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73,401 HEXAGONS: A GEODIVERSITY GAP ANALYSIS OF THE CROWN OF THE CONTINENT ECOSYSTEM

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Abstract

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73,401 Hexagons: A Geodiversity Gap Analysis of the Crown of the Continent Ecosystem

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The Crown of the Continent Initiative (CCI) is a transboundary collaborative of conservation groups who work to further conservation goals throughout the Crown of the Continent Ecosystem, located in Northwestern Montana and southern British Columbia and Alberta. CCI and their member groups are interested in using geodiversity as a conservation measure in the Crown Ecosystem. First suggested in 1988 (Hunter et al.), geodiversity, or land facets, are typically a combination of abiotic features used as surrogates for the overlying biotic features. Conservation planning often employs an approach of coarse and fine filters, gap analysis, and systematic reserve design to identify where those features are lacking sufficient protection and, in order to fill those deficiencies (Hunter et. al 1988; Margules and Pressey 2000). Recently, there has been renewed interest in land facets for their utility in incorporating climate adaptation into reserve planning. The concept is that by protecting abiotic features that currently host biodiversity, those features will continue to do so into the future, even if the biota they host changes due to climate change (Anderson and Ferree 2010; Beier and Brost 2010). CCI is interested in the land facets currently protected, as well as the applicability of land facets as a conservation measure for planning of future protected areas in the Crown of the Continent.

This report reviews the literature associated with systematic conservation planning, the incorporation of climate adaptation into conservation plans, and the use of land facets as a coarse-filter conservation measure. Data sources to apply this research in the Crown are identified and reviewed, and the methodology used to complete a land facet gap analysis in GIS (Geographic Information Systems) is described. Once gaps were identified, Marxan optimization software was used to identify reserve designs that efficiently meet the geodiversity conservation goals. That process is described and the results are summarized.

Both the gap analysis and Marxan reserve solutions showed a need for increased protection along the Eastern Slopes and in the southwest Crown. In both the United States and Canada, these areas include a mixture of federally and privately owned land. Given that both analysis methods show broad areas that are not adequately protected, it is suggested that these results may be best used to augment other conservation measures, rather than as a stand-alone measure for setting conservation priorities. This conclusion is supported by current practice of conservationists implementing land facets in their work (Lawler et al. 2015; Anderson et a. 2015).

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1.0 Introduction

The Crown of the Continent Ecosystem (CCE or Crown) encompasses approximately 18 million acres of the Northern Rockies, beginning in northwestern Montana and continuing into southern Alberta and British Columbia (Figure 1). The unique combination of northerly latitude, topography, elevation, and geology found in the Crown has attracted attention for centuries, leading to the establishment of protected areas in the form of national and provincial parks and wilderness areas. These designations afford the Crown more protection than similar sized tracts of land elsewhere, but still may not ensure the viability the ecosystem into the future.

There are a multitude of organizations working to further conservation in the Crown, including the Crown Conservation Initiative (CCI), based in Canmore, Alberta, and Bozeman, Montana. Formed in 2010, CCI's goal is to address climate change by facilitating collaboration between stakeholders and providing them with informational resources, including commissioning studies when applicable. Through these methods, CCI aims to implement, and assist its member groups in implementing, science-based climate change adaptation strategies in the Crown of the Continent. This collective of transboundary groups includes land trusts, academic institutes, and conservation non-profits who use a variety of strategies, including local, grassroots campaigns, to advocate for conservation (CCI 2014a).

For decades, conservation planners have evaluated various strategies for identifying areas of high productivity, high biodiversity, rare or endemic species, and intact habitat to be included in protected areas. In the early 1980s, The Nature Conservancy (TNC) began using coarse and fine filters to achieve this goal (Noss 1987; Beier et al. 2015). This strategy, now commonly used by many conservationists, utilizes coarse-filters to identify valuable, ecosystem-scale habitats, and the biotic life within them, while fine-filters target specific rare or specialized species. It is widely acknowledged that some level of climate change is inevitable and in order for current and future conservation to be most effective, climate adaptation must be included in the broader conservation planning process. The idea of using geodiversity, or land facets, as a coarse-filter has emerged as a possible method to incorporate climate adaptation into conservation portfolios (Hunter et al. 1988; Beier et al. 2015). The idea behind this strategy is that geodiversity as a coarse-filter will capture "stable land characteristics" which will not be altered by climate change and therefore provide a long-term platform for biodiversity (TNC 2015). This coarse-filter approach can then be combined with finer filters which identify endemic and rare species to be specially targeted.

Variables commonly used to define geodiversity include a combination of soil, geology, elevation, slope, and aspect. This data is readily available through remote sensing, which means geodiversity as a coarse-filter is applicable even in areas where traditional conservation planning has been hampered due to limited species-specific data. The growing field of Geographic Information Systems (GIS) has given rise to powerful software, able to process large amounts of spatial data and produce valuable map and statistical outputs, providing conservationists with robust tools to assist with landscape-scale planning. These approaches, combined with sound ecological research to inform conservation targets, create a powerful tool for setting planning priorities.

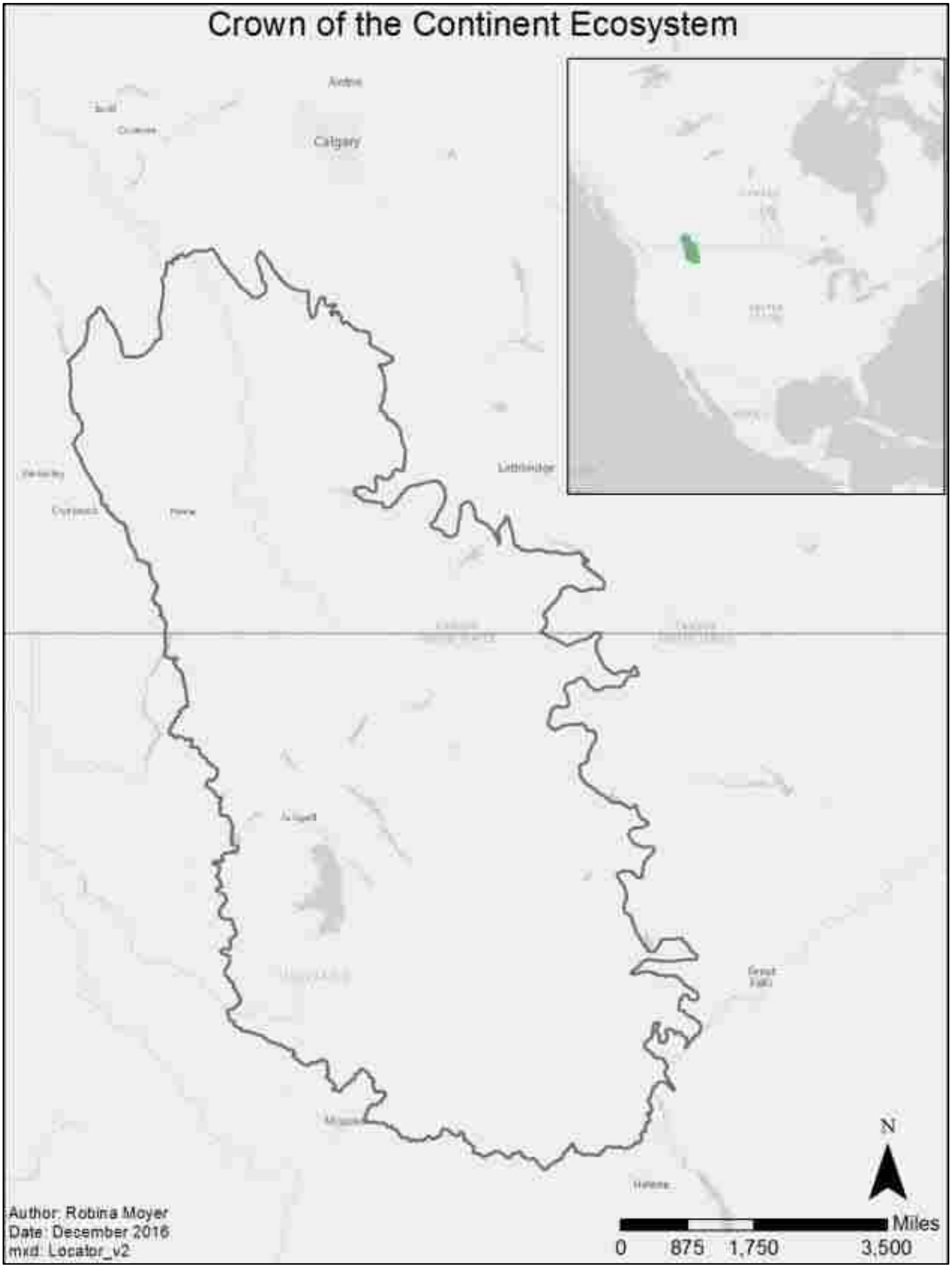


Figure 1: Map locating the Crown of the Continent Ecosystem within North America.

CCI is interested in using land facets as a conservation planning measure in the Crown of the Continent Ecosystem. Through the use of conservation planning literature, remotely sensed data, GIS, and Marxan optimization software, this report takes the first step in that process by identifying what land facets are present in the CCE, which are under-represented in existing protected areas, and how those deficiencies might be ameliorated. As the urgency of climate change increases, it is more important than ever to explore all possible options as to how climate adaptation measures can be incorporated into existing conservation in an effort to ensure the continued viability of countless global ecosystems.

2.0 Literature and Data Review

For decades, conservation biology has recognized the importance of preserving global biodiversity, particularly in the face of habitat loss, fragmentation, and degradation. With this goal in mind, a body of both theoretical and applied literature has been written regarding conservation planning, how to create effective reserve systems and protected areas, and more recently, how to incorporate climate change into these plans. From the outset, conservation planning necessarily includes an accepted amount of uncertainty; designating protected areas for specific species does not ensure that they will stay within that area and stochastic events such as wildland fires, avalanches, or hurricanes may alter habitat or species populations in unforeseen ways. In recent years, climate change has increased the amount and type of uncertainty that conservation scientists, planners, and resource managers must attempt to account for in their plans.

Potential outcomes of climate change, such as the extreme weather events mentioned above, have been criticized by some in the scientific community and are difficult to substantiate through models (Pielke 2010). Even with these limits, conservationists have attempted to use the models available in their work to preserve global biodiversity, predominantly through climate envelope modeling. This method typically includes a combination of other models such as carbon emissions, predicted precipitation and projected range shifts for a given species. Each of these inputs can contain considerable uncertainty, which is then propagated through their use in a climate model (Beier et al. 2015). Working with these challenges and uncertainty, conservation biologists are continuing to look for ways to supplement existing protected areas to ensure the persistence of biodiversity, particularly in those areas which may be most vulnerable to climate change (Mawdsley et al. 2009; Groves et al. 2012; Beier et al. 2015). This approach is known as climate adaptation planning and is not limited to conservation, it has also led to extensive literature in the fields of public policy and community planning. While often different in scope than conservation work, there are areas in which these fields overlap and inform each other. Authors from each field suggest there are opportunities for synergy in implementing climate adaptation measures that have both social and conservation benefits (Watson et al. 2011; VijayaVenkataRaman et al. 2012).

The following review covers a sample of the literature on conservation and conservation planning, climate adaptation as a way to mitigate climate change, the integration of climate adaptation into both conservation and social planning, and potential methods to achieve this. One approach, planning reserves which prioritize not just biotic diversity, but abiotic diversity as well, has recently gained attention and is reviewed closely. In addition, potential datasets for implementing this approach in the Crown of the Continent Ecosystem are reviewed.

2.1 Systematic Conservation Planning

A conservation ethic has been present in the United States since the turn of the century, embodied by such authors as John Muir (1875) and Aldo Leopold (1949), and codified with the establishment of the National Park Service in 1916. But it was not until 1973, with the passage of the Endangered Species Act (ESA) that the importance of biodiversity was legally recognized on a federal level (16 USC §1531-1544). While the ESA mandates specific protections of critical habitat for those species already listed, conservation planners work to protect and restore habitat, keeping additional species from being listed in the first place. In order to achieve this, a framework for identifying priorities and developing protected area reserves was necessary. In the early 1980s, The Nature Conservancy (TNC) began using a strategy of coarse and fine-filters to achieve this goal (Beier et al. 2015, Noss 1987). This strategy is now commonly used by many conservationists and it is generally recognized that coarse-filters are valuable for identifying ecosystem scale habitats, and the biotic life within them, while fine-filters target specific rare or specialized species. A common coarse-filter approach has been the use of vegetation communities as they are relatively static, convey a certain amount of information about the underlying soils, and can be mapped on a landscape level using remote sensing (Noss 1987).

In 2000, Margules and Pressey attempted to formalize this method by laying out a six-step process in their *Systematic Conservation Planning*. Their work established methodology for compiling species data, identifying conservation goals (or targets), assessing current protected areas and identifying new ones, implementing these actions and monitoring their effects. In 2002, Groves et al. expanded on this concept with the explicit goal of emphasizing conservation science in the process with *Planning for Biodiversity Conservation: Putting Conservation Science into Practice.* Their work covers much of the same ground as Margules and Pressey (2000) and they specifically recognize the contribution that *systematic* planning has made to the effective application of conservation planning. *Planning for Biodiversity Conservation* includes seven steps instead of six, with the additional step being an analysis of a conservation targets' ability to persist. Although the authors do not allude directly to climate change when making this point, it is a step toward the climate adaptation principles which recently gained traction. The framework laid out by Groves et al. has been used successfully by The Nature Conservancy to identify areas of which will effectively conserve biodiversity in a given ecoregion, though it is recognized that identification of these areas and the actual implementation of conservation are different.

One of the first steps in finding reserve designs that meet your study requirements is separating the study area into planning units. The shape of these units varies depending on design goals, they may be based on watershed boundaries, jurisdictions, or simply to break the study area into uniform units. When the latter approach is used, rectangular or hexagonal units are typically used (Nhancale and Smith 2010). In order to better understand the impact of planning unit shape and size on reserve design efficiency, Nhancale and Smith used Marxan conservation planning software to test a variety of alternatives (2010). They found hexagonal units produced less fragmented and more efficient reserve designs than rectangular units, thus bolstering the rationale for the use of hexagons in conservation planning.

2.1.1 *Gap Analysis*

Some form of gap analysis is included in the processes laid out by both Margules and Pressey (2000) and Groves et al. (2002). In its most basic form in conservation, a gap analysis is used to identify a specific variable which is under-represented in protected areas. Published in 1993, Scott et al.'s *Gap Analysis: A Geographic Approach to Protection of Biological Diversity* was the first paper to explicitly lay out the methodology which has become common in the decades since. Gap analysis is typically used to investigate a finite study area in relation to a specific set of criteria. Often these criteria include vegetation or land cover types, used as a surrogate for species-specific habitat. Traditional gap analysis relies on remotely sensed data, combined with input from conservation experts to set appropriate targets. These targets may have an additional spatial component and include an analysis of how target categories are distributed throughout the study area

2.1.2 *Conservation Targets*

Setting explicit conservation goals or targets is a necessary step of systematic conservation planning. Like gap analysis this is typically done for a finite area, in reference to specific criteria. There are competing schools of thought regarding if goals should be set to prioritize ecosystem health, or to account for the political and social challenges of implementing conservation (Noss et al. 2011; Locke 2013; MacKinnon et al. 2011; CBD 2010).

The Brundtland Report, also known as *Our Common Future,* is a publication of the United Nations World Commission on Environment and Development (WCED) that first introduced the concept of sustainable development (1987). The document covers a wide array of material, establishing current global conditions regarding development and conservation and suggests sustainable development as a way forward in an increasingly globabized world. The report does not lay out an explicit percentage of the terrestrial and marine environments that should be set aside for conservation, but calls for a tripling of the "nearly 4% of the Earth's land area" managed for conservation in 1987 (WCED 1987; Locke 2013).

In their 2012 editorial *Bolder Thinking for Conservation*, Reed Noss, Andrew Dobson, Robert Baldwin, Paul Beier, Cory Davis, Dominick Dellasala, John Francis, Harvey Locke, Katarzyna Nowak, Roel Lopez, Conrad Reining, Stephen Trombulak and Gary Tabor, some of the most prominent names in North American conservation, state their case for protecting half of the world's terrestrial and ocean environments. They argue that rather than being socially acceptable, conservation goals should be unapologetically based in ecology from the outset. They point to evidence that time and again, conservation targets set by scientists "far exceed targets set to meet political or policy goals" and with the continued worldwide loss of biodiversity, we need to reevaluate this deference to politics.

Locke echoes this sentiment in his 2013 *Nature Needs Half: A Necessary and Hopeful New Agenda for Protected Areas* where he discusses past conservation goals of 10-12%, suggested by the Convention on Biological Diversity (CBD) as being insufficient. As in the 2012 editorial, he addresses the fact that ambitious conservation targets are often curtailed to meet political and social expectations. He refers to this as self-censorship within the conservation community, acknowledging that many are reluctant to publicly promote a 50% target out of concern that it is unrealistic and they will not be taken seriously. However, Locke goes on to give examples throughout the world of ecosystems of which at least half have been successfully protected, and cites this as a reason for hope.

At the Tenth Meeting of the Conference of the Parties to the Convention on Biological Diversity (CBD) a set of targets were adopted in an effort to maintain global biodiversity and achieve the goal of “living in harmony with nature” (CBD 2010). Known as the Aichi Biodiversity Targets, these goals attempt to encompass many facets of conservation with succinct, easy to understand phrasing. Target 11 has gained considerable attention and calls for “at least 17 per cent of terrestrial and inland water areas…especially areas of particularly importance for biodiversity and ecosystem services [to be] conserved through effectively and equitably managed, ecologically representative and well connected systems of protected areas and other effective area-based conservation measures” by 2020 (CBD 2010). These goals were set in response to continued loss of biodiversity, despite previous global efforts by the CBD (MacKinnon et al. 2011). MacKinnon et al. found the final statement to be problematic as it gave a potentially wide definition to protected areas and left some countries, including their native Canada, struggling to interpret which protected areas counted toward the goal. In their opinion, it is unlikely that Canada will reach the 17% goal by 2020, let alone a higher target; however, they are optimistic that increased protection opportunities exist if the political and social will can be swayed.

Thus, various authorities suggest protected area goals for the conservation of biodiversity range from 17-50% depending on the driving factor behind their establishment. Based on this range in part, a mid-range target of 30%, seen as an achievable compromise between ecologically and politically driven targets, has been chosen for this analysis.

2.2 Climate Adaptation Planning

The definition of climate adaptation can differ depending on the source, but it has been broadly defined by the Intergovernmental Panel on Climate Change as an “adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities” (2007). From an applied perspective, climate adaptation literature typically falls into two categories: that which discusses man-made infrastructure and impacts to human lives or that which deals with conserving non-human biodiversity and habitat. In both cases, the concept of adaptation itself is grounded in a body of more esoteric literature that strives to define terms and establish its theoretical underpinnings. The body of literature discussing the definition of, and theory behind, adaptation is summarized in Section 2.2, the human applications are discussed in Section 2.2.1 and biodiversity and conservation literature is discussed in Section 2.2.2.

Bassett and Fogelman (2013) address that this is not the first time the concept and term “adaptation” has been popular in academic and policy literature. In the 1970s and 1980s, the concept of adaptation was proposed in relation to hazard planning as a way for communities to prepare for primarily natural disasters (Brookfield 1973). Over time the concept came under scrutiny from political economists and ecologists (Bassett & Fogelman 2013) as they felt it provided stop-gap solutions addressing symptoms, rather than the root of problems such as economically vulnerable populations and poorly placed development. In addition, economists argued that the concept relied on individuals making "rational" choices, but ignored the real-world financial and institutional context within which those choices were made. Given the increased inclusion of the concept of adaptation in climate change literature, Bassett and Fogelman set out to establish if the concept is "déjà vu or something new?" Based on their review of recent articles that discuss adaptation and the Intergovernmental Panel on Climate Change (IPCC) definition, they conclude that with few exceptions, the concept is mostly "déjà vu" and has not been updated to address the fundamental flaw of unsustainable development and the social and economic systems that create vulnerability in the first place. Their work serves to call into question the theory underlying the adaptation concept.

This article became the focus of academic debate when Lorenz et al. (2014) refuted the methodology used to reach the conclusion that the adaptation concept has not changed much since the 1970s. In this critique, Lorenz et al. suggest that by selecting four specific journals for their review, Bassett and Fogelman were overly subjective in their research parameters, thus biasing their results. Instead, they should have employed a systematic literature review (SLR) to analyze a larger selection of articles. In their rebuttal, the original authors argue that "SLRs are…a mismatch with the social sciences" and any study is subjective from its outset, based on the nature of the question you are asking (Fogelman & Bassett 2014).

Wise et al. (2014) summarize the frustrated sentiment that there has been much discussion of climate adaptation, but little actual implementation. They begin by arguing that since 1999, adaptation has been part of the climate change discussion, but application has been scarce. This is reflected in the literature, which they break into three categories: assessments of adaptation, which have found "limited evidence of actual adaptation action" and little attention to marginalized populations in adaptation plans (similar to the political economist critiques of adaptation discussed by Bassett and Fogelman); attempts to characterize the limitations of, and barriers to, climate adaptation; and literature which summarizes successful adaptation, which has primarily occurred in developing countries with resource-dependent communities who see an immediate improvement in their quality of life by implementing strategies which also increase their overall resiliency. The authors state that by discussing adaptation for nearly two decades, but failing to implement these strategies on an institutional scale, the effects of climate change are becoming undeniable and the time has come to re-conceptualize adaptation. Wise et al. urge those in the climate adaptation field to begin thinking outside of the box and consider options which up until now have been seen as "non-traditional" in order to encourage and increase implementation of adaptation on an institutional scale.

In *A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward?* Dittrich et al. (2016) echo Wise et al.'s conclusion that many adaptation strategies have been discussed but not implemented. They identify long term uncertainty as a possible reason for this and discuss several decision-making frameworks which may aid policy makers in when and how to incorporate climate adaptation, particularly in regard to infrastructure. The authors first discuss traditional decision-making approaches such as cost-benefit analysis, cost-effectiveness analysis and multi-criteria analysis; while these methods are well established, they are less applicable in scenarios such as climate change adaptation, where the costs are well defined, but the potential benefits are not. Rather than the aforementioned methods, Dittrich et al. suggest utilizing more robust approaches such as portfolio analysis, where the flaws of one approach will be balanced by another or real option analysis, which develops polices that can adapt over time depending on conditions. They next discuss several approaches to robust-decision making, acknowledging that some are costlier than others to develop and implement. A lower cost option is undertaking ‘low regret’ projects which will yield social and economic benefits regardless of the severity of climate change. The authors conclude that while different approaches are better suited to different scenarios, it is important that decision-makers begin to acknowledge that an investment today may no longer fit future circumstances and the best way to overcome that is by undertaking a robust-decision-making process.

2.2.1 *Climate Adaptation in Infrastructure and Community Planning Guidance*

In 2012, VijayaVenkataRaman et al. authored *A review of climate change, mitigation and adaptation* which seeks to explore some of the known causes and impacts of climate change, attempted mitigation measures, and potential social impacts. They find increased atmospheric concentrations of carbon dioxide and other greenhouse gases is leading to myriad environmental impacts, including rising sea levels, increased atmospheric and ocean temperatures, ocean acidification and melting ice sheets. Amongst other possibilities, these effects have the potential to impact worldwide agriculture, disrupt economic markets, and decrease food security. The authors review climate change mitigation and adaptation strategies that have been deliberated or implemented across the globe, with a particular focus on those policies which incorporate an economic component, aim to reduce carbon emissions, or promote carbon sequestration. The authors find that the impacts of climate change on the environment could be catastrophic – disrupting ecosystem services which provide humans with clean air and water, and decreasing global biodiversity. In turn, these combined with other impacts may have far reaching social and economic implications. They conclude that the synergy between mitigation and adaptation should not be underestimated and find that to be most effective in responding to climate change, local policies must be nested within national and global strategies, particularly when it comes to lower CO_2 emissions.

Included in *Applied Geography’s* “Health Impacts of Global Climate Change” Special Issue, Rodima-Taylor et al. set out to analyze the social dimensions to climate change in their *Adaptation as innovation, innovation as adaptation: An institutional approach to climate change* (2012). With the perspective that the most effective responses to climate change are place-based and require innovation, they argue that there is a disconnect between climate science and policy, which has resulted in research that is not easily applicable in the real world. Thus, innovative research should be based on policy needs and it should be geared toward solutions which can be integrated on both the local and global level, as these policy levels have become more intrinsically connected than ever before.

2.2.2 Climate Adaptation in Conservation Policy and Planning

2.2.2.1 Overview of Conservation Planning and Climate Change

Mawdsley et al. (2009) reviewed climate change adaptation literature and plans from five countries and identified sixteen general adaptation strategies that relate to conserving biological diversity. They break these strategies into those related to landscape protection, species specific conservation, monitoring and planning, and changes to law and policy. Many of the strategies in the first category are tools already utilized by natural resource managers, such as increasing the extent of protected areas, improving species and/or habitat representation and replication with protected areas, improving the management of existing protected areas to increase resilience (i.e. managing invasive species and restoring riparian areas), managing for holistic ecosystem function rather than specific species, and protecting and increasing movement corridors and landscape permeability. Species specific approaches include focusing conservation resources on at-risk species, translocating species, and reducing non-climate stressors. The authors conclude that while the familiarity of these tools may be reassuring, it is now necessary to view them through the lens of climate change, rather than business as usual.

Heller and Zavaleta's (2009) analysis was born out of a meeting of local resource managers searching for practical climate adaptation strategies they could apply in their daily work. With this starting point, the authors systematically review twenty-two years of climate change-related articles which included action recommendations. From these results, they synthesized a list of the most prevalent recommendations found in 121 articles. Their review produced a comprehensive list, with top recommendations including increasing connectivity between reserves, integrating climate considerations into existing planning such as grazing limits and reserve design, mitigating non-climate stressors, focusing conservation efforts on at-risk species, and improving inter-agency and regional coordination. This last point is one of the over-arching themes the authors identified. Given the likelihood of climate-induced range shifts for many species, it is more important than ever that agencies and other managers work cooperatively to create viable, regional management plans.

Acknowledging that in an effort to protect all biodiversity, even that of which we do not have explicit data, conservation planning has always relied on surrogates, Rodrigues and Brooks attempt to evaluate the effectiveness of these surrogates (2007). The authors layout the two typical categories of surrogates: a habitat, usually defined by land cover or vegetation-type, or another taxa which is easier to study and enumerate. They argue that understanding surrogacy effectiveness is crucial to effective conservation planning and efficient allocation of limited financial resources. The majority of the studies assessed use cross-taxon surrogates and found them to be effective when used within the intended realm – i.e. using terrestrial surrogates for a terrestrial target species rather than an aquatic one. They reviewed fewer surrogates based strictly on abiotic environmental data, but found them to be less effective in representing biodiversity.

In what is in many ways an update to *Planning for Biodiversity Conservation: Putting Conservation Science into Practice* (Groves et al. 2002), Groves et al. highlight climate change in their 2012 article. The study proposes five approaches to integrating climate change adaptation into existing and new conservation planning. The first strategy is to conserve the geophysical stage; however, they acknowledge that this approach has limitations and is likely to serve as an adequate surrogate for some, but not all species. In addition, it assumes that biodiversity is the primary conservation objective for a given area. The second strategy they suggest is protecting climatic refugia, typically defined as those locations likely to be least impacted by climate change. Refugia are inherently place-based and will thus differ from place to place, but may include locations with high topographic diversity, creating a high number of microclimates. The third and fourth approaches, enhancing regional connectivity and sustaining ecosystem functions, are more typical to conservation planning. Lastly, the authors suggest capitalizing on opportunities that emerge as a result of climate change, particularly in the social arena. As society becomes more aware of, and willing to act on climate change, there may be opportunities to allocate more money to climate adaptation strategies that will benefit both people and biodiversity.

In 2013, Hameed et al. published *The Value of a Multi-faceted Climate Change Vulnerability Assessment to Managing Protected Lands: Lessons from a Case Study in Point Reyes National Seashore*, in which they developed a site-specific climate change vulnerability assessment (CCVA) and presented it to managers for feedback. The goal of their CCVA was to evaluate "exposure, sensitivity, and adaptive capacity of organisms or biological communities to climate change" (2013). To achieve this, they integrated four facets: expert opinion, predictive vegetation mapping, predictive geophysical mapping and species-specific evaluations. Expert opinion was established through the Delphi method: soliciting the input of multiple experts, synthesizing their responses and redistributing them to the group for review and feedback. The authors found that similar patterns of predicated land change emerged from the first three methods. Overall, managers felt that they were better prepared to address climate change issues than they were prior to the CCVA. The authors acknowledged that the CCVA does not eliminate uncertainty, but with the appropriate inputs is capable of providing managers with a suitable tool for incorporating climate change into their work.

In the comprehensive report *Designing Landscapes for Biodiversity Under Climate Change: Final Report* and the succinct summary *Designing Landscapes for Biodiversity Under Climate Change: Summary for Landscape Managers And Policy Makers*, Doerr et al. (2013) lay out the ways in which current approaches to landscape design may be insufficient to deal with the impacts of climate change and summarize the salient points from their case studies. These include: act locally, while coordinating efforts on a landscape scale; pair restoration efforts with management of invasive species; focus efforts on priority landscapes; and acknowledge that there will inevitably be 'climate losers' that are unable to adapt, regardless of the effort put in to restore them.

Similar to the sentiments echoed above, Cross et al. have promoted transforming the conversation surrounding adaptation into action in their 2012 article *Accelerating Adaptation of Natural Resource Management to Address Climate Change* and Cross' related 2014 presentation "Moving beyond climate change impacts to adaptation actions." Through both these media, Cross et al. present an "Adaptation for Conservation Targets Framework" (ACT) which lays out a six-part process for resource managers to implement adaptation strategies. This iterative process begins with selecting a conservation feature and management goal, assessing the potential effects climate change will have on it, identifying points at which intervention and management activities can be implemented, prioritizing those actions, implementing those actions and monitoring their effectiveness. The first four steps constitute the planning phase, and practitioners are encouraged to reevaluate their goals as necessary prior to implementation. With ACT, Cross et al. provide managers with a step-by-step process to transform adaptation planning from an abstract concept, to a tangible component of their management plan.

2.2.2.2 *Species-Based Adaptation Planning*

Watson et al. (2012) review different approaches to integrating climate change planning into conservation planning with the explicit goal of maintaining biodiversity. Similar to other articles, they advocate the continuation and augmentation of existing practices, such as creating robust reserve systems, while also identifying species specific vulnerabilities and developing those into larger conservation plans. The authors go on to outline the characteristics that they believe constitute a good adaptation strategy; these include: incorporating flexible and efficient planning principles, accounting for uncertainty, understanding trade-offs, managing for long-term climate change and short-term climate variability, integrating human response, and setting clear adaptation goals. Their final point addresses the issue that adaptation can be a strategy to achieve resilience – systems that can absorb rapid change, or resistance – systems that are immune to rapid change, and many adaptation plans are not clear about which of these they are trying to achieve.

2.2.2.3 *Climate Adaptation Planning in the Crown of the Continent Ecosystem*

There has been a variety of climate change specific research done in the Crown of the Continent and Regan Nelson's *A Climate Change Adaptation Gap Analysis for the Crown of the Continent* pulls together much of it, along with expert and local opinion, to identify and prioritize adaptation measures that can be implemented in the Crown (2014). A gap analysis was completed for three ecological processes and six species important to the Crown and suggestions were made as to filling gaps in their protection. The utilization of land facets, covered in this report, was one of Nelson's recommendations for implementing climate adaptation in relation to addressing changing forest composition (2014).

2.2.2.4 *Landfacet/Geodiversity-Based Adaptation Planning*

Malcom Hunter, George Jacobson, and Thompson Webb first proposed using land facets as coarse-filter approach to conserving biodiversity in 1988, without the lens of climate adaptation (Beier et al. 2015). At the time, the idea was attractive because the inputs – elevation, soil, landform, HLI – could be derived via remote sensing, making it applicable to areas without extensive land cover or species distribution data (Hunter et al. 1988). In recent years, the concept has regained popularity for its utility as a coarse-filter when assembling climate adaptation based conservation portfolios. Several conservation scientists, as well as The Nature Conservancy (TNC), have embraced land facets for their potential effectiveness as surrogates for both current and future biodiversity, based on the premise that these "stable land characteristics…will not change in a changing climate" and therefore will provide a long-term platform, or stage, for biodiversity, even if the specific communities they host change over time (TNC 2015). In the course of this embrace, TNC has coined the term "conserving nature's stage" or CNS. In 2015, *Conservation Biology* devoted a special section to CNS.

In 2010, Anderson and Ferree, both with The Nature Conservancy at the time, published *Conserving the Stage: Climate Change and the Geophysical Underpinnings of Species Diversity,* an analysis of the correlation between geology and elevation and biodiversity completed for 14 U.S. states and three Canadian provinces. Within this study area, they had data for 18,700 known occurrences of rare species. Overall, they found a positive correlation between the occurrence of specific types of geology and rare species. This held for geologic diversity as well, with the nearly equal-sized states of Maryland, Vermont and New Hampshire having significant species diversity that corresponded to the geologic diversity. The authors concluded that geology and elevation showed enough of a positive correlation with biodiversity to argue for the inclusion of abiotic factors when developing long-term conservation strategies for climate change.

In the same year, Beier and Brost published *Use of Land Facets To Plan For Climate Change: Conserving The Arenas, Not The Actors,* supporting the utility of land facets in conservation planning (2010). They based much of their argument on the belief that existing climate-envelope models attempt to integrate separate models (i.e. emissions, global air circulation, or projected species response), each with their own uncertainty. By combining these models, the uncertainty may be amplified, leaving conservation planners and resource managers attempting to plan for scenarios that vary widely from one model to the next. By conserving "the arenas of biological activity, rather than the temporary occupants of those arenas" managers can attempt to plan for the present and the future.

In the June 2015, special section of *Conservation Biology,* guest editors Paul Beier, Malcom Hunter, and Mark Anderson open by reiterating the limitations of climate-envelope models, which are typically focused on one species and as stated above, can propagate the uncertainty of each individual component (Special Section). They cite its recent use in studies such as Anderson and Ferree (2010), the need for greater integration of climate adaptation into more traditional planning, and CNS' reliance on data already readily available as reasons it should be adopted by more planners.

Lawler et al. go on to expand on these sentiments in *The Theory Behind, and the Challenges of, Conserving Nature's Stage in a Time of Rapid Change* (2015). They too discuss the need for forward looking conservation planning, managers can no longer assume that what works today will work tomorrow, and incorporating land facets may be one way to ensure future biodiversity. They also emphasize that this should be seen as a coarse-filter approach and not used to the exclusion fine-filter methods, or other established conservation priorities for a given area.

In *Case Studies of Conservation Plans That Incorporate Geodiversity,* Anderson et al. analyze eight case studies that have used geodiversity as a surrogate for biodiversity (2015). They conclude that there are for steps to keep in mind when using geodiversity: "create land units based on species-relevant variables combined in an ecologically meaningful way; represent land units in a logical spatial configuration; apply selection criteria to individual sites to ensure they are appropriate for conservation; and developed connectivity among sites" (Anderson et al.

2015). Their analysis enhances the utility of existing geodiversity for those considering use of this strategy in their work.

Comer et al. echo many of the opinions above, but expand beyond the ecology behind geodiversity and discuss how to incorporate geodiversity into decision making and policy (2015). They conclude that with the increasing urgency of conservation due to climate change, the potential importance of including geodiversity for the biodiversity it may host in the future benefits should not be overlooked. They argue that with climate change, conservation scientists should implement more robust monitoring and reassessment – an accelerated version of the cycle described by Margules and Pressey (2000) and Groves et al. (2002) – that puts increased emphasis on the utility of preserving a full suite of land facets in order to better address climatic uncertainty.

2.2.3 *Summary*

The above articles highlight the increased importance of continuing and bolstering existing biodiversity conservation efforts, as well as developing new and innovative methods in the face of climate change. Section 2.2.1 emphasizes that this work is not limited to conservation and is becoming increasingly important across all facets of life. The importance of a systematic approach to conservation planning has been established, especially when trying to meet specific goals, such as those laid out in Aichi Target 11 (Margules and Pressey 2000, CBD 2010). The incorporation of land facets, or geodiversity, into planning may be one way to continue systematic planning while incorporating climate adaptation.

Given the relatively recent inception of CNS, there is not yet an agreed upon standard for what data should be used to define the land facets; each study is dependent on what types of data, and at what spatial resolution, are available for the study area. Commonly included variables include some combination of soil, geology, elevation, slope, and aspect. The aforementioned data are readily available, often from more than one source, and conservationists have begun creating land facet layers to be used in coarse-filter climate-adaptation conservation planning. The following section reviews available data sources for the Crown of the Continent Ecosystem.

2.3 Land Facet Data Sources

2.3.1 *AdaptWest*

AdaptWest is “A Climate Adaptation Conservation Planning Database for Western North America” produced by the Klamath Center for Conservation Research and hosted on DataBasin.org. In recent years, AdaptWest has created a variety of datasets to be used by the conservation community including: climate, climate velocity, land facets, and ecoregion climate data (Klamath Center for Conservation Research 2015, DataBasin 2015). Originally published in 2015, the AdaptWest land-facet dataset was created by Klamath researcher Carlos Caroll and landscape ecologist Julia Michalak and encompasses Western North America, including the Canadian provinces of Alberta and British Columbia, and the Yukon Territory; it has since been updated to include all of North America (2016). The AdaptWest land-facet layer was created using elevation, landforms, soils, and heat load index (HLI) as input variables.

2.3.1.1 Elevation

Elevation data was obtained from the Shuttle Radar Topography Mission (SRTM v4.1) for regions below 60° North. The Crown of the Continent Ecosystem extends to 50°N, therefore all elevation data for the study area is from SRTM. The SRTM data was resampled from 90 meter to 100 meter resolution. For regions north of the Tropic of Cancer (23.5°N), elevation was adjusted using a linear equation to account for decreased temperature and its potential impact on vegetation communities (Michalak et al. 2015, Colwell 2008). The five resulting classification bins adequately represented the diversity of the mountainous west, but left the topographic extremes – Alaska and the flat Southwest – lumped into bins on respective sides of the classification. To address this these classes were further subdivided to more accurately represent elevation ranges within the regions (Michalak et al. 2015). This classification resulted in ten latitude-adjusted elevation classes.

2.3.1.2 Landforms

A landform layer was created by adding a slope layer and a "Topographic Position Index" (TPI). The TPI was created using an ArcGIS Spatial Analyst Extension created by Jeff Jenness (2006). This index allows the user to represent the difference in elevation between the focal cell and the mean elevation values of its neighbors within a specified area. For this dataset a TPI was created using a 500 meter neighborhood window to show local topographic diversity, and a second TPI was created to show landscape level topographic diversity, using a neighborhood 2 km window (Michalak et al. 2015). Slope was classified into one of three categories: less than 2°, 2 to 5 degrees, and greater than 5 degrees. The resulting slope raster was combined with the TPI to create the landform layer (Michalak et al. 2015).

2.3.1.3 Heat Loading Index (HLI)

The HLI was created by integrating slope and aspect in order to quantify potential solar radiation, identifying relatively warm and cool areas within the region. The resulting HLI layer has three classifications: cool, neutral, and warm. All pixels defined as "plains" based on their slope value were automatically classified as neutral, while other pixels were given one of the three classifications based on their HLI number (Michalak et al. 2015).

2.3.1.4 Soil Classification

The Harmonized World Soil Dataset (HWSD), which has roughly 1 km spatial resolution, was used for the soil layer. Data was classified using soil order; 38 orders were included. Although finer resolution soil data is available in the United States and parts of Canada, it was not available for Western Canada and therefore the HWSD was the best option to avoid introducing any resolution bias (Michalak et al. 2015).

2.3.1.5 AdaptWest Methodology

Once the variables were processed appropriately, they were used to create two products: a raster with Facet ID values and a "TopoFacet" raster. Due to the significantly coarser spatial resolution of the soil data than the other inputs, it is excluded from the TopoFacet raster in order to produce a finer resolution product (Michalak et al. 2015).

The algebra behind these is:

$$\text{Facet ID Value} = (\text{Landform} + \text{HLI} + \text{Elevation}) \times 100 + \text{Soil Order}$$

$$\text{TopoFacet} = \text{Landform} + \text{HLI} + \text{Elevation}$$

2.3.2 United States Geological Survey

The United States Geological Survey, in cooperation with the Association of American Geographers, the Group on Earth Observations, and the Environmental Systems Research Institute (ESRI) recently published "A New Map of Global and Ecological Land Units" (Sayre et al. 2014). This dataset has global coverage (Figure 2) at 250 m spatial resolution and is a "classic physical geography approach to understanding ecological diversity" (Sayre et al. 2014). The ecological land units (ELUs) published in this dataset are beneficial for a variety of users. One identifed use is as a surrogate for vegetation classificiations in remote areas where remotetly sensed vegeation data can not be realistically ground truthed (Sayre et al. 2014). The amount of information available in this dataset is staggering and has many potential uses for conservation planning. The ELU dataset was created using climate regime (bioclimate), geology (lithology), landforms, and land cover layers as input variables. The inclusion of climate regime and land cover layers separates this dataset from the other two reviewed here, which include strictly abiotic inputs.

Figure 2: ELU Dataset Coverage Area. Image reproduced from Sayre et al. 2014, 24.

2.3.2.1 Bioclimate

The bioclimate layer is based on a modified version of the Global Environmental Stratification (GEnS) dataset published by Metzger et al. (2013). The original dataset was created with 1km temperature and precipitation data obtained from WorldClim. This data was classified using a Principle Component Analysis (PCA) which resulted in 125 clusters; these were further aggregated into 18 climate zones (Sayre et al. 2014). For inclusion in the ELU dataset, the 1km cells, representing 18 climate zones, were subdivided to 250m cells. It was assumed that the information within each 1 km cell was homongenous and therefore each of the resulting 16 subdivided cell was assigned the same value.

2.3.2.2 *Landforms*

There was not an existing global landform dataset, so for this project the USGS created one based the landforms concept as first proposed by the Missouri Resource Assessment Partnership (MoRAP) and developed by True (2002). This model has been used to create a 30 m landform layer for the United States, parts of Africa and Europe (Sayre et al. 2014). In order to have uniform resolution across the study area, these datasets were not used and instead 2010 Global Multi-resolution Terrain Elevation Data 2010 (GMTED) data was used to create a global, 250 m resolution, digital elevation model (DEM). A neighborhood analysis was run using a 1 km circular window to calculate slope and relative relief of each pixel. Pixels in the output were assigned a value of "gently sloping" (less than 8%) or "sloping" (greater than 8%) and relative relief was calculated as the difference between maximum and minimum elevation for each neighborhood (Sayre et al. 2014). Relative relief values and slope were added together to create the landform layer.

2.3.2.3 *Lithology*

The lithology layer was created using the Global Lithology Map (GLiM), created by Hartmann and Moosdorf (2012), which uses 16 lithological classes to describe rock at the earth's surface. This information "essentially reflect[s] areas of different substrate chemistry" and can therefore be a good surrogate for soil type and provide information about potential growing conditions (Sayre et al. 2014, 14). The GLiM was created from 92 regional lithology maps and originally produced as a vector layer with over 1 million polygons. The estimated average GLiM dataset scale is 1:3,750,000; similar to the bioclimate data, GLiM data was subsampled to produce 250 m cells with the assumption of homogenity within each polygon (Sayre et al. 2014). While the details of their subsampling method are not described, it is stated that subsampling is not an attempt to artifically enhance the resoltuion of the data, but rather to create input rasters of comperable resoltuion. Addititionally, it is acknowledged that this method may overlook "a considerable amount of heterogenity" in the data (Sayre et al. 2014).The output layer preserved the 16 litholigcial classes.

2.3.2.4 *Landcover*

For land cover, the USGS used the GlobCover dataset, produced by the European Space Agency and the Université Catholique de Louvain (Arino et al. 2008). This dataset has 300 m resolution and includes 23 land cover classes, interpreted from Medium Resolution Imaging Spectrometer (MERIS) satellite data. Since the beginning of the project a 30 m global dataset became available. But as it has only 14 land cover classes, its incorporation into future products would sacrifice classification resolution for spatial resolution (Sayre et al. 2014).

2.3.2.5 *Methodology*

Given these variables, the data was processed using the model shown in Figure 3.

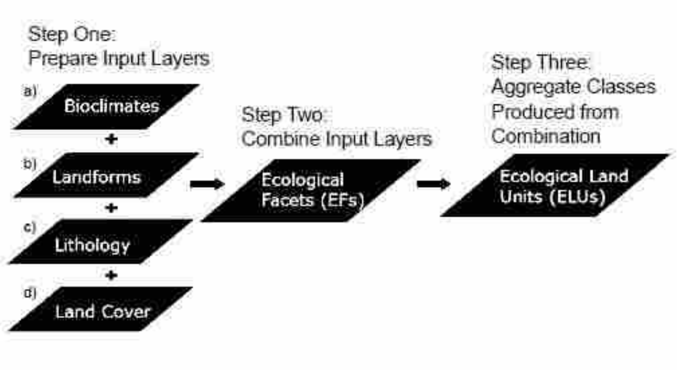


Figure 3: Data processing model used by USGS et al. to create Ecological Land Units. From Sayre et al. 2014, 11.

The ecological facets (EFs) produced in step two above resulted in the creation of 48,872 unique values; too many to be easily represented cartographically. To address this, Sayre et al. removed 1,222 suspect combinations (i.e. hot and wet bioclimate matched with ice land cover) and reclassified the remaining EFs, resulting in 3,923 ecological land units. Originally, a statistical method was explored to accomplish this reclassification, but was found to be inefficient due to the large volume of data and complications resulting from using categorical versus continuous data (Sayre et al. 2014). Instead, existing classes were generalized, so as to output fewer data categories (i.e. landform classes broadened to include only plains, hills, and mountains).

The resulting ELUs were named based on the information they contained, avoiding the step of deciding on what additional classification system to use. The authors have noted this as both a strength and weakness of the dataset and anticipate that users will apply local terminology to ELUs as appropriate. Due to the large volume of data produced by this methodology, a randomly-selected, field verified, accuracy assessment is unrealistic. To date, a small subset of the data has been field verified using a combination of selected and random points. Verification has been done using 300 m resolution satellite imagery from ESRI's World Imagery product in combination with user provided, on-the-ground photos.

2.3.3 *The Nature Conservancy*

The Nature Conservancy's "Resilient Terrestrial Landscape" dataset was created to identify sites in the Pacific Northwest (PNW) which may continue to support biodiversity in a changing climate (Figure 4; Buttrick et al. 2015). A similar approach has been used by TNC in the eastern United States (Anderson et al. 2010) and parts of that study were used as a model for the PNW dataset. The PNW project hopes to identify areas with high resiliency potential based on land facets and integrate them with permeability and topoclimatology (temperature range and soil moisture) diversity to identify sites with high climate adaptation potential, with the goal of ultimately including these locations in their conservation portfolio (Buttrick et al. 2015). The resulting outputs of this project include a land-facet layer and a terrestrial resilience layer, both of which cover the United States portion of the PNW at 270m resolution.

The TNC land facet layer was created with soil, elevation, and slope as input variables. An additional output of this study was a terrestrial resilience layer. This layer product included temperature range, soil moisture, permeability, and current conservation lands as inputs. The land facet variables are discussed below; both outputs are discussed in methodology.

Figure 4: TNC Dataset Coverage Extent showing land facet output.
Image reproduced from Buttrick et al. 2015, 28.

2.3.3.1 *Soil*

A soil layer was chosen as an input because of its potential to represent vegetation communities better than geology in the American West (Buttrick et al. 2015). The United States Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS) State Soil Geographic (STATESGO) data was used for the eastern portion of the project area, while the finer resolution NRCS Soil Survey Geographic (SSURG) dataset was used for the western portion of the project area (Buttrick et al. 2015). The extent of both datasets is limited to the United States. The use of these datasets resulted in the inclusion of 10 soil orders in the analysis.

2.3.3.2 *Elevation*

The TNC study area has a significant elevation gradient, ranging from sea level to over 3,200 meters, to encompass this, a USGS National Elevation Dataset (NED) DEM with 30 m resolution was used with class breaks at 600 m intervals, resulting in 7 unique categories (Buttrick et al. 2015).

2.3.3.3 *Slope*

A slope layer was created by resampling the NED DEM into three classifications: less than 6 degrees, 6 to 18 degrees and greater than 18 degrees.

2.3.3.4 *Methodology*

An additional goal of the TNC study was to create a repeatable methodology that could be applied to other landscapes. As a result, several approaches were considered when developing their methodology and TNC worked closely with Dr. Joshua Lawler, a conservation biologist at the University of Washington, who was exploring similar research questions. Lawler analyzed three approaches: statistical clustering based on similarity; an overlay that combined geographic distribution of land facets and identifies unique intersections of facets; and a hybrid of the first two methods (Buttrick et al. 2015). Ultimately, 162 unique land facet classifications were created for the study area based on the following model:

Land Facet = Soil + Elevation + Slope

A separate terrestrial resilience layer was created based on these equations:

Topoclimate diversity = Temperature range + soil moisture

Permeability = degree of development + land use conversion

Terrestrial Resilience = topoclimate diversity + permeability

A 450 m window was used to perform a neighborhood analysis in the creation of the topoclimate diversity layer.

2.3.4 Discussion of Land Facet Layers

While all three datasets discussed include similar initial inputs, the final outputs vary significantly in resolution, level of classification, extent of data manipulation, and intended use. Table 1 compares several attributes of the datasets.

Table 1: Selected attributes for AdaptWest, TNC, and USGS land facet datasets

	AdaptWest	**TNC**	**USGS**
Inputs	Elevation, Landforms, Soils, HLI	Elevation, Slope, Soil	Climate Regime, Geology, Landforms, Land Cover
Spatial Resolution	100 m	270 m	250 m
Extent	Western North America	U.S. Pacific Northwest	Global
Intended User	Conservation	Conservation	Conservation, Ecology, Economic Planning

2.3.4.1 Complexity/Data Transparency

The USGS dataset in particular has straightforward inputs that have undergone minimal reclassification and raster algebra. The AdaptWest data set includes slightly more complex variables, but all classification, algebra and indices are well documented, allowing the user to easily recreate the methodology and track the steps taken to create the final output. Although this is a stated goal of the TNC dataset, many of the technical details, including resolution of input variables, are buried in the appendices of accompanying report, making it more difficult to follow the data flow. However, due to the limited size of the study area, the TNC report does provide more robust information about the history, theory, and physical characteristics of the study area than the other publications. This strength of the TNC dataset could be seen as weakness of the AdaptWest data. While AdaptWest includes good technical documentation, there is less contextual background in the associated report; the assumption being the user is familiar with the study area. The USGS report provides a solid overview of the technical methodology and theoretical history and is the only dataset to address the need for an accuracy assessment.

2.3.4.2 *Resolution/Spatial Extent*

The USGS dataset is impressive for its 250 m global coverage. However, for use at a regional scale, its subsampling of 1km bioclimate data and variably scaled lithology data, could be problematic. Given that more accurate data is available for the CCE, it may make sense to use an alternative land facet layer for this region. By assuming that these larger areas are homogenous, significant local land facet variation could be lost during subsampling.

While the TNC dataset contains higher resolution inputs compared to the USGS data, its use for analyzing the CCE is limited given its exclusion of the Canadian portion of the Crown. The TNC product is otherwise robust with a well-documented (albeit buried) methodology and more history than the other datasets, particularly when Anderson’s work on the east coast is considered. It is unfortunate that the data stops at the Canadian border, particularly given the highly interconnected, transboundary ecosystems of the American West.

Of the three datasets analyzed, the AdaptWest dataset has the highest spatial resolution and the dataset extent aligns most closely with the CCE, making it preferred for this project.

2.3.4.3 *Summary*

An exploration of the input variables of these land facet datasets provides an understanding of the type of data available for the CCE region and how it may impact the final product. While the TNC and USGS dataset have important strengths, the AdaptWest dataset seems the best option for use in a geodiversity gap analysis for the CCE because of its input parameters, spatial resolution, coverage extent, and the flexibility afforded by having both land and topo facet data.

3.0 Methods

3.1 Data Collection

Once preferred data sources, such as AdaptWest, were identified, GIS data was downloaded from those sources. Additional spatial data, such as Crown Ecosystem boundaries, protected areas, and jurisdictional data was downloaded from a variety of sources as described below.

3.1.1 *Crown Managers Partnership*

Given that the project crosses an international boundary, finding datasets that covered the entire study area, rather than piecing together data from multiple jurisdictions was preferred. The Crown Managers Partnership (CMP), a working group of resource managers in the CCE, has created and compiled GIS data for the CCE, including land ownership, road and railways, watersheds, and the generally agreed about boundary of the CCE. This data is available on ScienceBase, a geospatial data library hosted by the United States Geological Survey (CMP: TCI 2016). All available CMP geospatial files were downloaded from ScienceBase as a data bundle, though only some of these files were used. All data was projected in a North American Datum (NAD) 1983 Universal Transverse Mercator (UTM) Zone 11 North Coordinate System and pre-processed to have the same resolution and extent across federal and provincial boundaries.

3.1.2 AdaptWest Land and Topo Facets

Review of available datasets identified AdaptWest as the best suited land facet dataset as it covers the entirety of North America. AdaptWest's land facet data is hosted on Data Basin, a "science-based mapping and analysis platform" (AdaptWest 2015). AdaptWest has land facet data, topo facet data, and the corresponding data descriptions, available for download separately or individually. The complete AdaptWest land facet dataset, including associated spreadsheets with additional details about each facet's unique factors, were downloaded. The AdaptWest dataset has 100 meter resolution, meaning each pixel is 100 m in length on each side and has an area of 10,000 m^2, the equivalent of 1 hectare or 2.47 acres.

Each unique land or topo facet is given an identification number based on the sub-values of each factor, such as landform, HLI, elevation and soil order. Landform values range from 1-9; HLI values can be 0, 100, or 200 (neutral, cool, and warm respectively); adjusted elevation class ranges from 1-10; and soil order ranges from 1-35. For example, valleys are given a landform value of 1000, a neutral HLI is given a value of 0, an elevation of 0-200 meters is given an ID value of 1, and acrisols are given a value of 1; therefore, these sub-values are combined as shown in Figure 5 to create a land facet value of 100101. Topo facet values follow the same order, without the last two digits for soil ID. Table 2 shows a sample of land facet values and sub-values; Table 3 shows a sample of topo facet values and sub-values.

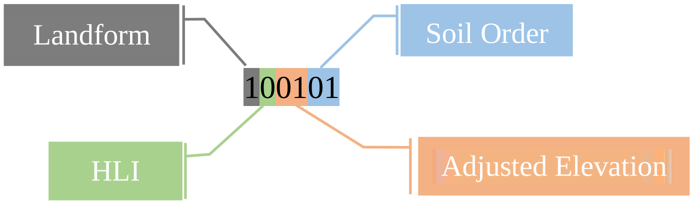


Figure 5: Diagram explaining how each sub-value corresponds to the digits in land facet values

Table 2: Example of AdaptWest land facet values and their corresponding sub-values.

Value	**Landform ID**	**Landform**	**HLI ID**	**HLI**	**Adjusted Elevation ID**	**Adjusted Elevation (meters)**	**Soil ID**	**Soil Order**
100101	1000	Valley	0	Neutral	1	0- 200	1	Acrisols
110701	1000	Valley	100	Cool	7	4500- 5000	1	Acrisols
200101	2000	Hilltop in Valley	0	Neutral	1	0- 200	1	Acrisols
300101	3000	Headwaters	0	Neutral	1	0- 200	1	Acrisols
320201	3000	Headwaters	200	Warm	2	200- 800	1	Acrisols

Table 3: Example of AdaptWest topo facet values and their corresponding sub-values.

Value	**Landform ID**	**Landform**	**HLI ID**	**HLI**	**AdjEl ID**	**AdjEl**
1001	1000	Valley	0	Neutral	1	0- 200
1101	1000	Valley	100	Cool	1	0- 200
2101	2000	Hilltop in Valley	100	Cool	1	0- 200
2102	2000	Hilltop in Valley	100	Cool	2	200- 800

3.1.3 *International Union for the Conservation of Nature (IUCN) Protected Areas*
IUCN protected area geospatial data was not readily available to download through the IUCN website. Given the science and conservation mission of Data Basin, it seemed possible that they, or one of their users, would host this data and a search was performed on Data Basin using the term "IUCN protected areas." This returned several results, all of which were broken into geographic regions. No one layer for the entire CCE, but the Conservation Biology Institute had uploaded a series of protected area layers, including "Protected areas of Northern Mountain States (USA) 2008" and "Protected areas of Canada 2008" (CEC 2008a, CEC 2008b). Originally published by the Commission for Environmental Cooperation (CEC), these layers had the same metadata, resolution, and were based on the IUCN definition of protected areas. Both layers were downloaded.

3.1.4 *The Nature Conservancy Lands*
In addition to IUCN protected areas, land owned or leased by The Nature Conservancy was considered to be a protected area. This data was downloaded as two layers, "TNC Lands Montana" which includes conservation easements, grazing permits and fee lands and "Transferred TNC Lands Montana" from TNC's geospatial data portal (TNC 2016).

3.1.5 *Bob Marshall and Scapegoat Wilderness*
As a result of the 2014 passage of the Rocky Mountain Front Heritage Act, the Bob Marshall and Scapegoat Wildernesses, both in the Montana portion of the CCE, have recently been expanded. This expansion is not yet reflected in the IUCN protected area layers obtained from CEC. Instead, updated boundaries were downloaded from wilderness.net, a collaborative website run by The University of Montana, the Arthur Carhart National Wilderness Training Center, and the Aldo Leopold Wilderness Research Institute, which provides history, policy, and geospatial information about wilderness areas in the United States.

3.1.6 *Castle Wildland Provincial Park*
For decades, conservation groups have urged the government to provide protections for the Castle-Crown area in Southwestern Alberta. In September 2015, this goal was finally achieved when the Albertan government announced that it would protect the Castle area as a Provincial and Wildland Provincial Park (Alberta 2015). However, since that time an official management plan has not been released (Castle-Crown Wilderness Coalition 2016). Because of this, digitized boundaries and a management plan defining what protections will be put in place was not available. Future work building on this project should include the Castle if it is given adequate protection to meet the standards for IUCN protected area categories Ia, Ib, or II.

3.1.7 *Proposed Waterton Park Expansion*
There has been ongoing interest in expanding the Canadian portion of Wateron-Glaicer International Peace Park, located in Alberta, into British Columbia. The proposed expansion has been supported by the federal and provincial governments and would include the Akamina-Kishinena Provincial Park in British Columbia and additional provincial land (Parks Canada 2009). A polygon of the proposed area, obtained from the Miistakis Institute, was used as a trial area to refine Marxan methodology (R. Nelson, personal communication 2016).

3.2 Software

In addition to already installed programs such as ESRI ArcGIS, and Microsoft Excel, Marxan optimization software and ArcGIS add-ons were downloaded.

3.2.1 Microsoft Excel 2016

Microsoft Excel was used for initial viewing of AdaptWest datasets, managing exported GIS data, creating Marxan input files, and keeping track of Marxan output files.

3.2.2 ESRI ArcGIS Software Package

ArcGIS 10.3 and 10.4.1 with an advanced license were used for this project (ESRI 2014, 2016). ArcCatalog was used for initial extraction of the AdaptWest rasters, as they were too large to efficiently display in ArcMap. ArcMap was used for all other data preparation, visualization, initial gap analysis, and creation of input maps. Marxan solutions were brought back into ArcMap for visualization and final map creation.

3.2.2.1 Tabulate Area Tool

The Tabulate Area Tool, part of the Spatial Analyst, Zonal Toolbox was used in the creation of Marxan Planning Unit versus Conservation Feature input files, as described in Section 3.6.3. This tool "calculates cross-tabulated areas between two datasets and outputs a table;" the required input parameters for Tabulate Area include two raster files, two vector files, or one of each (ESRI 2016).

The resulting table is a matrix showing the area of the attribute defined in *Class field* per zone defined in *Zone* field; area units depend on the resolution of the input dataset and the processing cell size.

3.2.3 Marxan

Marxan, its associated input file editor, Inedit and the conversion tool, Convert Matrix, were downloaded from marxan.net (Ball et al. 2009). These programs were used in combination to create an optimal conservation network based on the AdaptWest dataset. The *Marxan User Manual* was relied on heavily at the outset to determine how to properly format input files and execute Marxan (Game and Grantham 2008). This explains the utility of Inedit and Convert Matrix and incorporates them into directions as appropriate; their use in this analysis is discussed further in the following sections.

3.2.4 Protected Area Tools

The PAT Add-On is an ArcGIS toolset published by The Nature Conservancy, Conserve Online, and the University of Southern Mississippi to facilitate the use of Marxan, as well as the Environmental Risk Surface, and Relative Biodiversity Index within a GIS environment (Schill and Raber 2012). Their goal is to help conservation organizations around the world more easily utilize these powerful planning tools. The PAT Add-On allows users to create planning unit hexagons of variable sizes for a given extent, convert Marxan files between formats, and create input files, streamlining the Marxan workflow within ArcGIS. It requires on Marxan and its associated executable tools to be installed. PAT was downloaded from the University of Southern Mississippi's website and installed as an add-on to ArcMap.

3.3 Computing Power

The project was initially run on a Dell Inspiron 5559 laptop with 16GB of RAM, a one terabyte solid state drive (SSD), and a Core i7 Intel processor, running Windows 10. When memory limitations arose, work was transferred to a desktop at the University of Montana in hopes of improved performance. This machine, a Dell desktop with 16GB of RAM, a 226GB hard drive, and a Core i7 Intel processor, running Windows 7 Enterprise also encountered memory limitations when attempting to cross-tabulate planning unit and land facet distribution data.

Through Geography Professor Dr. Anna Klene, information technology specialist Aaron Deskins provided access to a virtual machine (VM) that had an 8 core Xeon 2.6GHz processor, 96GB RAM, 250GB RAID10 storage, and was running Windows 7 OS. Access to the virtual machine allowed for the topo facet dataset to be processed across the entire study area, but was still insufficient to process the land facet dataset (discussed further in Section 3.6.3).

3.4 Data Processing

3.4.1 AdaptWest

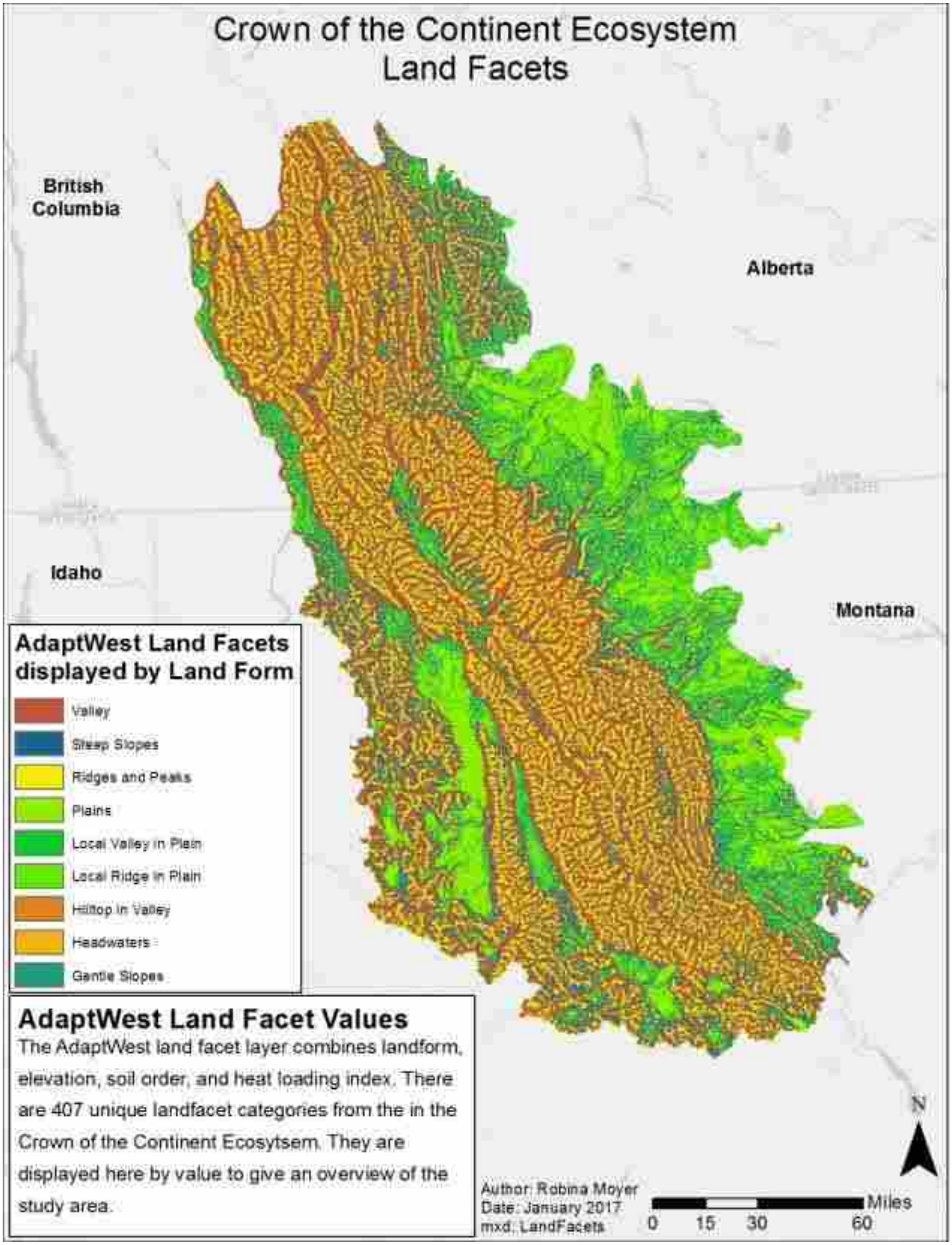
As discussed in Section 2.3.4.3, the topo and land facet datasets incorporating latitude-adjusted elevation were used. Due to the large size of the land and topo facet rasters, they were both clipped to the CCE boundary in ArcCatalog to eliminate the need for visualization during the process. This was accomplished using the Extract by Mask tool. When extracted to the CCE, the topo facet layer contains 107 unique values and the land facet layer contains 407 unique values. Tables summarizing these results can be found in Appendix A.

Each land and topo facet has a unique identifier based on its combination of soil type, elevation, land form and HLI value (see Section 3.1.2). These identifier values are correlated with each raster's pixel values and summarized in their respective attribute tables. Each attribute table was extracted as a text file and opened in Microsoft Excel. Figure 6 and Figure 7 show land and topo facet values for the Crown of the Continent respectively.

3.4.2 IUCN Protected Areas

Canadian and U.S. IUCN data was brought into ArcMap and each layer was re-projected into NAD 1983 UTM Zone 11N; the layers were then clipped to the CCE 2008 Boundary downloaded from CMP (Section 3.1.1). The clipped layers were then merged in ArcMap to create a uniform IUCN protected area layer for the Crown Ecosystem.

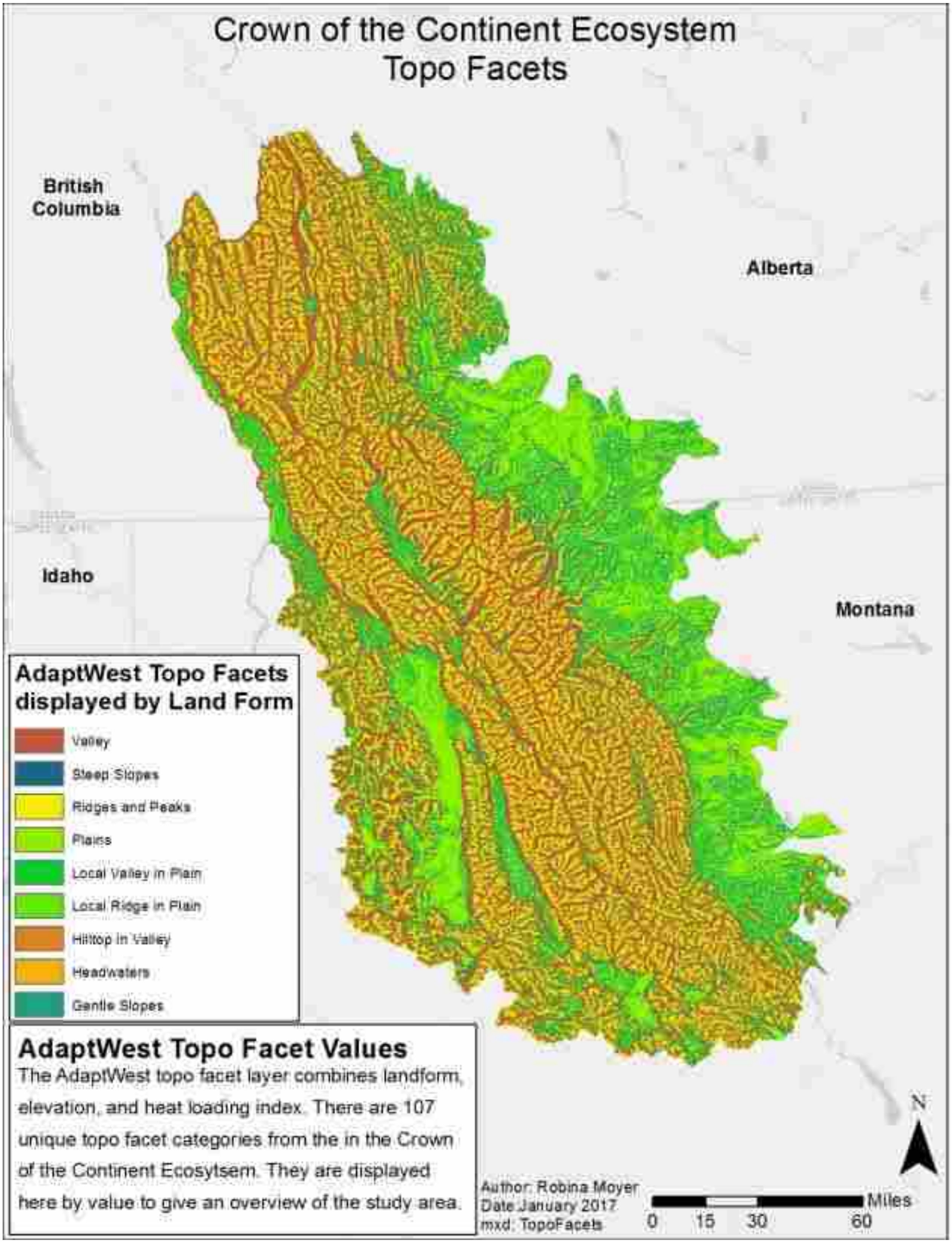
There are seven IUCN Protected Area Categories, for this project, IUCN Category Ia, Ib, and II designations are considered to be adequately protected areas (R. Nelson 2016; L. Broberg 2016). These designations correlate to strict nature reserves, wilderness areas, and national parks respectively. Within ArcMap, these designations were selected and exported as a separate layer, creating a project-specific protected areas layer. Figure 8 shows all IUCN protected areas in the Crown of the Continent.



AdaptWest Land Facet Values

The AdaptWest land facet layer combines landform, elevation, soil order, and heat loading index. There are 407 unique landfacet categories from the in the Crown of the Continent Ecosytsem. They are displayed here by value to give an overview of the study area.

Figure 6: AdaptWest Land Facet layer clipped to the Crown of the Continent Ecosystem and displayed by land form, a measure of local topography.



AdaptWest Topo Facet Values

The AdaptWest topo facet layer combines landform, elevation, and heat loading index. There are 107 unique topo facet categories from the in the Crown of the Continent Ecosytsem. They are displayed here by value to give an overview of the study area.

Author: Robina Moyer
Date January 2017
mxd: TopoFacets

Figure 7: AdaptWest Topo Facet layer clipped to the Crown of the Continent Ecosystem and displayed by land form, a measure of local topography.

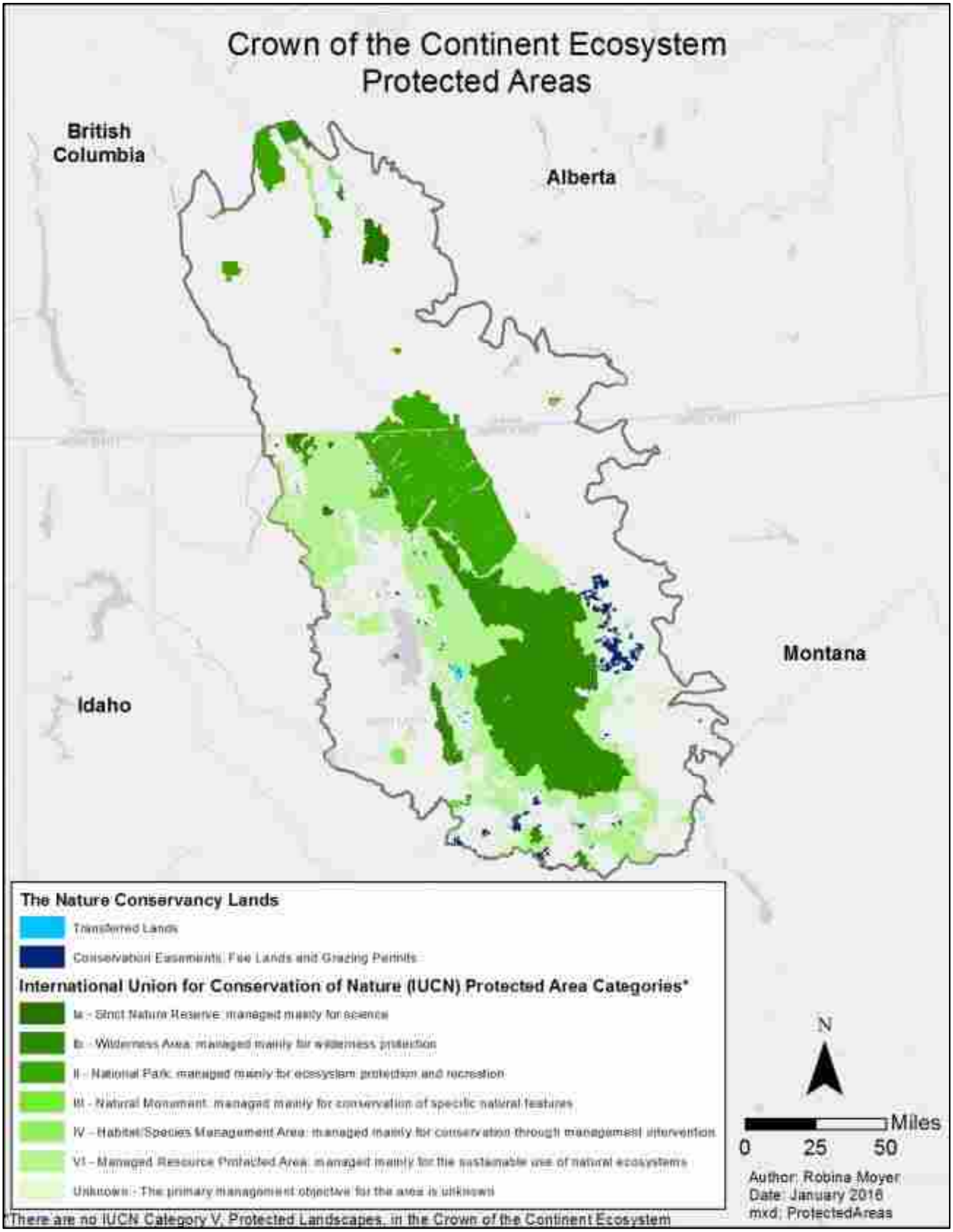


Figure 8: IUCN and The Nature Conservancy Protected Areas in the Crown of the Continent.

3.4.3 *Wilderness Areas*

As discussed in Section 3.1.3, the IUCN protected area layer does not include the most up-to-date boundaries for Montana Wilderness Areas. To remedy this, the updated Bob Marshall and Scapegoat wilderness layers from wilderness.net were projected into NAD 1983 UTM Zone 11N and merged with the IUCN protected areas layer described above with the appropriate IUCN Category Ib designation.

3.4.4 *The Nature Conservancy*

The TNC Lands Montana and Transferred TNC Lands Montana layers were brought into ArcMap and projected into NAD 1983 UTM Zone 11N. Figure 8 shows The Nature Conservancy lands in the Montana portion of the Crown of the Continent.

3.5 Gap Analysis

The preliminary project goal was to identify what land facets are underrepresented in protected areas in the Crown of the Continent Ecosystem. To achieve this, the Extract by Mask tool was used in ArcMap to create a raster of land facets already in protected areas. The AdaptWest land facet layer, clipped to the CCE, and IUCN protected areas layer described above were used. A pixel count field was added to the output raster's attribute table, thus summarizing the area of a given facet already under protection; this table exported to Excel. The attribute table for the AdaptWest land facet raster, clipped to the CCE (including a pixel count field), was also exported into Excel.

The pixel count field on the full raster was re-named "Total" and that on the IUCN-masked table was re-named "Protected." The Excel function "VLOOKUP" was used to put the pixel counts from each raster in columns adjacent to the land facet identification value, when applicable. If there were no protected area pixels of a given value, a zero was entered. Thus, a pixel count of land facet values for protected areas was formatted to be comparable with pixel counts for the entire CCE. A percentage field was added and a "Percent Protected" field was calculated. This table was brought back into ArcMap and joined to a copy of the original land facet raster, allowing land facets to be displayed based on the percent to which they are already protected.

3.6 Marxan Input Files

Marxan requires Species, Planning Unit, and Species vs. Planning Unit input files. These files must be in .dat format, a generic file extension that can be associated with a variety of programs. To accommodate computing limitations, the project area was initially broken into six sections. After access to a more robust virtual machine was gained (discussed in Section 3.3), an analysis was run for the entire study area. Details about the parameters of each input file can be found in Appendix B.

3.6.1 *Conservation Feature File*

Also referred to as the Species File and saved as 'spec.dat,' the Conservation Feature File contains information about the project's conservation features, be they individual species, habitat type, or in this case, land facets. This file includes a species identification number, conservation targets for each species, a penalty factor for not meeting a given conservation target and optional fields for species name, secondary conservation targets and a separation distance between occurrences. Figure 9 shows a sample of the species table for the CCE Topo Facet analysis. A summary of the Marxan input fields and the complete Conservation Feature File used for this project can be found in Appendix C.

For both the segmented and Crown-wide analyses, the AdaptWest land and topo facet values discussed in Section 3.1.2 were used as Conservation Feature IDs. Block Definitions were not used in the Marxan analysis, therefore no Conservation Feature Type value was used in any of the analyses. Thirty percent was the desired conservation target for all land facet categories within the study area (Section 2.1.2). To achieve this, the attribute tables for the land facet and topo facet layers, masked to the CCE and including the total pixel count for each facet-value (equivalent to the area in hectares as described in Section 3.1.2), were exported from ArcMap into Excel. GIS software often summarizes raster data in terms of pixel counts; the direct correlation between hectares and pixels eliminated the need for conversion between the raster's native units and an area of measure applicable to the study. Therefore, 30% of the total pixels, or hectares, were calculated for each facet and the resulting value was used as the conservation target.

For Marxan parameters not dictated by the research question, the *Marxan User Manual* and *Good Practices Handbook* were relied on for guidance (Game and Grantham 2008, Ardon et al. 2010). One such parameter is the conservation feature penalty factor (spf); a multiplier, added to the total reserve cost if the conservation target for specific feature is not met. Multiple spf values were tried during sectioned and Crown-wide analysis in an attempt to have all targets met without a significant cost increase. Based on this, an spf value of 60 was used in the sectioned and Crown-wide analysis. No minimum clump size or target feature occurrence values were used. Conservation feature names were a concatenation of land form and HLI values. Feature occurrence targets can be used that in addition to a percentage representation target being met, a feature also meets a representation minimum, meaning it appears in multiple planning units, thus dispersing risk. Minimum separation distance addresses the same issue but through the use of a distance by which features must be separated, rather than a minimum number of occurrences. Based on Marxan documentation, neither of these parameters were utilized in this analysis. This, and other Marxan input decisions are discussed further in Section 5.4.2.1.

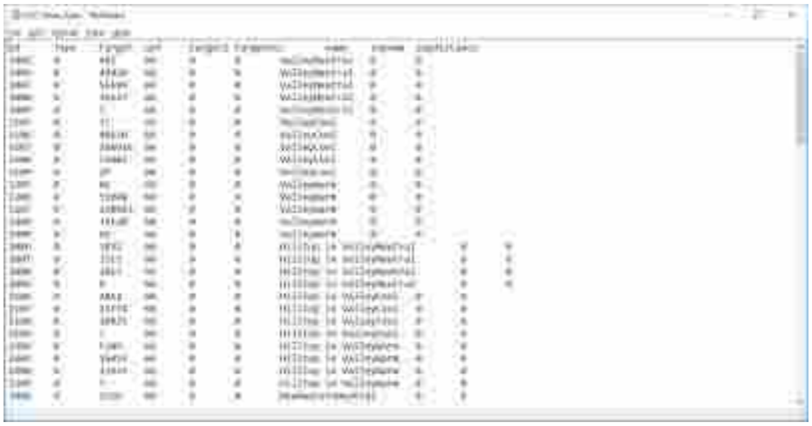


Figure 9: Example of Conservation Feature File, or Species File, used as an input for the Marxan analysis of topo facets in the Crown of the Continent Ecosystem.

3.6.2 Planning Unit File

The Planning Unit File, often saved as 'pu.dat,' contains information about the cost and status of each planning unit, based on a unique numeric identifier. Spatial location is only required if a minimum separation distance, is specified in the Species File. Although the Planning Unit file does not contain spatial data, the Planning Unit ID number correlates to spatially explicit planning units, typically defined in GIS software. Planning units do not have to be a specific size or shape, but suggested delineations include watershed boundaries, jurisdictional boundaries or hexagons (Game and Grantham 2008).

For this project, hexagonal planning units were used; each hexagon is a unique planning unit. Given the extent of the study area, the uniform size and shape of hexagons was deemed an advantage over irregular watershed or jurisdictional boundaries (Nhancale and Smith 2010). Due to initial computing power limitations, the study area was broken into six sections: Alberta, British Columbia, Northwest Montana, Northeast Montana, Southwest Montana, and Southeast Montana, each of which was processed individually. The study area within Montana was broken into these quadrants based on watershed boundaries (Figure 10). Fifty hectare hexagonal planning units were created using the Protected Areas Tool Add-On (Section 3.2.4) in ArcMap. The PAT Add-On assigns each hexagon a unique Unit ID number and allows you to designate a starting value; in all cases, this number was used as the planning unit ID for the Marxan input file.

Once access to a VM was obtained, a 100 hectare hexagon planning unit layer was created for the entire CCE using the PAT Add-On. The resulting layer contained 73,401 hexagons.

For both the sectioned and Crown-wide analyses, existing protected areas were given a status designation of '2,' meaning they were fixed into the reserve design. Additional status options allow you to exclude planning units from solutions, however no additional statuses were assigned. For the initial analysis, no cost layer was used. For the Crown-wide analysis cost layer was created based on jurisdiction using the values in Table 4. Cost was determined based on *Marxan Good Practices*, personal communication with David Albert (TNC Juneau), and consultation with Regan Nelson, based on estimated relative effort to conserve land in each jurisdictional category Figure 11 shows an example of the planning unit input file used for the Crown-wide analysis (D. Albert 2016; R. Nelson, personal communication 2016).

Table 4: Unit-less cost values used in the planning unit file for the Crown-wide Marxan analysis; cost based on jurisdiction.

Jurisdiction	**Cost**
Tribal	4
Canadian and U.S. Private Land	4
Montana State Trust Land	4
Uncertain	4
Canadian Federal and Provincial Land	3
Montana Fish, Wildlife & Parks	3
U.S. Federal Land	2
Existing Protected Area[1]	1

[1] *Includes IUCN Categories Ia, Ib, II and TNC Lands*

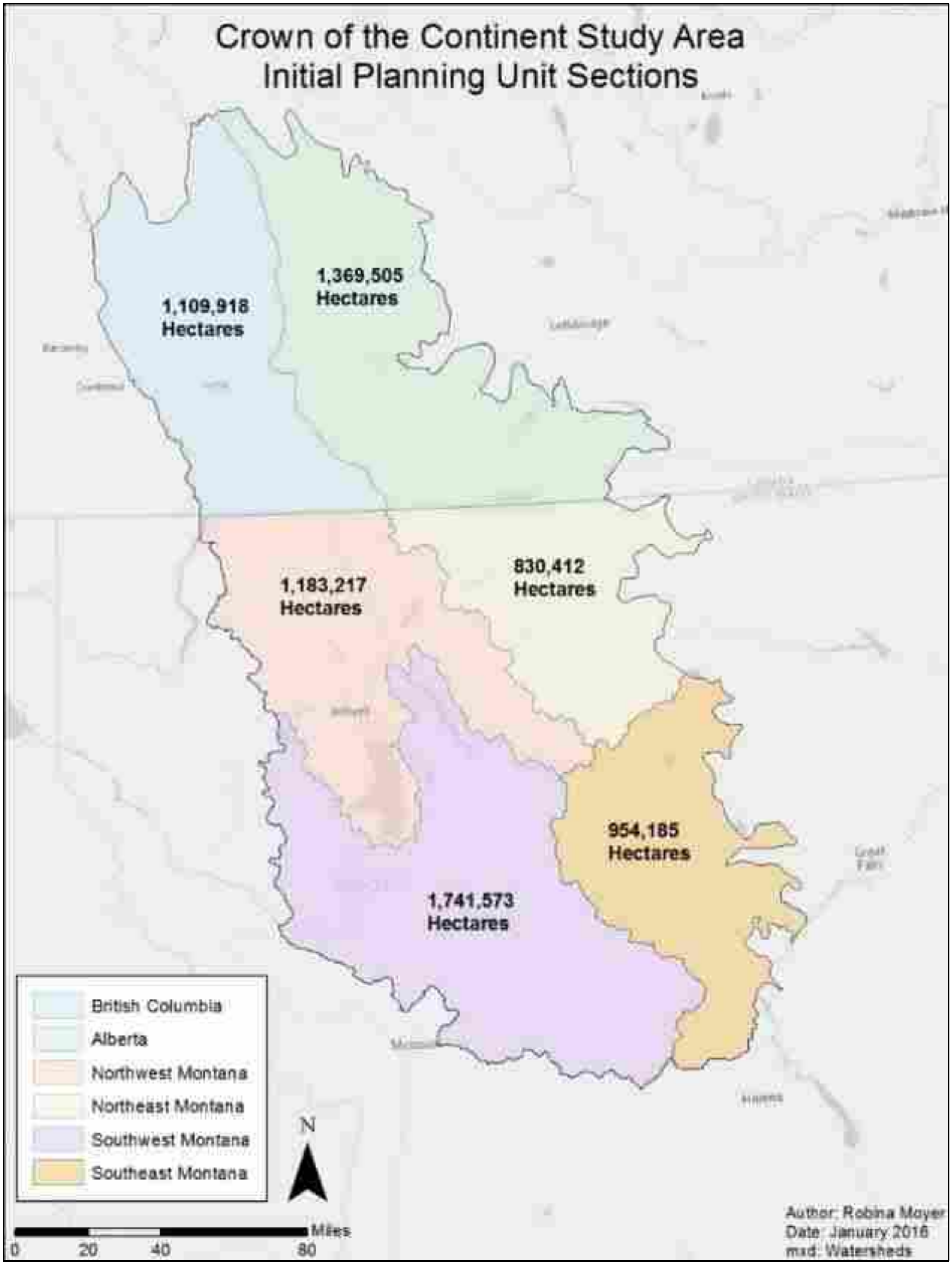


Figure 10: Sections used to create planning units for the initial Marxan analysis.

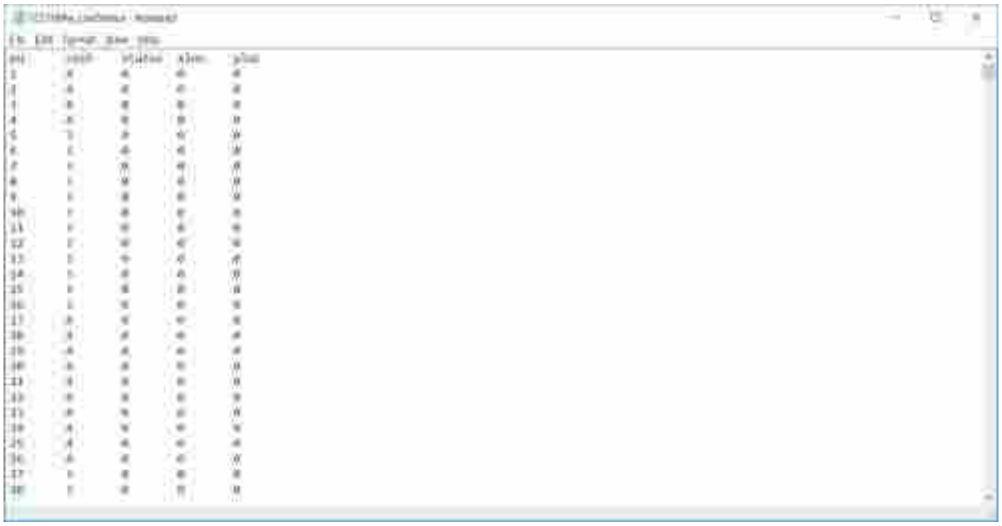


Figure 11: Example of Planning Unit File, used as an input for the Marxan analysis of topo facets in Crown of the Continent Ecosystem.

3.6.3 *Planning Unit versus Conservation Feature File*

The Planning Unit versus Conservation Feature (or Species) File, commonly saved as ‘puvpsr2.dat’ summarizes the distribution of conservation across planning features. This information is displayed in three deceptively simple fields, summarized in Table 5.

Table 5: Summary of inputs for the Planning Unit versus Conservation Feature File, adapted from Game and Grantham 2008.

Field	**Variable Name**	**Description**
Conservation Feature ID	species	The unique numeric identifier for each species or feature referenced in the Conservation Feature File
Planning Unit ID	pu	The unique planning unit identifier referred to in the Planning Unit File
Conservation Feature Amount	amount	The amount of a given feature within the given planning unit, in the same units as defined in the Conservation Feature File

Calculating the number of features within a given planning unit requires cross-tabulating the hexagonal planning unit layer with the conservation feature layer. This was achieved using the ‘Tabulate Area’ tool within the ArcGIS Spatial Analyst, Zonal Toolbox (discussed in Section 3.2.2.1; ESRI 2014). This proved to be the most memory-intensive computation of the project and required extensive trial and error as described below.

For the Proposed Waterton Expansion trial analysis, it was determined that the using 100 ha or smaller hexagon planning units resulted in a memory error, thus, 500 ha hexagons were used. The resulting table was exported from ArcMap and brought into Excel. The native resolution of the input raster was 100 meters, meaning each pixel contains 10,000 m^2, the values in the tabulated output table were based on this. Meaning if a planning unit contained one pixel of a given land facet, it had a value of 10,000 in the output table. To maintain consistency with the

Conservation Feature File, in which facets were enumerated by pixels, the tabulated area table was divided by 10,000, thus converting the units from square meters to pixels.

In order to be input into Marxan, the Planning Unit versus Conservation Feature File must be formatted as a sparse, or relational matrix (Game and Grantham 2008; Table 5), rather than the tabular matrix produced by Tabulate Area. To achieve this, the Excel file was re-formatted so the headers contained only the numeric facet value, using Notepad the files were converted to the '.dat' extension. Marxan downloads with 'conver_mtx.exe,' an executable conversion tool, to expedite this process. Tabulated output files were converted using this tool through the PAT Add-On GUI interface. Examples of the tabular matrix and sparse matrix formats are shown in Figure 12 and Figure 13 respectively.

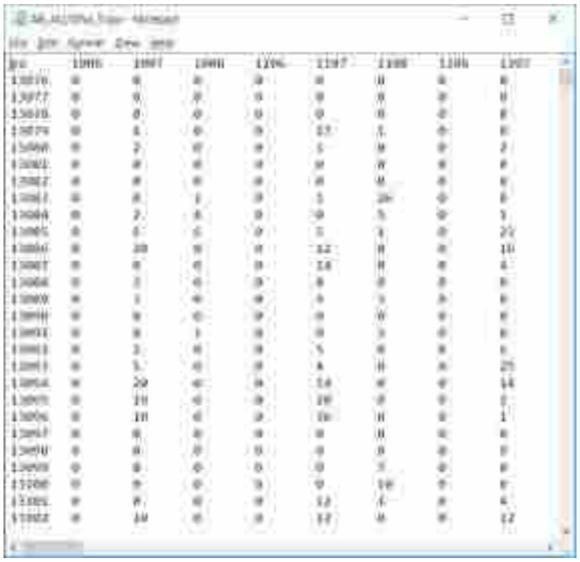
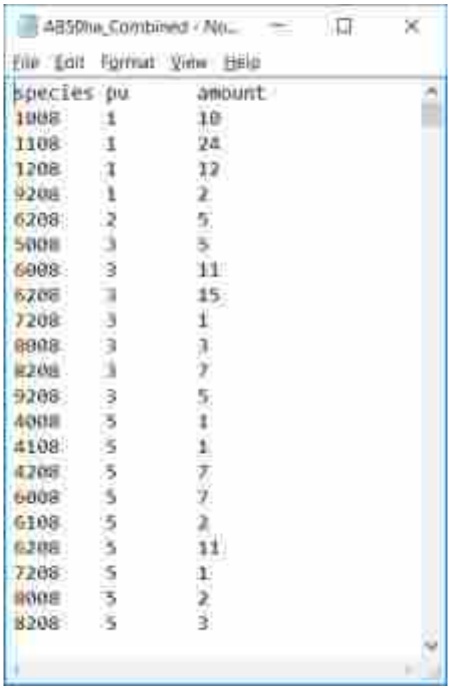


Figure 12: Tabulate Area results shown in tabular matrix format, planning unit IDs are in the first column and topo facet values across the top. Numbers in the matrix indicate the number of pixels of a topo facet in a given planning unit



```
species pu      amount
1008    1       10
1108    1       24
1208    1       12
9208    1       2
6208    2       5
5008    3       5
6008    3       11
6208    3       15
7208    3       1
8008    3       3
8208    3       7
9208    3       5
4008    5       1
4108    5       1
4208    5       7
6008    5       7
6108    5       2
6208    5       11
7208    5       1
8008    5       2
8208    5       3
```

Figure 13: Tabulate Area results converted into the sparse matrix format needed for the Planning Unit versus Conservation Feature File, using Marxan's 'convert_mtx' executable; 'amount' references a given species' pixel count within that planning unit.

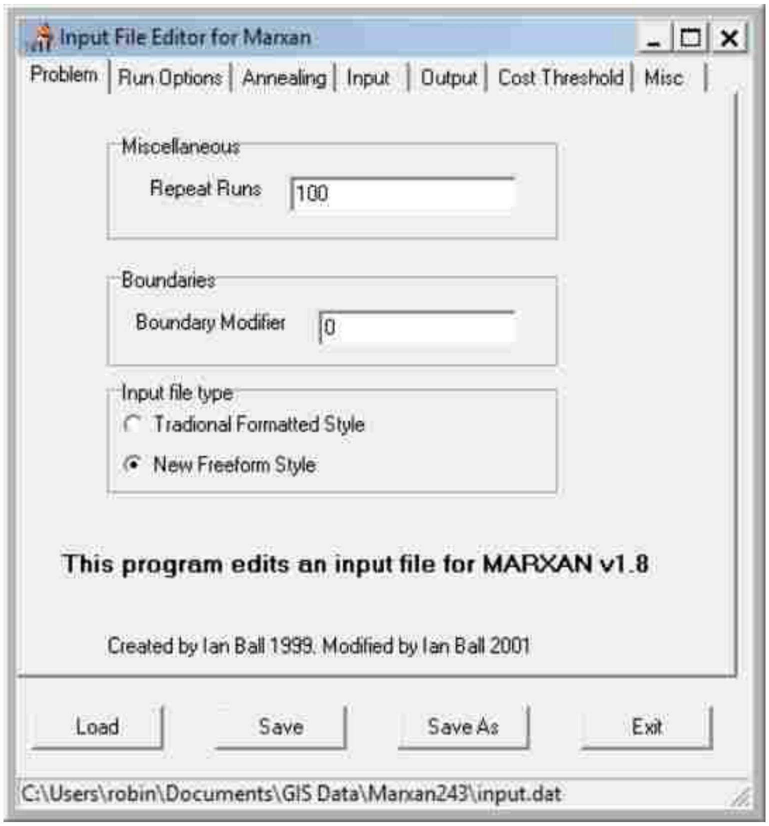
Given the memory allocation issues encountered creating the Waterton Planning Unit versus Conservation Feature File, it was logical that this continued to be an issue when the analysis area was scaled up to entire Crown of the Continent study area. Based on Marxan documentation and previous user's experience, it was determined that the large number of land facet categories (407 across the total study area) was likely contributing to the memory error (Game and Grantham 2008, D. Albert, Personal Communication 2016). As a result, it was decided to use the AdaptWest topo facet layer, containing only 107 categories, instead. Even with this smaller dataset, ArcMap was unable to cross-tabulate planning units and topo facets for the entire study area. Tables summarizing the land and topo facets in the Crown Ecosystem can be found in Appendix A.

With this limitation, trial and error was used to identified the largest extent, with the smallest planning unit size, that could successfully be cross-tabulated. It was determined that the Alberta and British Columbia portions of the Crown could each be processed using 50 ha hexagon planning units and the topo facet layer. Montana required further parsing and was ultimately broken in to four quadrants. These quadrants were initially based on arbitrary lines, but before Marxan analysis were revised to reflect watershed boundaries, in an effort to create ecologically-informed delineations (CMP Watersheds 2015). The resulting sections are shown in Figure 10.

Following the initial analysis, access was gained to virtual machine at the University of Montana (Section 3.3). Again, trial and error was used to determine the largest extent and smallest planning unit size that could be cross-tabulated for both the land facet and topo facet rasters. It was determined that 100ha hexagon planning units were the smallest area that could be successfully cross-tabulated with the topo facet layer for the entire Crown.

3.6.4 Input Parameter File

The three files described above are used in tangent with the Marxan executable 'Inedit' file editor to create the Input Parameter File, typically saved as 'input.dat.' This file defines the parameters which control how Marxan finds a solution and directs Marxan to the location of the three input files discussed above (Game and Grantham 2008). Inedit has seven tabs, each containing a suite of parameters; the Problem tab is shown in Figure 14. A table summarizing each tab's key parameters can be found in Appendix B.



Repeat Runs 100

Boundary Modifier 0

○ Tradional Formatted Style

● New Freeform Style

This program edits an input file for MARXAN v1.8

Created by Ian Ball 1999. Modified by Ian Ball 2001

C:\Users\robin\Documents\GIS Data\Marxan243\input.dat

Figure 14: Screenshot of Inedit, the GUI input file editor for Marxan

The *Marxan User Manual* and *Marxan Good Practices Handbook* explain each of these parameters, their potential synergy, and recommended starting values (Game and Grantham 2008, Arden et al. 2010). Initial inputs were based on those recommendations and experimentation was undertaken as appropriate. The final inputs used for the Crown-wide analysis using 100 ha planning units and inputs for the sectioned analysis can be found in Appendix D. Of note, to find the most compact reserve design, values from 0 - 100,000 were tried for the boundary length modifier (BLM). Based on a comparison of these results, a value of 10,000 was used in the final analysis. Values above that began to miss conservation feature targets.

3.7 Running Marxan

Once all inputs have been created, formatted, and saved in the location specified in the Input Parameter File, Marxan can executed. Progress will be displayed in a command line output as the program completes each run (Figure 15). Each of the six section scenarios and the Crown-wide scenario were run for 5,000 iterations.

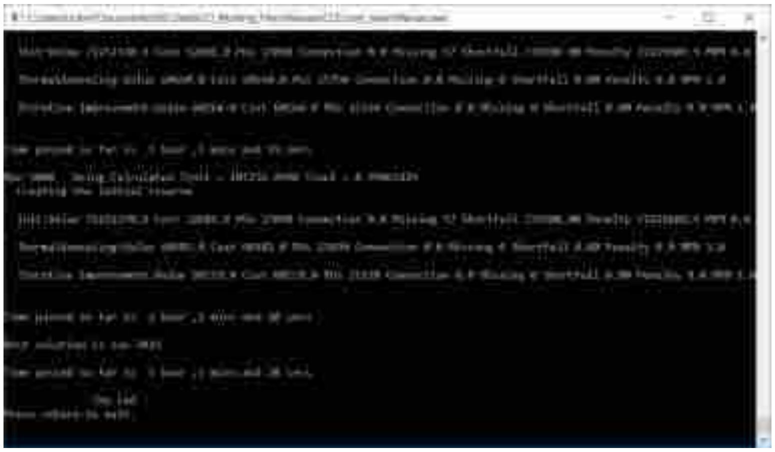


Figure 15: Example of Marxan progress output during processing.

3.8 Marxan Output Files

Marxan can provide multiple output file formats, in part based on what parameters are selected in the ‘Output’ tab of Inedit. The basic Marxan output file has two columns: ‘planning_unit’ which contains planning unit IDs and ‘solution,’ which has a value of 1 if a unit is included in the solution, or 0 if a unit is not included. Marxan will return an output in this format for each run completed, as well as the best solution from a given analysis, as determined by cost and target conservation achievement. The best solution will be identified in the Marxan output screen (Figure 15) and can saved separately. In addition, Marxan creates a Summed Solution, which summarizes the number of times a planning unit appeared in the total number of runs executed.

3.8.1 Displaying Solutions

Marxan solutions were brought into ArcMap and joined to the original planning unit layers, based on planning unit ID. Individual runs and best solutions were symbolized based on their ‘solution’ value; summed solutions were symbolized quantitatively using Jenks Natural Breaks to create nine classes. The more times a planning units was included across runs, the more valuable its contribution to a complete reserve system.

4.0 Results

The results of the gap analysis and Marxan analysis are discussed below. Land ownership for the Crown of the Continent is displayed in Figure 16 for reference. The map was created using jurisdictional data from the Crown Managers Partnership.

4.1 Gap Analysis

As discussed in Section 3.4.3, a gap analysis was performed for both land and topo facet layers in ArcMap, with protected areas designated as IUCN Categories Ia, Ib, and II, The Nature Conservancy conservation land, and additional land designated as privately conserved by the Crown Managers Partnership. Using these criteria, 3,590,664 acres, or 20% of the land area of the Crown Ecosystem is protected. In addition, the current percent protected was calculated for each facet category and those results are shown in Figure 17 and Figure 18.

4.1.1 Land Facets

The land facet gap analysis showed that out of 407 classifications, 91 classifications, totaling 137,494 hectares currently have no protection, while only 20 classifications, totaling 7,980 hectares have 100% protection. Percent protected values are summarized in Table 6, broken into categories based on the Aichi Biodiversity target, the project target, and an ecologically-based target; these are visually displayed in Figure 17. Table 7 shows the details for those land facet classifications which currently have no protection in the Crown of the Continent.

Table 6: Summary of land facet gap analysis.

Percent Protected	Number of Classes	Total Area (hectares[1])	Protected Area (hectares[1])	Percent of Total CCE[2]
0-0.99%	91	137,494	151	1.9%
1-17%	186	4,205,086	280,901	58.3%
18-30%	28	891,200	224,830	12.4%
31-50%	29	981,443	354,775	13.6%
51-99%	53	990,695	571,068	13.7%
100%	20	7,890	7,899	0.1%

[1] *As a result of the raster resolution, 1 pixel = 1 hectare*

[2] *Caluculated by using the total area shown above in the third column and a total area of 7,213,808 hectares for the Crown of the Continent.*

From this summary, it is evident that although there are 91 classifications with less than 1% protection, they make up a relatively small percentage of the total area of the Crown ecosystem. Many of these classifications contain a small number of pixels, potentially dispersed throughout the Crown. In an effort to filter out classifications unlikely to be the target of conservation, Table 7 shows the 24 classifications which have 0% protection and are larger than 1,000 acres. Of greater concern is those classifications with 1-17% protection which make up 58% of the total Crown. As shown in Figure 17, the facets in this category are predominant along the eastern and southwestern portions of the Crown. The eastern portion of the Crown, often referred to as the Rocky Mountain Front or Eastern Slopes, is dominated by high plains, much of which is First Nations and Native American reservations or in private ownership (Figure 16).

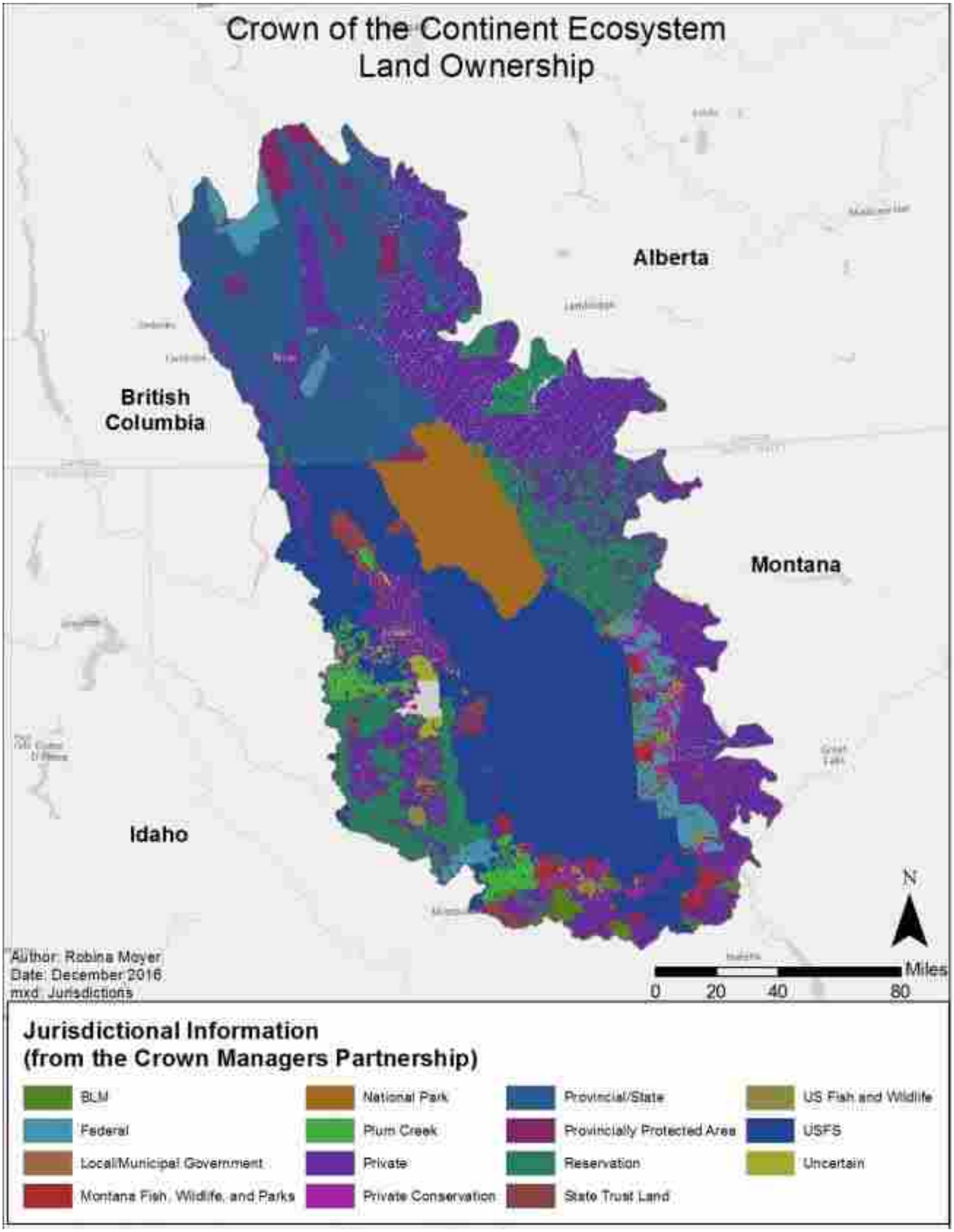


Figure 16: Jurisdictional data for the Crown of the Continent

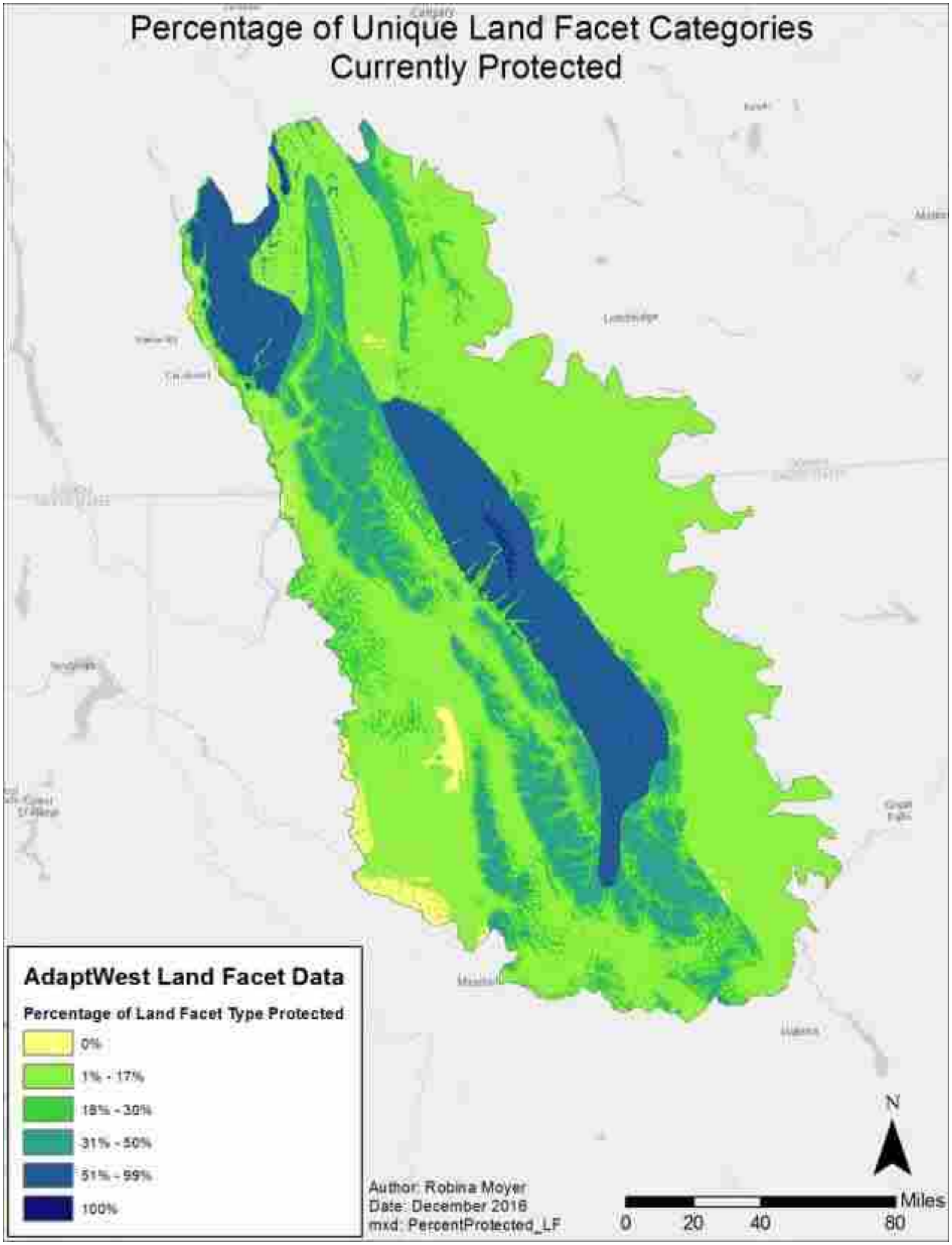


Figure 17: Gap analysis results showing the percentage of Unique Land Facet Categories Currently Protected

Table 7: Summary of the 24 land facet classifications greater than 1,000 acres, with no protection, in the Crown of the Continent Ecosystem.

Land Facet Value	Total Pixel Count (hectares)	Protected Area Pixel Count (hectares)	Percent Protected	Landform	HLI	Adjusted Elevation	Soil Order	Total Area (acres)	Protected Area (acres)
110515	727	0	0%	Valley	Cool	3900 - 3900	Kastanozems	1,796	0
110703	5807	0	0%	Valley	Cool	3900 - 5000	Andosols	14,343	0
120515	903	0	0%	Valley	Warm	3900 - 3900	Kastanozems	2,230	0
120703	2485	0	0%	Valley	Warm	3900 - 5000	Andosols	6,138	0
210703	986	0	0%	Hilltop in Valley	Cool	3900 - 5000	Andosols	2,435	0
220703	605	0	0%	Hilltop in Valley	Warm	3900 - 5000	Andosols	1,494	0
310603	841	0	0%	Headwaters	Cool	3900 - 4500	Andosols	2,077	0
310703	2667	0	0%	Headwaters	Cool	3900 - 5000	Andosols	6,587	0
310803	1024	0	0%	Headwaters	Cool	3900 - 6000	Andosols	2,529	0
310815	497	0	0%	Headwaters	Cool	3900 - 6000	Kastanozems	1,228	0
320603	642	0	0%	Headwaters	Warm	3900 - 4500	Andosols	1,586	0
320703	1178	0	0%	Headwaters	Warm	3900 - 5000	Andosols	2,910	0
320815	514	0	0%	Headwaters	Warm	3900 - 6000	Kastanozems	1,270	0
410716	407	0	0%	Ridges and Peaks	Cool	3900 - 5000	Leptosols	1,005	0
410815	1521	0	0%	Ridges and Peaks	Cool	3900 - 6000	Kastanozems	3,757	0
420603	2122	0	0%	Ridges and Peaks	Warm	3900 - 4500	Andosols	5,241	0
420716	459	0	0%	Ridges and Peaks	Warm	3900 - 5000	Leptosols	1,134	0
500515	806	0	0%	Plains	Neutral	3900 - 3900	Kastanozems	1,991	0
500603	882	0	0%	Plains	Neutral	3900 - 4500	Andosols	2,179	0
620716	448	0	0%	Local Ridge in Plain	Warm	3900 - 5000	Leptosols	1,107	0
820716	491	0	0%	Gentle Slopes	Warm	3900 - 5000	Leptosols	1,213	0
910703	4451	0	0%	Steep Slopes	Cool	3900 - 5000	Andosols	10,994	0
910803	552	0	0%	Steep Slopes	Cool	3900 - 6000	Andosols	1,363	0
920703	2190	0	0%	Steep Slopes	Warm	3900 - 5000	Andosols	5,409	0
Total	33,205	0	N/A	N/A	N/A	N/A	N/A	82,016	0

4.1.2 Topo Facets

From the topo facet gap analysis, it was calculated that out of 107 classifications, 10 classifications, totaling 1,226 hectares currently have no protection, while only 1 classification, totaling 2 hectares has 100% protection. Percent protected values are summarized in Table 8, broken into categories based on the Aichi Biodiversity target, the project target, and an ecologically-based target; these are visually displayed in Figure 18. Table 9 shows the details for those topo facet classifications which currently have no protection in the Crown of the Continent.

Table 8: Summary of topo facet gap analysis. One pixel equals one hectare.

Percent Protected	**Number of Classes**	**Total Area (hectares)**	**Protected Area (hectares)**	**Percent of Total CCE[1]**
0%	10	1,226	1	0.0%
1-17%	49	3,953,766	299,167	54.8%
18-30%	6	706,296	191,280	9.8%
31-50%	25	2,552,809	946,323	35.4%
51-99%	16	4,951	2,851	0.1%
100%	1	2	2	0.0%

[1] Caluculated by using the total area shown above in the third column and a total area of 7,213,808 hectares for the Crown of the Continent.

The unprotected topo facets are concentrated in the southwest area of the Crown (Figure 18) and are predominantly localized ridges and valleys. As with land facets, the 1-17% protection category has the greatest number of topo facet classifications, which cover 55% of the Crown Ecosystem. However, unlike the land facet analysis, the 51-99% category has only 16 topo facet classes which make up less than 1% of the total study area. Figure 18 shows the spatial dispersion of topo facet protection, which is similar to that of land facets, albeit with less definition. Again, the Rocky Mountain Front/Eastern Slopes and southwestern portion of the Crown are shown to be lacking sufficient protection.

Table 9: Summary of the 8 topo facet classifications with no protection in the Crown of the Continent Ecosystem.

Land Facet Value	**Total Pixel Count (hectares)**	**Protected Area Pixel Count (hectares)**	**Percent Protected**	**Landform**	**HLI**	**Adjusted Elevation**	**Total Area (acres)**	**Protected Area (acres)**
1105	235	1	0%	Valley	Cool	2800- 3900	580	0
5005	820	0	0%	Plains	Neutral	2800- 3900	2025	0
7005	126	0	0%	Local Valley in Plain	Neutral	2800- 3900	311	0
7105	17	0	0%	Local Valley in Plain	Cool	2800- 3900	42	0
7205	7	0	0%	Local Valley in Plain	Warm	2800- 3900	17	0
8005	8	0	0%	Gentle Slopes	Neutral	2800- 3900	20	0
8105	4	0	0%	Gentle Slopes	Cool	2800- 3900	10	0
8205	7	0	0%	Gentle Slopes	Warm	2800- 3900	17	0
Total	1,224	1	N/A	N/A	N/A	N/A	3,022	0

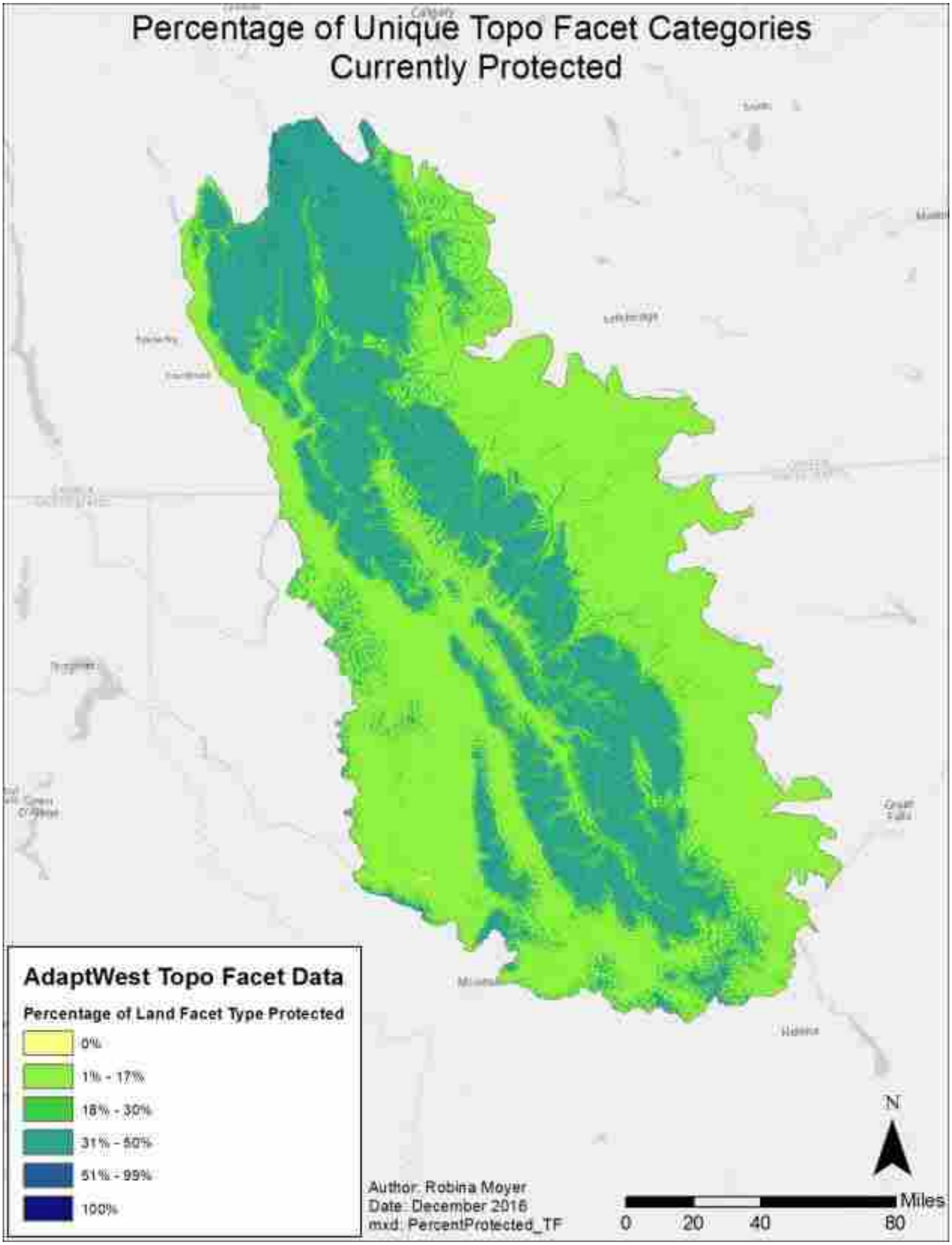


Figure 18: Gap analysis results showing the percentage of Unique Topo Facet Categories Currently Protected

4.1.3 Summary

Given the distribution of land and facets across the Crown (Figure 6 and Figure 7), there are countless ways to achieve the 30% protection target for both measures, but under any circumstances, it will require the additional protection of approximately 2,000,000 acres. This gap analysis highlights the discrepancies in protection levels between the core of the CCE and western edge and Rocky Mountain Front. Table 10 compares protection rates between land and topo facets. From this it can be seen that those topo facet classifications which are 31% or more protected make up 35.5% of the land area in the CCE, though almost none of these classes are more than 50% protected. However, when the more nuanced land facet layer is used, those classes above 31% protected make up only 27.4% of the land area in the CCE. In both cases, those facets with less than 17% protection should be considered when proposing future protected areas. When these results are overlaid with jurisdictional data it can be seen that in the United States, much of this under-protected land is privately held or managed by the United States Forest Service; in Alberta, the majority is privately owned, and in British Columbia, it is provincially owned. This presents a unique set of challenges for achieving greater protection in each state and province.

Table 10: Comparison of the percent protected by classification of land and topo facets. One pixel equals one hectare.

Percent Protected	**Number of Classes**		**Total Area (hectares)**		**Protected Area (hectares)**		**Percent of Total CCE**[1]	
	LF[2]	**TF**[2]	**LF**	**TF**	**LF**	**TF**	**LF**	**TF**
0%	91	10	137,494	1,226	151	1	1.9%	0.0%
1-17%	186	49	4,205,086	3,953,766	280,901	299,167	58.3%	54.8%
18-30%	28	6	891,200	706,296	224,830	191,280	12.4%	9.8%
31-50%	29	25	981,443	2,552,809	354,775	946,323	13.6%	35.4%
51-99%	53	16	990,695	4,951	571,068	2,851	13.7%	0.1%
100%	20	1	7,890	2	7,899	2	0.1%	0.0%

[1] *Caluculated by using the total area shown above in the third column and a total area of 7,213,808 hectares for the Crown of the Continent.*

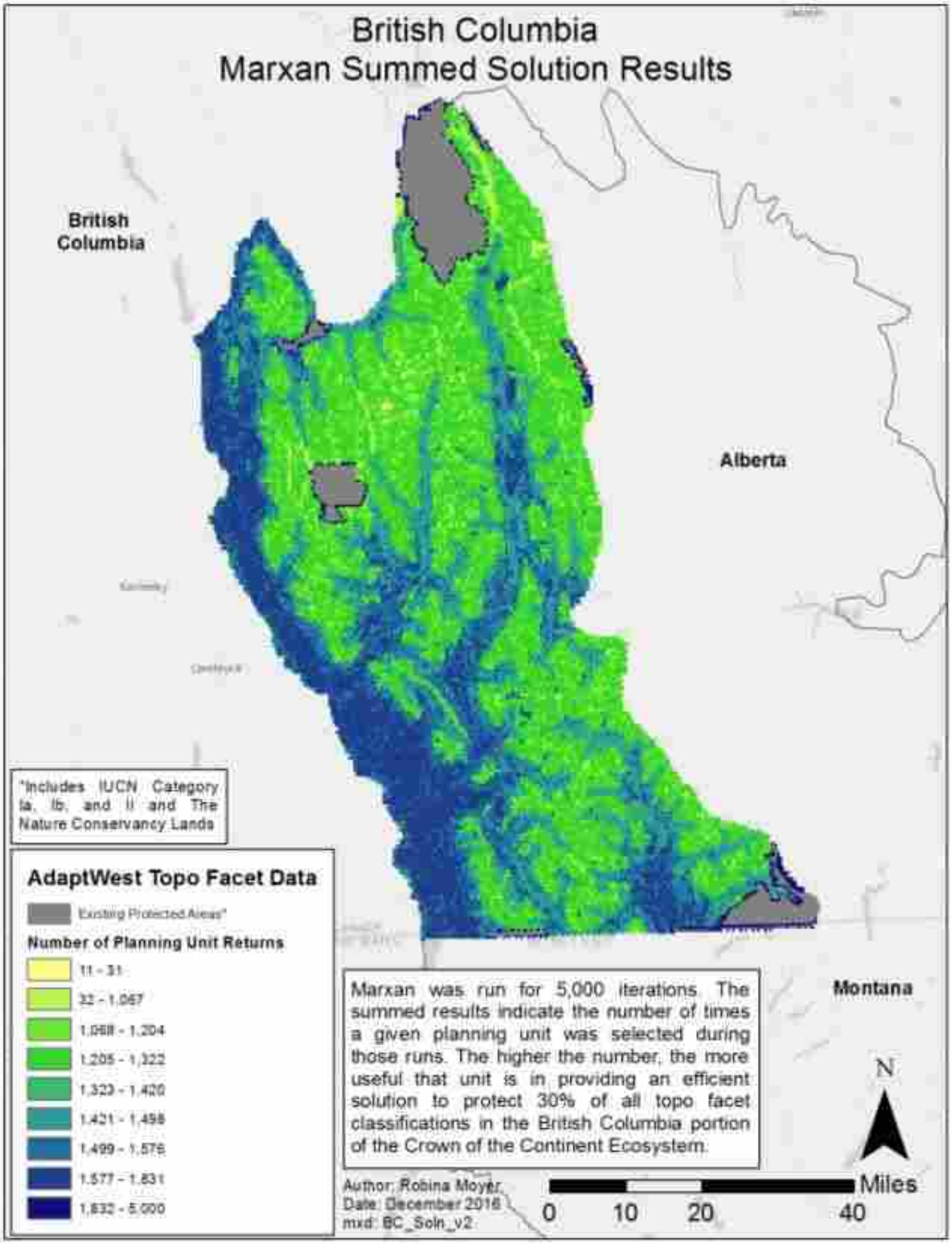
[2] *LF = Land Facet; TF = Topo Facet*

4.2 Marxan Results

In an attempt to identify areas that will most efficiently reach the 30% representation target for each land facet classification in protected areas, Marxan conservation planning software was used. Due to computing limitations, it was run several times and on multiple scales in an attempt to produce the most accurate and useful results.

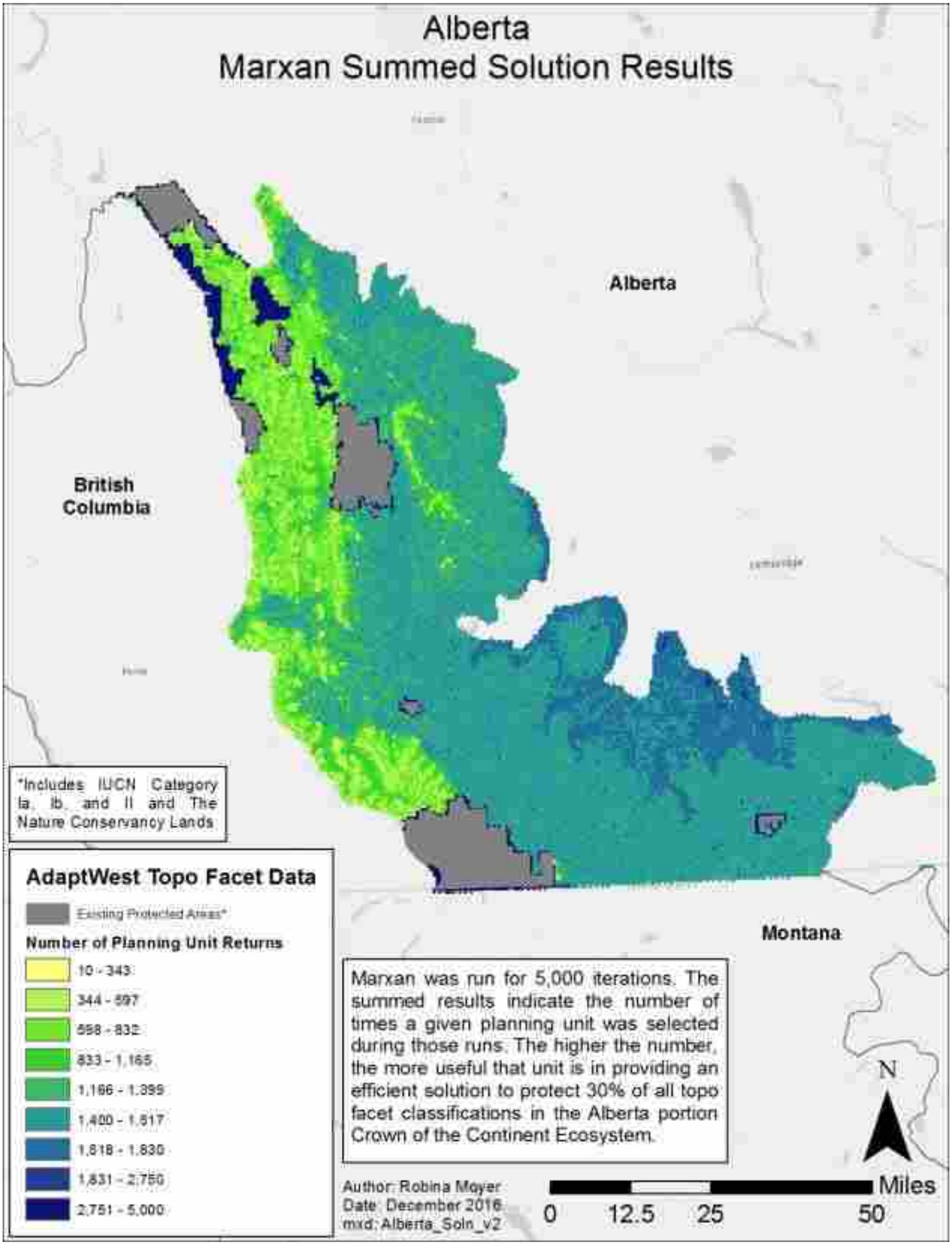
4.2.1 Sectioned Topo Facets Analysis

As discussed in Section 1.0, the study area was initially broken up into six sections, which were processed through Marxan individually. In each section, areas were identified which appeared consistently across 5,000 iterations and therefore could help efficiently reach topo facet protection goals. In British Columbia, areas of particular note were along the western edge of the CCE, northwest of Akamina-Kishinena Provincial Park (the existing protected area along the Montana border), and a corridor west of the continental divide (Figure 19). In Alberta, initial



Marxan was run for 5,000 iterations. The summed results indicate the number of times a given planning unit was selected during those runs. The higher the number, the more useful that unit is in providing an efficient solution to protect 30% of all topo facet classifications in the British Columbia portion of the Crown of the Continent Ecosystem.

Figure 19: Marxan results for British Columbia using 50ha planning units, the AdaptWest topo facet layer and a 30% topo facet representation target.

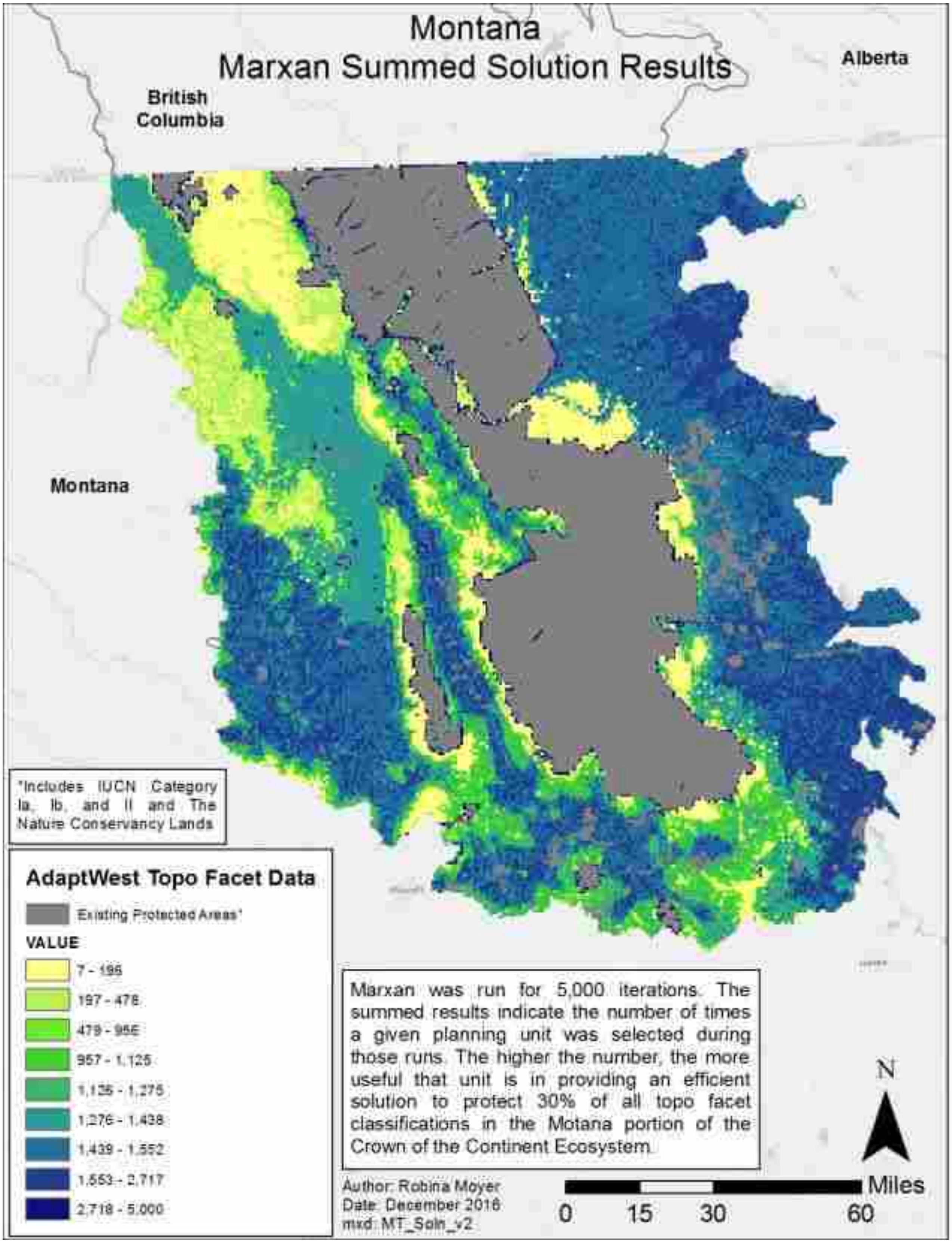


*Includes IUCN Category Ia, Ib, and II and The Nature Conservancy Lands

Marxan was run for 5,000 iterations. The summed results indicate the number of times a given planning unit was selected during those runs. The higher the number, the more useful that unit is in providing an efficient solution to protect 30% of all topo facet classifications in the Alberta portion Crown of the Continent Ecosystem.

Author: Robina Moyer
Date: December 2016
mxd: Alberta_Soln_v2

Figure 20: Marxan results for Alberta using 50ha planning units, the AdaptWest topo facet layer and a 30% topo facet representation target.



Marxan was run for 5,000 iterations. The summed results indicate the number of times a given planning unit was selected during those runs. The higher the number, the more useful that unit is in providing an efficient solution to protect 30% of all topo facet classifications in the Motana portion of the Crown of the Continent Ecosystem.

Author: Robina Moyer
Date: December 2016
mxd: MT_Soln_v2

Figure 21: Marxan results for Montana using 50ha planning units, the AdaptWest topo facet layer and a 30% topo facet representation target.

results showed some well-defined areas along the eastern front. However, once the Marxan inputs were refined and iterations were increased to 5,000 fewer distinct areas appeared (Figure 20). This could be in part due to the homogeneity of the topography in this portion of Alberta and reflects the general lack of protected areas there and the multitude of ways to reach the target that all would have a similar "cost." Montana showed a similar trend with southern portions of the Rocky Mountain Eastern Front, the southwestern edge of the CCE, and the North Fork Flathead River valley appearing as areas of particular interest (Figure 21).

4.2.2 *Crown-wide Topo Facets Analysis*

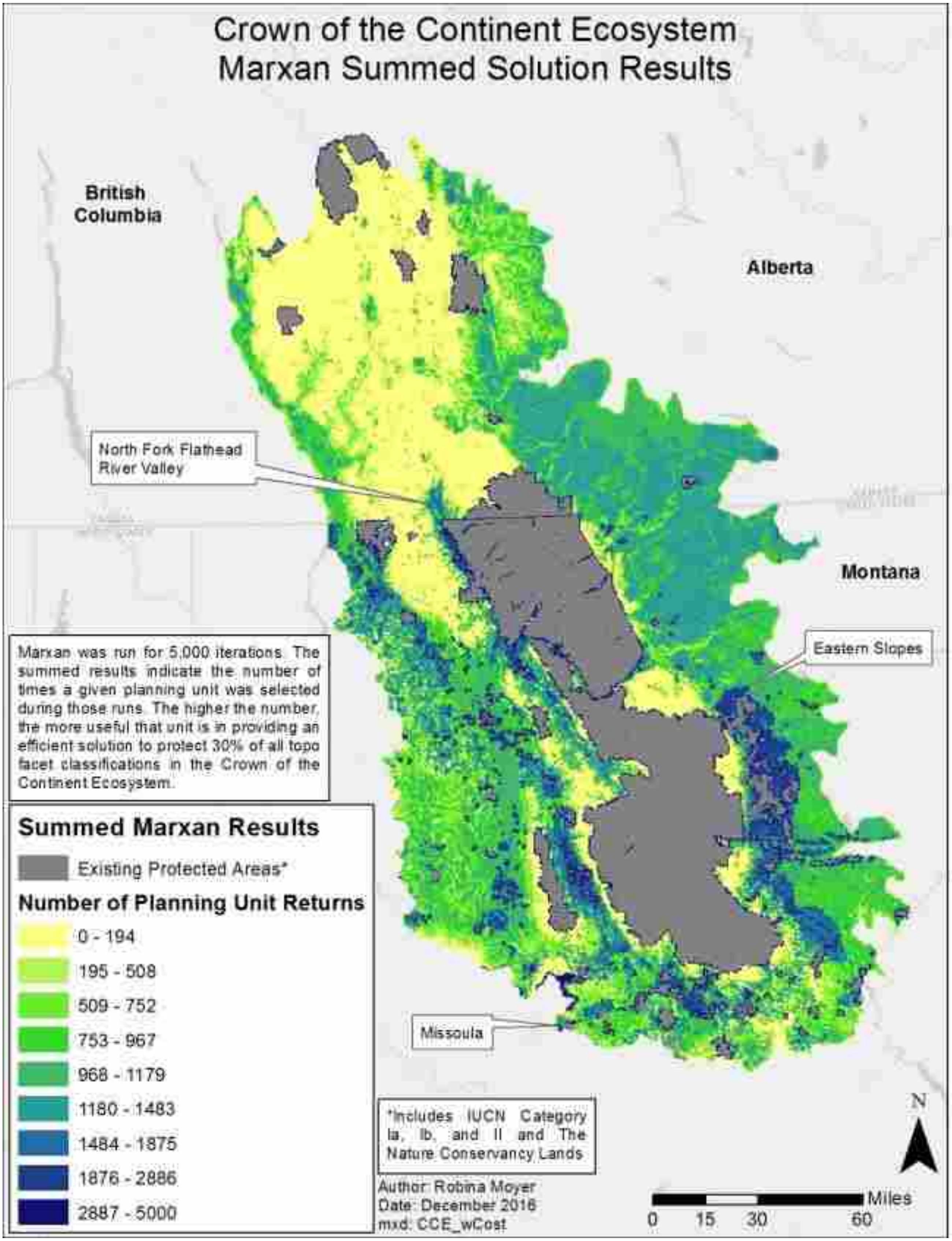
The entire Crown was analyzed in Marxan using 100 ha hexagon planning units and a cost layer (Section 3.7); this scenario was run 5,000 times with a boundary length modifier (BLM) of 10,000. Two Marxan outputs, the summed solution and best solution, were used to create map products summarizing the results.

4.2.2.1 *Summed Solution*

The summed solution results (Figure 22) indicate the number of times a given planning unit was selected during those runs. The higher the number, the more useful that unit is in providing an efficient solution to protect 30% of all topo facet categories in the Crown of the Continent Ecosystem. There are a range of options for increasing land facet representation in protected areas, unsurprisingly these are most concentrated in same areas shown to be lacking sufficient protection in the gap analysis. In particular, the southern portion of the Rocky Mountain Front and a small area just north of Missoula emerge as efficient places to expand or create protected areas. Both of these areas include land generally described as federally owned in the CMP jurisdictional data. In addition to these core areas, the North Fork Flathead River valley, just north of the Montana-British Columbia River, shows a high density of planning unit returns.

4.2.2.2 *Best Solution*

In the best solution (Figure 23), planning units are included or excluded based on their efficiency in reaching the defined parameters. The use of a BLM value of 10,000 increased the density of this best solution compared to scenarios run with a smaller value, however the results are still fairly dispersed. The same area north of Missoula appears in the best solution, as well as a general concentration of planning units along the Rocky Mountain Front and southwestern portion of the study area.

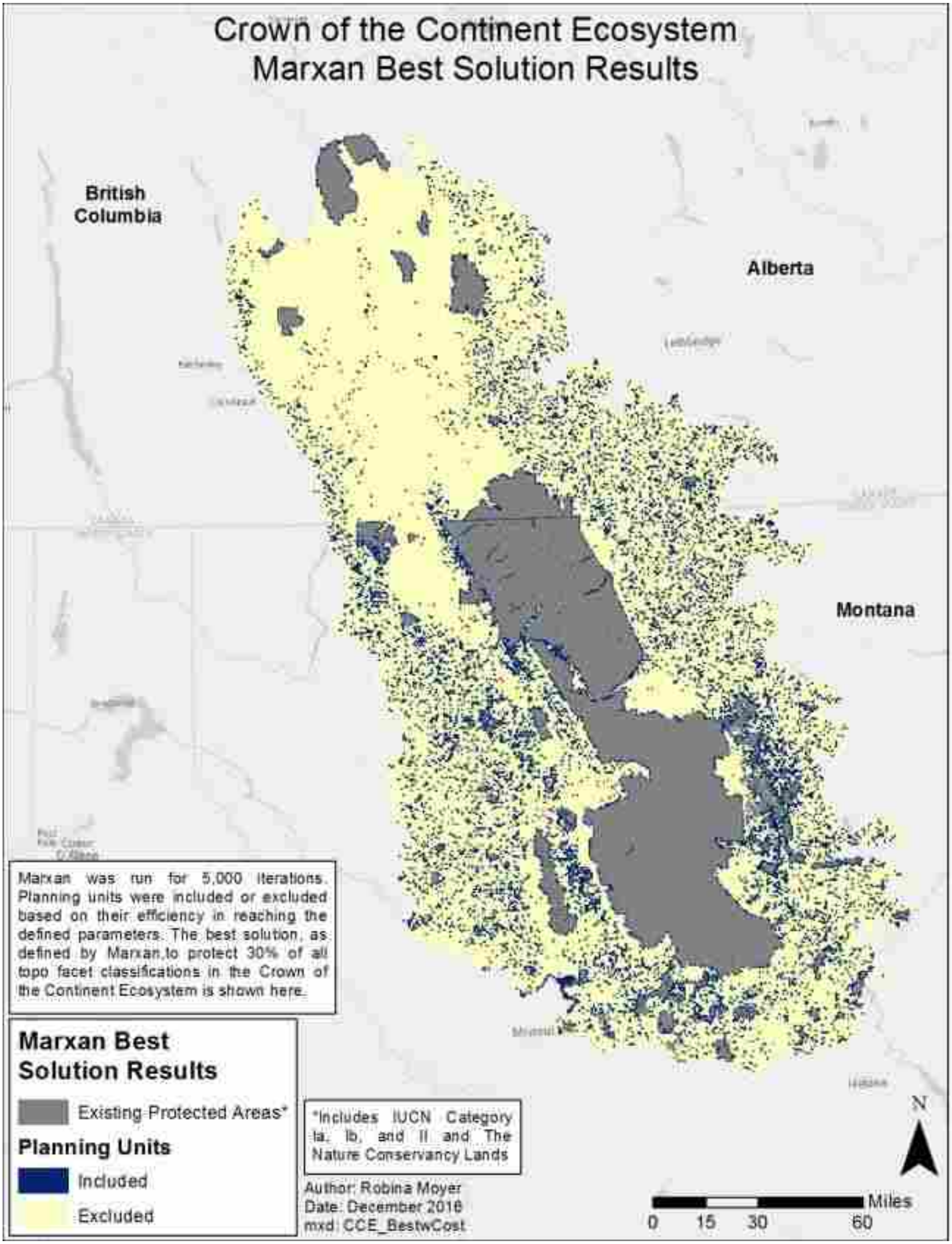


Marxan was run for 5,000 iterations. The summed results indicate the number of times a given planning unit was selected during those runs. The higher the number, the more useful that unit is in providing an efficient solution to protect 30% of all topo facet classifications in the Crown of the Continent Ecosystem.

*Includes IUCN Category Ia, Ib, and II and The Nature Conservancy Lands

Author: Robina Moyer
Date: December 2016
mxd: CCE_wCost

Figure 22: Summed topo facet Marxan solutions for the Crown of the Continent Ecosystem



Marxan was run for 5,000 iterations. Planning units were included or excluded based on their efficiency in reaching the defined parameters. The best solution, as defined by Marxan, to protect 30% of all topo facet classifications in the Crown of the Continent Ecosystem is shown here.

*Includes IUCN Category Ia, Ib, and II and The Nature Conservancy Lands

Author: Robina Moyer
Date: December 2018
mxd: CCE_BestwCost

Figure 23: Best topo facet Marxan solution for the Crown of the Continent Ecosystem.

5.0 Discussion

5.1 Background Literature and Review

5.1.1 Conservation Planning and Conserving Nature's Stage

The literature discussed supports the overall goal and methodology of the project, and it builds on previous systematic conservation planning efforts in the Crown of the Continent (Cross 2014; Nelson 2014). A land facet analysis by a cooperative organization such as Crown Conservation Initiative has the potential to be particularly robust as it combines the suggested practices such as replicating protected areas (Mawdlsey et al. 2009) and the benefits of working on a regional-scale (Heller and Zavaleta 2009). That does not mean that geodiversity-based planning is not without its detractors. Rodrigues and Brooks (2007) found it to be less effective than biodiversity-based planning in their review of surrogates. It is worth noting that study was completed before more recent geodiversity studies (Anderson and Ferree 2010; Anderson et al. 2015; Buttrick et al. 2015).

Based on the recent attention garnered by a land facets approach to conservation planning, the Crown Conservation Initiative was interested in applying the concept and completing a land facet-based analysis of the Crown of the Continent ecosystem to identify those facets that are under-represented. The literature reviewed in Section 2.0 supported this approach and the topographic and climatic variability within the Crown seemed likely to provide valuable results.

5.1.2 Setting Conservation Targets

Initially, there was discussion of having two representation targets, one at 20% and another at 50%. The 20% target was based on the Aichi Biodiversity Target and in recognition of planners who emphasize the challenges of balancing social and economic goals with conservation (CBD 2010, MacKinnon, et al. 2015), while the 50% target was ecologically-driven (Noss et al. 2011; Locke 2014). Ultimately, 17%, 30%, and 50% targets were used in the gap analysis, but only one target, 30%, was used in Marxan scenarios (CBD 2010, Noss et al. 2011, Locke 2014). It was decided that using only one target would lead to a more straightforward analysis As Marxan input files were created, it became evident that given the learning curve in learning Marxan, streamlining the process and using only one conservation target was more feasible. Even at 30%, the gap analysis results showed an overwhelming need for further protection along the Rocky Mountain Front and the western edge of the Crown. Given this result, it seemed that a 50% threshold was likely to further highlight those areas, potentially returning an overwhelming number of planning units without providing much actual utility for CCI (R. Nelson, Personal Communication 2016). Thus, 30% was chosen as a compromise between the two original values.

5.2 Datasets

5.2.1 AdaptWest

The AdaptWest dataset was chosen for this project because it covers the entirety of North America, not just the United States, eliminating the need to process multiple transboundary datasets into a uniform format. Additionally, multiple combinations of the AdaptWest data are available, providing the option to download just one of the components (elevation, latitude-adjusted elevation, land form, HLI, or soil order) or to download the already-combined topo facet or land facet layer, with raw or adjusted elevation (Carroll et al. 2015; Michalak et al. 2015).

AdaptWest was used because of its uniform 100 m resolution for the entirety of North America, however, once data processing began, it became apparent that this high resolution led to an unwieldy amount of data across the entire study area (approximately 7,219,096 pixels). The topo facet and land facet layers classified these pixels into 107 and 407 categories respectively, the former of which was much more manageable. As discussed above, the data is available in multiple pre-processed formats, allowing for an easy transition when the decision was made to use the topo facet layer instead of land facets. Still, the cross-tabulation of planning unit hexagons and land or topo facets turned out to be the most memory-intensive part of the project, resulting in memory errors when processed within ArcMap (Section 3.6.3).

The decision to use topo facets, instead of the more detailed land facets, was made in an effort to overcome the computing limitations being encountered during the cross-tabulation step. However, this trade-off is a limitation of the project results, which do not incorporate soil type. On one hand, the high number of land facet categories in the Crown reflects the diversity present, strengthening the case for conserving the area as a whole, but it also creates a logistical challenge for data management and processing.

AdaptWest data includes both raw elevation and latitude-adjusted, which attempts to account for the amplifying effect that latitude can have on temperature at higher elevations. For regions north of 23.5° north (the Tropic of Cancer), elevation was adjusted using a linear equation to account for decreased temperature and its potential impact on vegetation communities (Michalak et al. 2015, Colwell 2008). It was decided that latitude-adjusted elevation was approriate for the study area, which extends from approximately 46.6° to 50.6° north, spanning four degrees of latitude and high elevation terrain.

5.2.2 *IUCN*

At the outset of the project, there was considerable discussion as to what standard to use when designating protected areas within the study area. Initial conversations considered using designations unique to each country, state, and province, but the author and committee’s greater familiarity with United States’ designations and the lack of readily available information regarding Canadian designations made this option a challenge. A further review of available information led to the decision to use the existing IUCN protected areas database and categories, as they provide an established international standard and removed the guess work for transboundary management practices (IUCN 2014).

There are seven IUCN Protected Area designations to choose from. Based on the goals of the project, as established through discussion with Regan Nelson and Dr. Len Broberg (2016), it was decided to limit the categories used to only those that do not allow for the use of off-road vehicles, or any resource extraction. To align with these goals, Categories Ia, Ib, and II were used. As a result, Category VI, managed for “sustainable use of natural ecosystems,” was excluded; the designation given to Inventoried Roadless Area (IRA) of the United States Forest Service (IUCN 2014). Given that IRAs are currently managed with limits on timber harvest and road building in the US (36 CFR §294), this decision was discussed by Ms. Nelson, Dr. Broberg and Ms. Moyer; as a matter of international continuity and in acknowledgment of the potential for a change in management in the future, it was decided to use the top three categories listed above. It should be noted that there are no Category V designated areas within the Crown of the Continent.

Using IUCN protected area designations was not an immediately apparent option, as they are not talked about in American conservation planning as are domestic designations. If it were not for the transboundary nature of the project, it is likely that United States Geologic Survey Protected Areas Database, or a similar federal dataset would have been used instead. The ultimate use of the IUCN dataset broadened the applicability of the project and provides a methodology which could be replicated in other transboundary areas worldwide.

5.2.3 *Additional Protected Areas*

Within Montana, data was available for private land, owned or managed by The Nature Conservancy, primarily through conservation easements (TNC 2016). Based on conversations with Ms. Nelson, TNC lands were considered protected areas during the second suite of analyses, which looked at the Crown as a whole. However, Nature Conservancy Canada and other land trusts have protected areas that were not included in the analysis (most notably Mount Broadwood). Inclusion of these areas is recommended in any future analysis.

5.3 Software and Computing Power

5.3.1 *Computing Power and Limitations*

Creating the Planning Unit versus Conservation Feature input file for Marxan led to significant issues with available processing power. Some of these were overcome with the access to a VM provided by Aaron Deskins, but it too was incapable of cross-tabulating the land facet raster with a planning unit layer of high enough spatial resolution to provide any meaningful analysis. For future work, it would be useful to gain access to a larger machine, or explore the possibility of Google Earth Engine (GEE), a beta product from Google which allows for web-based analysis (2015). GEE relies on a mosaic system which farms-out processing tasks to hundreds of remote machines in order to efficiently process large datasets.

5.3.2 *ESRI ArcGIS Software Package*

ArcMap, the most widely-used program of ESRI’s ArcGIS software suite, is notoriously buggy and prone to crashing. At times during this project it earned this reputation, as memory limitations were encountered and crashing resulted from ArcGIS not providing a straightforward way to tally the type of pixels in each planning unit and instead performing a more complicated overlay operation. Aside from this issue, ArcGIS handled the high-resolution, large datasets well.

Both ArcMap 10.3 and 10.4 seamlessly integrated the Protected Area Tools Add-On (Section 0) (Schill and Raber 2012). Additionally, ArcMap’s join function allowed for the Marxan result files to be visually displayed without additional conversions. Frustratingly, at the conclusion of this project an updated set of GUI tools to integrate Marxan into Q-GIS and ArcGIS were released, these may be useful in future work (Wiens 2016).

5.3.3 *Protected Area Tools Add-On*

PAT was invaluable for the creation of hexagons and conversion from the tabular file structure that Excel produces and the matrix structure that Marxan requires. PAT provides a workflow for the entire process, but due to work that had already been done in other programs, it was only used for the above-mentioned processes. If the project were to be re-done, it may be advisable to incorporate the PAT Add-On at an earlier stage of the process as it allows users to streamline their workflow and operate almost entirely within the ArcMap environment.

5.4 Methods

5.4.1 *Research and Literature Review*

A significant amount of time was spent at the outset of the project researching conservation planning, land facet-based planning, climate adaptation and available datasets. While important theoretical background for the author, given that the question was already formulated around land facets, it may have been better to allocate more time to learning the intricacies of Marxan, as discussed below.

The methodology itself was straightforward, but limited prior knowledge of completing a gap analysis in GIS and no prior knowledge of Marxan resulted in a convoluted workflow and backtracking was required. The availability of IUCN and AdaptWest datasets, as well as Crown Managers Partnership vector files, which covered the entire study area and did not require any additional processing, streamlined the data collection process. It would have been infinitely more difficult if data from Montana, British Columbia, and Alberta needed to be collected and converted into uniform projections and designations prior to the gap analysis.

5.4.2 *Marxan*

Similar to the AdaptWest data set, Marxan provides a fine line between utility and an overwhelming number of options. Given the nearly 18 million acre size of the study area and the 100 m resolution of the land facet data, getting the data into the appropriate Marxan input format was a challenge in itself. It required clipping the data to the CCE in ArcMap, exporting the tables from the resulting rasters into Excel, formatting headers and removing extraneous columns, saving as a .dat file in Notepad, and then ensuring that all of the input files were in the same location to create a Marxan input file. Once this process was established, it was relatively straightforward, but finding the appropriate format and technique were time consuming. Additionally, finding other Marxan users at the University of Montana was difficult, making it hard to ask questions directly of another user familiar with the software. Eventually, through a separate project, Dave Albert, Conservation Science Director with The Nature Conservancy in Juneau, Alaska provided invaluable first-hand guidance.

Prior knowledge of ArcGIS and Microsoft Excel proved to be invaluable and general familiarity with command line, conversion between file formats, and basic coding were also helpful. The steepest learning curve was in understanding and using Marxan optimization software. If the process were to be repeated, participation in a Marxan course would be highly recommended. Having a better understanding of Marxan’s capabilities and input requirements would have helped better inform the questions asked of CCI at the outset.

5.4.2.1 Marxan Inputs

The decision to initially split the analysis into six sections was done with an understanding that it would be less robust than a Crown-wide analysis, but given the limited computing power available at the time seemed to be the best compromise rather than losing spatial resolution by drastically increasing the size of the planning unit hexagons. It was a valuable exercise in learning the functionality of Marxan and the results provide higher spatial resolution for the specific areas of interest. Fortunately, this challenge was ultimately overcome with access to a virtual machine.

Establishing appropriate input values took time and in some cases, such as the creation of a cost layer with Ms. Nelson, was a collaborative effort. Once input files were created, they were put into Inedit, which has an additional set of required parameters. These proved to be equally complex and required additional research and trial and error. In some cases, such as the BLM, the *Marxan User Manual,* provided explicit suggestions for the iterative process to use while testing possible values. For others, such as annealing settings, they stated that the defaults are produce satisfactory for beginner users and tinkering was not suggested (Game and Grantham 2008). The final inputs (Appendix D) were based on a combination of trial and error, the manual's guidance, and consultation with other users (D. Albert, personal communication 2016). When trial and error resulted in illogical results, that was noted and values were changed accordingly. Marxan input variables were arguably the most subjective portion of the study. A more experienced user may have used more nuanced values, however, based on the process described above and the results produced, it is believed that the final inputs are logical and defendable.

5.4.2.2 Marxan Outputs

Similar to the challenges of understanding the inputs and variables needed to run Marxan, there was a learning curve in understanding the results as well. The user manual and consultation with Dave Albert provided insight here as well. Mr. Albert was in favor of the utility of the summed solution output, as it tells you the frequency a planning unit is returned in multiple scenario runs. His experience includes an analysis of a similarly sized study area, albeit with significantly fewer conservation features used. Knowing that a unit was returned a high number of times speaks to its use in an efficient reserve design and helps account for some of the uncertainty inherent in conservation planning. In addition, Ms. Nelson was interested in the best run solution from multiple scenario iterations for its utility in providing more definitive boundaries for future protected areas. Both solutions are displayed for the Crown-wide analysis.

5.5 Results

5.5.1 Gap Analysis

The use of a gap analysis was a logical and useful first step for the (Section 2.1.1; Scott et al. 1993; Margules and Pressey 2000; Groves et al. 2002). Unsurprisingly, the results of the CCE land facet gap analysis using IUCN protected areas and TNC land (Figure 17 and Figure 18) show that the land facets unique to the core of the CCE, along the spine of the Rocky Mountains are well protected, while those on the fringes, particularly the prairie along the Eastern Front are under-protected. These areas are dominated by private land, First Nations and Native American reservations, and provincial land (Figure 16). This ownership pattern is in part the result of desirable agricultural lands and historic resource extraction, which has led to limited protected areas along the outer extent of the Crown. While the gap analysis results may seem like a redundancy of the protected areas map (Figure 8), it emphasizes the need for increased conservation on private land in the United States and on provincial land in Canada.

5.5.2 Marxan Topo Facet Analysis

As initial Marxan results were analyzed, it was clear that similar to the gap analysis, they too highlighted the western and eastern edges of the CCE (Figures 19 - 23). Though at first frustrating, upon further reflection this result makes sense – Marxan is providing a solution which most efficiently helps you reach the set target, in this case 30% of all land or topo facets. Given that the initial inputs included only the inherent spatial costs, not additional factors such as land ownership, it is logical that there would be myriad ways to protect more plains, for instance, and reach the 30% goal. As discussed in Section 5.4.2, one of Marxan's strengths is its flexibility and ability to provide many options regarding how to most efficiently reach a set target. However, depending on your hoped for outcome, this strength may also be a weakness, as Marxan may provide an overwhelming number of options, of equal efficiency. Marxan creator Hugh Possingham has addressed this stating: "For any reasonably complex Marxan problem there are more possible solutions than there are stars in the universe" (Ardron 2010).

Keeping this in mind highlights the necessity of using Marxan results in concert with other desired criteria, such as connectivity or known rare species occurrences. This conclusion is supported by conservation scientists, including Lawler et al. who state "conserving abiotic diversity alone will not be sufficient for protecting biodiversity in a changing climate. Theory and practice both suggest that conservation of different abiotic settings must always be complemented with conservation efforts that attend to species themselves, particularly species sensitive to human actions and landscape intervention" (2015). This is especially important in an area such as the Crown, which has existing conservation projects underway and an extensive human impact. The fact that the Marxan results do not highlight some of the areas where targeted conservation work is already occurring, such as Badger-Two Medicine and the Castle Wildland Park should not be seen as detracting from the importance of those projects (CCI 2014b). By looking at only abiotic factors, Marxan is inherently unable to parse out areas of cultural importance, or that are species-specific as identified by a fine-filter. Marxan is better viewed as a coarse-filter method to enhance support for, or refine the boundaries of, already proposed protected areas rather than the foundation for an entirely new set of proposed protected areas. The presence of underrepresented topo/land facets in areas proposed for conservation for other reasons is an additional motive to conserve those lands. Such locations may not emerge in a Marxan analysis but are found through the gap analysis, illustrating the value of those results.

5.5.3 Results Validation

Validation of results was an iterative process throughout the project. Based on the *Marxan User Manual* and consultation with Dr. Anna Klene, the primary method of validation was visual assessment, achieved by confirming that findings seemed reasonable to those familiar with the study area (Game and Grantham 2008). With the initial runs of Marxan in British Columbia, an artifact of a merged planning-unit layer resulted in a noticeable line across the province in the Marxan output. Through visual inspection, Dr. Broberg and Ms. Nelson both caught this error and the method for creating the hexagon layer was reassessed and refined, eliminating the error in future runs. Throughout the process, Dr. Broberg and Ms. Nelson reviewed visual outputs, in part to evaluate if they seemed to show reasonable trends given their extensive knowledge of the Crown of the Continent Ecosystem.

While visual analysis is the primary method of validation discussed in the user manual, they also suggest some form of sensitivity analysis; Dr. Klene agreed with the value in this method. Sensitivity analysis typically involves changing the values of input variables and assessing the results, looking for results that vary from the anticipated outcome, indicating a problem with the model, or a misunderstanding of a variables function (Jensen 2016). Again, this process was somewhat integrated into the workflow as Marxan variables were explored through trial and error. Given the nature of the research question and time limitations, some variables, such as conservation targets were not played with, while others, such as boundary length modifier (BLM) were tweaked extensively. In the course of establishing the limits of available computing power, planning unit size was altered to some extent. Trial runs were completed with planning units larger than 50 ha and 100 ha and the same general pattern emerged. Additionally, the initial sectioned analysis showed similar results to the Crown-wide analysis with the Eastern Slopes and southwest corner being highlighted as priorities for future protected areas.

It is not uncommon for remote sensing validation to include some sort of statistical analysis, but given the nature of the project, no statistical methods were employed. Statistics will often look at the accuracy of a model based on known values (i.e. landcover), but given the high number of variables and human subjectivity involved with reserve planning, there is no ‘correct answer’ with which to compare the results. This conclusion was discussed with Dr. Klene, who was in agreement.

6.0 Recommendations

The results of the gap analysis show, that while the core of the CCE is well protected, that when using land or topo facets as a conservation measure, there is still significant work to be done as the facet categories which do not meet the 17% Aichi target threshold make up more than 50% of the area within the Crown (Table 10). As shown in Figure 22 and Figure 23, Marxan identifies several areas where additional conservation can the boost the CCE protected area portfolio toward 30% protection for topo facets.

Based on those Marxan results, it is recommended that CCI explore options for the creation and expansion of protected lands along the Rocky Mountain Front/Eastern Slopes and in the southwestern portion of the Crown. In particular, opportunities for private conservation in both the US and Canada should be investigated along the Front. The plains ecosystem has been perennially under-represented in protected areas and the land facet analysis highlights an additional reason why it is important to all ecosystems, current and future, within the Crown.

However, it is not recommended that land facets alone form the basis for a protection campaign, but rather in concert with fine-filter conservation measures to enhance established conservation priorities. This is particularly true in the Crown, where there are numerous ongoing protection campaigns. For example, the North Fork Flathead River valley, which has been a conservation priority for decades, and appears in the summed solution results (Figure 22) as an important area for topo facets. This information could supplement the existing campaign, highlighting that in addition to having current ecological value, the North Fork is important for land and topo facet representation within the Crown. Alternately, the topo facet results layer could be overlaid to identify overlap with the proposed area, or if increased topo facet representation is possible by slightly modifying proposed boundaries.

Identifying the presence of under-represented land or topo facets within areas identified as conservation priorities is another useful application of the data. For instance, it is likely that some under-represented facets are present in the Badger-Two Medicine area, even though Marxan does not include them in the most efficient outcomes for a Crown-wide facet focused conservation plan. Moreover, conservation of land facets in large regional planning efforts, such as U.S. Forest Service forest planning would be useful. This Crown-wide gap analysis has identified under-represented facets for emphasis in such processes.

With the Crown-wide analysis available, the jurisdictional analyses can be placed in a larger perspective, but adapted to work with the policy/management systems that are tied to those political jurisdictions (provincial, state, tribal, US/Canada). Thus, while the full Crown analysis was the overall goal of this work, the regional analyses in Marxan could prove very useful in working with governments to achieve conservation of nature's stage. Use of the two analyses together is recommended.

6.1 Further Work

It is suggested that topo/land facets are mapped in current conservation targets, such as the proposed Waterton National Park Expansion. This process should focus on under-represented facets, in an effort to identify how protecting these targets may increase those facet's representation in protected areas. As discussed previously, the presence of under-represented facets in a conservation target provides yet another reason as to why that area is valuable and should be protected. Alternatively, if it is found that under-represented facets exist just beyond the boundaries of an area currently proposed for conservation, slight modification of those boundaries to include those facets could be explored.

The gap analysis and Marxan process should be redone with the inclusion of Canadian conservation land, such as the Elk Valley Heritage Conservation Area, owned by Nature Conservancy Canada (NCC) and Tembec, a Canadian forest products company (NCC 2016). This area, located in British Columbia, includes Mt. Broadwood, as well as corridors identified as for large carnivore movement. These lands, as well as other private conservation in Canada, were not included in the CMP jurisdictional layer and ultimately omitted from the gap analysis and Marxan results. It is recommended that they be included in future work.

A Montana-wide Marxan analysis may provide more specific results, useful for both public and private conservation planning. Federal agencies, such as the U.S. Forest Service, now have a mandate to consider climate change as they develop projects and management plans. The availability of under-represented facet data would enable these agencies and other interested parties to review how proposed plans impact facets. Including under-represented facets in conservation plans may be an avenue for agencies to show that they are considering climate adaptation in their planning process.

Finally, a Crown-wide analysis using the land facet layer should be explored. It was not possible within this project due to computing limitations, but alternative methodologies to achieve an analysis may be possible. This could include the use of resources such as Google Earth Engine, which allows users to process large amounts of data by utilizing a network of remote machines. Based on the results of the gap analysis and the familiarity with the datasets gained through this project, it is hypothesized that a Marxan land facet analysis would show a similar trend to the topo facet results, but with more refined areas of efficiency shown in the final solutions.

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