then the automated and manual methods were deemed to be similar. Overall conclusions of similarity were based on the number of photos (landscapes) that did not show a statistical difference in the OBM; the higher the number of landscapes that were not statistically different, the higher the likelihood that segmented objects were similar to manual polygons.

Segmented objects were classified into forest cover classes using multivariate CART analysis; a hierarchical decision process which recursively partitions data into 'classes' based on splits in multiple input variables (Morgan & Gergel, 2013). Comparative classification accuracy was assessed using standard confusion matrices within photos and across all photos. The CART models were built using random subsets of 90% of the data. The error matrices used to assess classification accuracy were created using the validation data: the 10% of the data not used in the classification procedure. The 16 elements together explained 76.5% of the variance within all 138 original factors.

Heterogeneity Element (Cluster)	Definition	OBM with high loadings	Ecological relevance
Sub-object variability	Overall variability/heterogeneity of sub-objects/pixels	sub-object density/area/texture/tone	Represents within object heterogeneity, or local variability, and may be related to biodiversity
Tone	Average spectral reflectance	Mean Tone	Reflectance is related to biophysical characteristics
Proximity to border	Continuous measure of distance to the super-object border.	(Distance to super-object center)	Habitat conditions vary at forest stand edges as compared to interior forest
Texture variability	The degree of texture variation within the object: smooth versus coarse	(Standard deviation of correlation/variance	Related to variation in crown size, tree species type, canopy closure, and stand structure
Aspect	Object aspect: north/south/east/west	Standard deviation of correlation/variance	Relates to local solar energy and water regimes which affects vegetation pattern
Compactness	Object shape complexity	(Compactness, length/width	Feature recognition, such as geomorphic landforms
Landscape position	Topographic position of the object within the landscape.	Ratio to super-object DEM/TWI	Topographic position influences patterns of moisture, natural disturbance and thus, vegetation
Position within super-object	Categorical measure of whether the object is interior or border. within	Is end/center of super object	Habitat conditions vary at forest stand edges as compared to interior forest
Object orientation	Object direction derived from object's location within the landscape	Main direction	May be related to geomorphic landforms, such as crest and swale patterns, or river channels
Slope orientation	The aspect of the object in relation to the landscape	Ratio to super-object aspect	Relates to solar energy and water regimes over coarse scales
Texture content	The texture of neighboring/surrounding objects.	Mean difference to neighbors homogeneity/entropy	Useful for differentiating stand age or species composition of contrasting, neighboring tree stands
Landscape context	Relates to whether an object is higher/lower in elevation than its neighbors.	Mean difference to neighbors DEM/TWI	Neighboring topography is related to moisture potential, natural disturbance and thus, vegetation
Dissimilarity to super-object	Measure of how different an object's tone/texture is to the tree stand it's located within.	Standard deviation ratio to super-object entropy/correlation/tone	Identifies anomalous habitat features within a stand, and may be indicative of specialized or rare habitat types
Curvature	Relates to the sum of changes in direction of the main line of the object, or sinuosity.	Curvature/ length, border length	Indicative of specific geomorphic features, such as water channels or mountain ridges
Size	Object size	Area	Forest patch size can be linked to habitat quality
Site	Local topography of the object (micro-topography).	Mean DEM/TWI	Reflects microclimatic and local moisture conditions, and therefore, local species

Table A-8: Heterogeneity elements explored by Morgan & Gergel (2010)

Appendix B: Multi-Criteria Evaluation Data

B.1 Opax/Isobel Photos

Year	Scale	Type	Source	Photo-Roll
1951	1:70,000	b&w	NEODFC	A13246
1952	1:70,000	b&w	NEODFC	A13493
1959	Large (1:15000 – 1:40000)	fbw	BC Gov historical air photo index map viewer (google earth)	Bc2652/(26-32)113 Bc2655/1-3 Bc2654(80-85) Hist. Mapsheet (092i_e_1948_1963)
1964	1:35000	b&w	NEODFC	A18495
1965	1:30000	b&w	NEODFC	Rr2645-V
1966	1:15840	fbw	BMOS	Bc4372(234-241)(23-17)(202-198), bc4373
1971	1:80000	b&w	NEODFC	A22417
1974	1:16000	fbw	BMOS	Bc7647
1978	1:60000	b&w	NEODFC	A24961,a24992
1980	1:20,000	fbw	BMOS	Bc80126
1981	1:40,000	fbw	BMOS	Bc81013
1986	1:15000	fbw	BMOS	Bc86033
1987	1:70000 1:15000	Fbw fc	BMOS	Bc87084 Bcc774
1988	1:15000	fc	BMOS	Bcc877
1990	1:15000	fc	BMOS	Bcc90031, bcc90033
1992	1:30,000 1:15000	Fbw fc	BMOS	Bcb92016 Bcc92011
1993	1:5000	fc	BMOS	Bc93033(151-143), bcc93042, bcc93043
1994	1:5000	FC	BMOS	Bcc94030(113-121,6-16,43-49,74-69)
1995	1:5000 1:15,000	FC FC	BMOS	Bc95108(101-91) – Bcc95105(43-54,33-44,77-67) Bc95019(51-55)
1996	1:5000	FC	BMOS	Bc96051(81-89,68-61,48-57)
1997	1:40,000	FBW	BMOS	Bcb97025(109)
2000	1:15,000	FC	BMOS	Bcc00008(127/124)
2001	1:30000	FC	BMOS	Bcc01024(14/15)
2011	1:20,000	DC	BMOS	Bcd11304(519-227) (700-693) Bcd11301 (761-759) Bcd11300(35-32)

Table A-9: Complete list of photos found for Opax/Isobel study area in MCE

B.2 Arrowstone Photos

Year	Scale	Type	Source	Photo-Roll
1948	Medium scale	fbw	BCGIve historical air photo index map viewer (google earth	BC629 (98) Hist. Mapsheet (092i_1948_1953)
1950	Medium scale	fbw	BCGIve historical air photo index map viewer (google earth	BC1134 ((38-43) Hist. Mapsheet (092i_1948_1953)
1951	1:70,000	b&w	NEODFC	A13246, A13324
1959		fbw	BCGIve historical air photo index map viewer (google earth	BC2586 (39-42) BC2587 (10-16, 39-46) BC2588 (12-19, 39-42) Hist. Mapsheet(092i_1957_1960)
1965	1:31860	fbw	BMOS	Bc5170,bc5168
1969	1:16000	fbw	BMOS	Bc7224
1971	1:15,000 1:80,000	fbw	NEODFC	A22239 A22417
1975	1:30,000	fbw	BMOS	Bc5678
1977	1:10,000	fbw	BMOS	Bc77072
1977	1:60,000	fbw	NEODFC	A24777
1980	1:20,000	fbw	BMOS	Bc80125, bc80126
1981	1:40000	fbw	BMOS	Bc81013
1984	1:30,000	fbw	NEODFC	A26558
1986	1:15,000	fbw	BMOS	Bc86034
1987	1:70,000	fbw	BMOS	Bc87084
1992	1:10,000 1:15,000 1:30,000	Fbw Fc fbw	BMOS	Bcb92003 Bcc92002, bcc92015 Bcb92014,bcb92017
1995	1:15000	FC	BMOS	bcc95019/11-14 bcc95016(170-167) bcc95042(232-236) bcc95013/24-27
1995	1:30000	FC	BMOS	Bcc95034(73-74)
1997	1:40000	FBW	BMOS	Bcb97020/208-207(90-91)
2000	1:35,000	FBW	BMOS	Bcb00013/12-11
2000	1:15000	FC	BMOS	Bcc00031/180-177 (4-7) Bc00030/146-142 Bc00008/199-195(166-169)
2004	1:30000	FC	BMOS	Bcc04029(6-8) Bcc04028(230-232)(180)
2010	1:20000	FC	BMOS	Bcc10014/(11-13)
2011	1:20000	DC	BMOS	Bcd11304/(462-470) Bcd11300/(532-538)(501-506) Bcd11305/(494-500)(486) Bcc11110(76-79) BC11105(187-189)

Table A-10: Complete list of photos found for Arrowstone study area in MCE

Appendix C: Cost/Benefit Analysis

C.1 Cost Estimate Template

We are looking to derive **rough estimates** of the **costs** (*time* and *financial* if applicable) associated with an image analysis protocol that would be used to address key gaps in BC's Cumulative Effects Framework (CEF) forest biodiversity assessment procedure.

The method outlined in the following table is derived almost entirely from two papers (Morgan & Gergel, 2010, 2013). The object-based image analysis method described in these papers would be adapted to determine if:

1. Automated analysis of aerial photographs (historical and recent) can delineate relatively homogenous forest cover polygons that meet VRI standards?
2. Object-based metrics can improve information about the structural legacies within stands better than using age as a surrogate?
    - See if heterogeneity metrics generated through automated analysis have any relationship with
        - structural complexity attributes (using research plots)
        - partial disturbance type (managed / natural)

Assumptions:

- **12 medium scale aerial photographs** (~12-20km²) (4 photos from 3 different points in time; 4 black and white and 8 colour)
- Photos would be provided

<table>
<tr><th>Task</th><th colspan="2">Sub-task</th><th>Time estimate</th></tr>
<tr><td rowspan="5">1. Data Preparation</td><td colspan="2">Scan Photos</td><td></td></tr>
<tr><td colspan="2">Image enhancement/correction
e.g. Auto-dodged</td><td></td></tr>
<tr><td colspan="2">Orthorectification
o Add elevation
o Resample for uniform spatial resolution</td><td></td></tr>
<tr><td rowspan="2">Create Auxiliary Layers</td><td>Texture Layers
o Calculation of texture layers using co-occurrence matrix (e.g. Entropy, correlation and homogeneity)
o Correlation analysis of original photos and derived texture layers (Remove redundant layers based on results)
o Rescale retained layers to same range of tonal values as original photos</td><td></td></tr>
<tr><td>Terrain Layers
o Generate DEM from TRIM data
o Generate derivative terrain layers (e.g. aspect, slope) from DEM
o Generate topographic wetness index layer
o Correlation analysis of layers
o Selection of layers based on ecological relevance and between-layer correlations</td><td></td></tr>
</table>

Table A-11: Cost template (data preparation)

Task	Sub-task	Time estimate
2.Image Analysis	**Segmentation** *Goal : produce forest cover polygons similar to VRI standards* *3 factors: input layers and assigned weights; scale parameter; and homogeneity criterion)* *8 input layers: tone (photograph), texture layers (variance, correlation, homogeneity, entropy), topography (elevation, aspect, topographic wetness index))* o Iteratively run segmentation process to determine settings for 3 factors which produce results closest to VRI polygons - Determine appropriate scale parameters based on scale breaks evident in two object metrics: number of objects and minimum object size o Generate object-based metrics for segmented polygons	
	Comparison of polygons and objects o Generate object-based metrics for segmented objects o Use VRI polygons to create objects and generate object-based metrics for these objects o Run nonparametric statistical tests: - Wilcoxon signed rank test: local comparisons (paired polygon/objects) , - Wilcoxon rank-sum test: comparison between polygon and object mean values, and - Kolmogorov-Smirnoff tests: landscape-level comparison of the distribution of metrics from each approach	
	Manual Interpretation o Use VRI standards to manually delineate polygons of historical aerial photographs	

Table A-12: Cost template (image analysis

Task	Sub-task	Time estimate
3.Classification **Forest cover classification similar to VRI* standards. *Age of forest stands is most important in CEF biodiversity assessment procedure*	**Automated: CART** o Use object-based metrics as predictor variables for target VRI classes (assume 5 classes) o Gini-splitting algorithm o build models for individual photo-pair landscapes to account for tonal and textural variability o combine data from all photo-pair landscapes to assess CART model accuracy o Determine tree sizes and accuracies using minimum cost complexity and 10 V-fold cross-validation method	
	Manually o Classify according to VRI standards. o Five classification schemes to define polygons and then assign attributes o WANT AGE attribute o For recent photos, use existing VRI data	
	Comparative analysis o Comparative classification accuracy using validation data to create confusion matrices	

Table A-13: Cost template (classification)

Task	Sub-task	Time estimate
4.Calculate heterogeneity metrics (Using segmentation results)	**Factor Analysis** (identify independent axes of landscape pattern over various landscapes) o Calculate object-based metrics for objects created in segmentation o Calculate pair-wise Pearson correlation coefficient for metrics to identify highly correlated metrics and eliminate less ecologically meaningful factors o Factor analysis of remaining factors using varimax rotation. Use latent root criterion to identify significant factors	
	Cluster Analysis (group related factors together into elements of heterogeneity) o Agglomerative hierarchical clustering to group remaining factors together into elements of heterogeneity o Average linkage method to group factors based on factor pattern (correlation between all input metrics and factor itself) o Calculate a distance matrix to represent pair-wise measures of dissimilarity among input entities o Plot of fusion distances to represent degree of dissimilarity among clusters	
	Calculate 3 measures to represent overall importance of clustered factors o *Universality* (percentage representation of how often an element was identified over all landscapes) o *Strength* (average eigenvalue and percent variance explained by each element) o *Consistency* (average Pearson's among each element	
	Exploratory regression analysis (ArcGIS) Are heterogeneity measures o associated with structural complexity - Using GIS research plot data (e.g. VRI plots) o Related to different stressors? (managed disturbances vs. natural disturbances) - Using GIS ancillary data (disturbance history, management history)	

Table A-14: Cost template (calculate heterogeneity metrics)

C.2 Benefits – Summary of Comparative Analysis

Paper	Results and relevance to HAPHA
Improved Landsat-based forest mapping in steep mountainous terrain using object-based classification(Dorren et al., 2003)	The study demonstrates the ability of object-based methods to more accurately portray the field situation in forested steep, mountainous terrain. In particular, it was able to distinguish between different forest types and characteristics where multiple smaller scale disturbances had taken place. In contrast, pixel based classifications classified these areas as large homogenous areas. The data type and scale used in this study limit any direct comparison to the proposed methodology: the much smaller scale Landsat images and usage of near infrared and shortwave infrared bands (compared to aerial photography). However, the results are promising. The authors noted the relevance of object-based methods, particularly in complex forests systems where forest stands are elements with gradual and fuzzy transitions. In these cases, both a sophisticated segmentation procedure and an intelligent classifier are needed. A sophisticated segmentation procedure should be able to segment complex, gradual changing elements in images into realistic objects. Within current segmentation and pattern recognition research such procedures have already been developed and tested. Intelligent classifiers could be based on membership functions in combination with an extensive hierarchical or multiple-scale knowledge base or on neural networks. It is also worth noting that the authors concluded that Landsat TM images could provide basic information at regional scale for compiling forest stand type maps especially if they are classified with an object-based technique. This could add additional information to the BC's cumulative effects framework.
Preliminary evaluation of eCognition object-based software for cut block delineation and feature extraction (Flanders, Hall-Beyer, and Pereverzoff 2003)	This study demonstrates how eCognition software is capable of identifying traces of logging and other forest structures effectively and with significant improvements in accuracy over pixel-based approaches. The software is efficient, versatile and easy to use, making it a powerful tool in this context. This study uses Landsat data and is thus not directly related to the proposed use of aerial photography. It also does not look at the residual structure of different partial disturbances, but rather the general landuse (e.g. forest cut block, past cut block) It does however demonstrate the importance of the context used in OBIA methods in distinguishing cut-blocks from these images. Furthermore, it uses data from BC which indicates that OBIA methods within eCognition are capable of distinguishing harvesting patterns.
Quantifying Historical Changes in Habitat Availability for Endangered Species: Use of Pixel- and Object-Based Remote Sensing (Pringle et al. 2009)	This article concluded that object-based tools are an effective means of tracking trends in habitat using historical aerial photography. They conclude that the contextual information used in OBIA methods was an effective means of bolstering classification approaches of images with limited spectral information (historical photographs). However, the level of detail desired in this paper was limited in comparison to what HAPHA would be aiming to achieve. Pringle et al 2009 used only 3 land-cover classes and was mostly only interested in identifying the presence of exposed rock. Vegetation type was not important for examining the habitat suitability for the snakes in question. Nonetheless, OBIA methods are a promising tool for assessing habitat trends using historical photographs which is essential for sound management of natural resources.
Quantifying historic landscape heterogeneity from aerial photographs using object-based analysis (Morgan and Gergel 2010)	Quantification of heterogeneity: The authors found that there was a high degree of similarity in heterogeneity definitions between landscape ecology (categorical classification of patches), aerial photograph interpretation (qualitative description of polygons), and object-based analysis (quantitative variability within objects) despite very different approaches. The identification of similar landscape elements amongst very different approaches may emphasize how general these characteristics are for describing heterogeneity.

Paper	Results and relevance to HAPHA
	However the object-based approach provides a unique and novel description of landscape variability. This approach is consistent, and relies on statistical variability within the data to generate an almost limitless range of scales from various sources of remotely sensed data (as opposed to the single scale present in most thematic maps). Furthermore, as information derived from an object-based classifier can be calculated and used simultaneously over numerous spatial sales, this broadens the potential scope of including ecological scales meaningful to multiple species, entities, or spatial processes. Heterogeneity over landscapes with different structure: The similarity between, and relative importance of, elements identified for both riparian and upland landscapes is surprising. This similarity suggests that overall landscape heterogeneity may be described using similar elements for both landscape types, despite their obvious ecological and biophysical differences. Overall, it appears that finer-scale variation in local characteristics of objects may be slightly more important for describing riparian heterogeneity, whereas upland landscape heterogeneity may be related to processes occurring over coarser scales ...Further exploration is warranted to explore differences among landscape types. OBIA as a landscape analysis tool: Object-based analysis acts as a hybrid approach between landscape ecology and remote sensing by utilizing the rich information found in spatial datasets, within the framework of a patch-based perspective. As such, this approach addresses some problems with the use of categorical data as the basis for landscape analysis. Potential may also exist in the use of object-based techniques to help address some of the scaling issues inherent to landscape analysis. The quantification of contextual data or object/patch border characteristics in the absence of class data is a new way of incorporating such relationships, and may be helpful in overcoming the categorical limitations of previous approaches used to define heterogeneity.
Grossmann and Mladenoff 2007	The authors were able to assess the transition of forest types as a result of a mixed-disturbance scenario (natural and anthropogenic). Knowledge of disturbance history and forest practices helped to interpret the findings, generate new insight and identify landscape management priorities. The method of analysis was a bit different as they used hand digitized polygons as the basis for the coarse level of segmentation (although Morgan and Gergel show that this is comparable). They used largest patch index, median polygon area and fractal dimension.
(Halounová 2004)	This paper demonstrates the successful use of object-oriented analysis to classify a mixed-use area. The three criteria for success stated by the author were image enhancement techniques, object-oriented segmentation and classification, and multi resolution segmentation. This paper used eCognition software to assess black and white areal orthophotographs at a scale of 1:23,000. High accuracy was achieved (averaging 80%) with the average only being brought down by urban areas. This paper clearly demonstrates the potential to extract more information from forested areas in BC using OBIA.
Morgan and Gergel 2013	This paper clearly demonstrates the use of OBIA in analyzing historical photos and thus as a critical tool in establishing baseline conditions. The results show that OBIA is capable of delineating objects that are indistinguishable from manually interpreted polygons in several important ways at different scales. It also showed that OBIA can achieve desirable classification accuracies. This study was done on some old photographs and thus dealt with a number of issues inherent in older photos. The success with these photos is promising for applications with more contemporary photos.

Paper	Results and relevance to HAPHA
Land-use history and topographic gradients as driving factors of subalpine Larix decidua forests (Garbarino et al., 2013)	This paper is very relatable in terms of methods. eCognition was used to segment and classify historical aerial photographs. Historical disturbance data and structural data derived from forest plots were used in a multi-variate analysis to assess the relationship between variables. This was accomplished successfully, and the authors were able to assess the change in landscape composition in relation to these disturbances. However, this study area lacks the complex disturbance regime often found in BC forests. It focused mostly on the impact of grazing and of agricultural abandonment. It does not contain an assessment of forestry impacts or natural disturbances such as fire. Nonetheless, this paper demonstrates the ability to effectively extract historical data from aerial photographs using OBIA methods and to incorporate this data with existing historical data to draw conclusions for management. Garbarino et al. (2013) used historical and recent aerial photographs to investigate the anthropogenic disturbance regime and its impact on landscape composition. Based on an object-based segmentation and classification procedure to produce 6 classes (dense forest, sparse forest, grazed forest, shrubland meadow landcover and rock), they calculated patch/mosaic metrics using Fragstats to (e.g. patch size and density, edge, contagion, connectivity, and diversity). These metrics, which are relatable to the OBM and heterogeneity elements of HAPHA, were used to determine the change in landscape composition over time. Garbarino et al. (2013) then used ancillary thematic data to model the degree of anthropogenic influence on landscape change: historical grazing data, stand structure data from field plots, topographic variables and anthropogenic variables from thematic maps (proximity to features). The results indicate that anthropogenic variables were key determinants in shaping forest and landscape structure, with topography acting as a constraint (Garbarino et al., 2013). This study area lacks the complex disturbance regime often found in BC forests and focused mostly on the impact of grazing and of agricultural abandonment. Nonetheless, this paper demonstrates the potential relationship between OBM and cumulative effects. They concluded that historical ecology can serve as a source of quantitative data on human pressure to inform ecosystem models for prediction of future scenarios of landscape change and species compositional shifts.
An object-oriented approach to assessing changes in tree cover in the Colorado Front Range 1938–1999 (Platt & Schoennagel, 2009)	This study showed how OBIA can be used to compare historical photos with more recent photos accurately. It lacks the inclusion of a wider array of natural and anthropogenic disturbances and is fairly limited in its assessment of forest attributes (focused on tree cover). The results of the study can help managers prioritize forest treatments aimed at restoring pre-suppression forest structure
Comparison of Nearest Neighbor Methods for Estimating Basal Area and Stems per Hectare Using Aerial Auxiliary Variables (LeMay & Temesgen, 2005)	This paper demonstrated the ability to predict forest structural information from aerial variables and plot data. This has important implications for HAPHA as this demonstrates the ability to accurately predict variables that would otherwise be costly to obtain, and that can be imputed using available data.
Object-oriented classification of repeat aerial photography for quantifying woodland expansion in central Nevada (Pillai et al., 2005)	The approach used in this study facilitates the development of essential information for land managers by assessing the vegetation change over a period of time. It also contributes to our understanding of the importance of scale while studying landcover changes. Though the accuracy of OBIA and pixel-based classification in this example was not significantly different, the OBIA method allows for extracting small objects like trees from panchromatic aerial photos of high resolution in an automated routine, where only minor changes to the thresholds of the membership functions based on image-specific variation in brightness and contrast is necessary. Given that much

Paper	Results and relevance to HAPHA
	older aerial photography is panchromatic with scale ranging from 1:12,000 and 1: 24,000, the availability of an automated procedure for tree and wooded patch delineation should be of great utility for studies of historical vegetation change in xeric woodland environments."
Field validation of 1930s aerial photography: What are we missing? (Browning, Archer, & Byrne, 2009)	This paper may have some relevant implications for the usefulness of historical aerial photography. It must be interpreted with caution, as it uses manual interpretation and is interested in shrubs, as opposed to a forested landscape in BC. However the authors found that the information extracted from these photos was on par with what can be extracted from more recent aerial photography. With an automated object-based approach, it is conceivable that information can be extracted with even more accuracy.
Employing Measures of Heterogeneity and an Object-Based Approach to Extrapolate Tree Species Distribution Data (T. Jones et al., 2014)	This study used Landsat data as the basis for image analysis and Lidar data to calculate forest metrics, and therefore must be interpreted with caution. However, the results demonstrate the usefulness of an object-based approach and regression tree analysis to calculate and extrapolate heterogeneity metrics, which are noted to have pertinence to a variety of ongoing and/or potential management initiatives. Importantly, it was found that using he heterogeneity metrics to extrapolate to increasingly coarser spatial resolutions resulted in less severe information altering than the common technique of majority filtering. The Landsat bands used as the predictor variables would not be relatable to HAPHA (NIR, SWIR). However, this paper clearly demonstrates the relationship between spectral properties and heterogeneity metrics which were calculated based on forest attributes.

Table A-15: Summary of research papers included in benefits analysis according to evaluative criteria