ECOSYSTEM GOODS AND SERVICES SOUTHERN ALBERTA

A FRAMEWORK FOR ASSESSING NATURAL ASSET CONDITION

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SUBMITTED TO:
ALBERTA ENVIRONMENT

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Society's well-being, to a large extent, is underpinned by a wide range of Ecosystem Goods and Services (EGS) that are provided by natural assets. These include:

- provision of clean air and water;
- water storage and flood control;
- carbon sequestration and greenhouse gas regulation;
- pollination of crops and native vegetation; and
- the fulfillment of cultural, spiritual, and recreational needs.

The transfer of EGS to future generations is compromised if land use planning does not prevent the degradation and loss of natural assets in the landscape. Alberta's new Land Use Framework (LUF) provides opportunities to address interactions between society, nature, and EGS to promote sustainable development. The ecosystem services concept frames land use planning and natural resource management issues to explicitly link ecosystems and human welfare. This provides decision makers with more information to help them achieve an appropriate balance between the many costs and benefits of land use decision-making. Building on previous work, this report contributes to this process by identifying indicators of natural asset conditions, linking these indicators to ecosystem services, and suggesting a methodology for assessment in a land use planning context.

Several key findings should be highlighted from the literature review. One prevalent theme suggests that focusing management efforts on provisioning services (i.e., crops, timber, fossil fuels) often results in tradeoffs where other ecosystem services are degraded as a consequence. Another key theme is the importance of multi-scale approaches to ecosystem service assessments (e.g., regional, landscape, watershed, site). A third key finding is the lack of available biophysical methodologies to quantify ecosystem service magnitudes, as most quantification studies utilize economic valuation techniques. In addition, appropriate thresholds and targets are rarely identified through scientific research, although some science-based targets have been identified for wetland cover (3% to 7% of a watershed), impervious surfaces (<10% of a watershed), riparian buffer widths, and road densities. In most cases, target-setting requires integration of science and societal valuation. The landscape context also must be considered when setting targets, as appropriate values often vary considerably throughout a given region.

Building on the information gained from the literature review, this report identifies a suite of indicators to assess ecosystem conditions and related services at multiple scales. Six criteria were used to assess the suitability of indicators:

- comprehensibility for both professionals and the lay public;
- range of applicability to multiple ecosystem services;
- responsiveness to management practices;
- measurability of cost effectiveness;
- ease of integration with existing programs and data; and,
- relevance within land use planning (predictable in scenario modelling and related to published scientific thresholds).

Indicators are necessary at both fine and broad scales. The suggested set of broad-scale indicators includes (in order of highest to lowest total scores for the assessment criteria):

- impervious surfaces in watersheds (% of area);
- natural asset composition of the landscape (% of area);
- landscape-specific natural assets (e.g., % coniferous forest in the foothills, etc.);
- natural asset patch sizes;
- riparian buffers (naturally vegetated);
- wetlands (% of area);
- connectivity through corridors and stepping stones;
- road density; and,
- habitat diversity.

Broad-scale indicators, natural asset condition, and ecosystem services relate strongly to one another. This report qualitatively outlines these relationships using extensive references to peer-reviewed literature to illustrate that:

- Watersheds with less impervious surfaces contain lakes, rivers, and land in better condition, providing more EGS;
- Large patches of natural vegetation provide more EGS than small, fragmented habitats;
- Naturally vegetated riparian areas provide more EGS than those that are cropped or built out;
- Watersheds with more wetlands contain lakes and rivers in better condition, providing more EGS;
- Natural patches connected by corridors or stepping stones provide more EGS than more dispersed habitats; and,
- Areas with low road densities are in better condition and provide more EGS than areas with high road densities.

The assessment and selection of fine-scale indicators aims to build on the existing work of provincial resource management and ecological specialists. For cost-effectiveness, it is suggested that the broad-scale indicator assessment be used to prioritize areas for fine-scale assessment. Those areas that are both important to EGS and under imminent land use threat may be the most important areas for targeting fine-scale site assessments. However, fine-scale assessments should also be part of pure and applied research on baseline conditions and reclamation techniques.

The set of recommended fine-scale indicators includes (organized by natural asset type):

- Grassland, Prairie Shrub and Forest Shrub: (i) Range Health Assessment Score, (ii) Soil Organic Matter
- Deciduous and Mixed Forest: (i) Canopy Structure, (ii) Presence + Abundance of Dead Wood Resources
- Coniferous Forest: (i) Age Class Distribution, (ii) Tree Crown Condition

- Riparian: (i) Riparian Health Index
- Lentic: (i) Water Levels, (ii) Trophic Status (chlorophyll-a)
- Lotic: (i) Alberta River Water Quality Index, (ii) Indicators of Hydrological Alteration, and (iii) Fish-Based Index of Biotic Integrity
- Wetlands: (i) Wetland Water Storage Functional Capacity Index, (ii) Wetland Health Score

This report also provides a methodology to integrate broad and fine scale conditions into a common framework for assessment, which has been structured to provide application to land use planning in the near future. The suggested process for applying this framework is outlined as follows:

- Define boundaries of regions and sub-regions (landscapes, sub-basins, etc.);
- Assess broad-scale indicators and provide maps of regional and landscape conditions linked to EGS;
- Based on the methods identified through previous research [165], map ecosystem services, including the EGS hotspots most important for multiple goods and services (note: this is only one approach to EGS mapping and more sophisticated tools can be developed in the future);
- Integrate the above steps using a Geographic Information System (GIS) to identify the existing Green Network of Natural Assets that provides an important set of EGS;
- Set targets for broad-scale indicators by considering available scientific information, stakeholder feedback, land-use planning tradeoff analyses, and desired land-use outcomes;
- Conduct a gap analysis to identify areas where restoration may be required to improve the Green Network and meet the selected targets (e.g., denuded riparian areas targeted for permanent cover programs);
- As part of the planning process, identify current and potential land use threats or stressors to the Green Network;
- Prioritize areas within the Green Network for more intensive site sampling of fine-scale indicators (this detailed information is particularly important where compensation for impacts is considered); and,
- Develop a management and conservation strategy for high priority lands; this may include best management practices for operating within the Green Network, and/or protection incentives (e.g., zoning, conservation easements, transfer of development credits, etc.).

The assessment framework above focuses primarily on broad-scale indicators, as they provide the most immediate links to land use planning. Fine-scale condition assessments do not translate easily into land use planning processes, as they are typically expensive and impractical to conduct over regional scales. However, many broad-scale indicators affect fine-scale conditions, and knowledge of these relationships will likely improve over time as more research is conducted. Therefore, it is suggested that long-term adaptive management be undertaken to improve knowledge of the interrelationships between broad-scale indicators, fine-scale indicators, and ecosystem services. In this manner, continual improvements in resource management will occur within iterative land use planning processes.

1.0 INTRODUCTION

In 2006, an assessment of ecosystem goods and services (EGS) in southern Alberta was initiated by Alberta Environment (AENV). The EGS assessment was intended to provide important background information in support of developing the Southern Alberta Landscapes (SAL) regional strategy and to identify areas of further investigation and study regarding the importance of EGS in southern Alberta. The geographical scope of the EGS assessment includes the southern portion of the province of Alberta, referred to as 'southern Alberta' in the current document (Figure 1-1). For the most part, the northern limit of the area generally corresponds with the boundary of the South Saskatchewan River watershed.

The project was conceived as a two-phase effort: Phase one involved the completion of a survey of ecosystem goods and services initiatives in southern Alberta and elsewhere (*Ecosystem Goods and Services Assessment – Southern Alberta, Phase 1 Report: Key Actors and Initiatives*) [164] while the second phase was a subjective, qualitative evaluation of the relative priority of ecosystem services to society in southern Alberta (*Ecosystem Goods and Services Assessment – Southern Alberta, Phase 2 Report: Conceptual Linkages and Initial Assessment*) [165]. The purpose of the Phase two EGS study was to identify which ecosystem goods and services are a priority in southern Alberta for sustaining the region's vibrant economy and quality of life. The objectives of the Phase two EGS assessment were to: a) inform people about ecosystem goods and services and how they are important to economic production in southern Alberta, b) help people understand how land use decisions and human activities impact these services, c) determine what landscape patterns are required to sustain the ongoing delivery of ecosystem goods and services and, d) undertake a gap analysis to identify directions for further study and investigation.

A subsequent third phase, executed in 2008, identified and mapped ecological infrastructure in southern Alberta and explored the linkage between landscape patterns and the provision of ecosystem goods and services (*Ecological Infrastructure Mapping – Southern Alberta Region*) [255]. Geographic Information Systems (GIS) models were constructed and applied to the southern Alberta region in order to identify areas of ecological infrastructure.

Since completion of the first three phases, the SAL initiative was replaced by the Southern Alberta Regional Plan (SARP) concept, which, as of December 2008, was replaced by the South Saskatchewan and the Red Deer Planning Regions in the new Land-Use Framework (LUF). The current study is intended to support the inclusion of ecosystem services within planning efforts under the LUF [143]. This project builds on the first two project phases by developing a framework to assess the condition of natural assets (land cover types) in southern Alberta with respect to the provision of ecosystem services and goods. There is a direct, though not always linear, relationship between the condition of natural assets and the type, quantity, and quality of services they provide. The objective of the current project is to explain and summarize this relationship. The focus is on identifying key components that constitute asset condition and providing measurable indicators of ecosystem services.

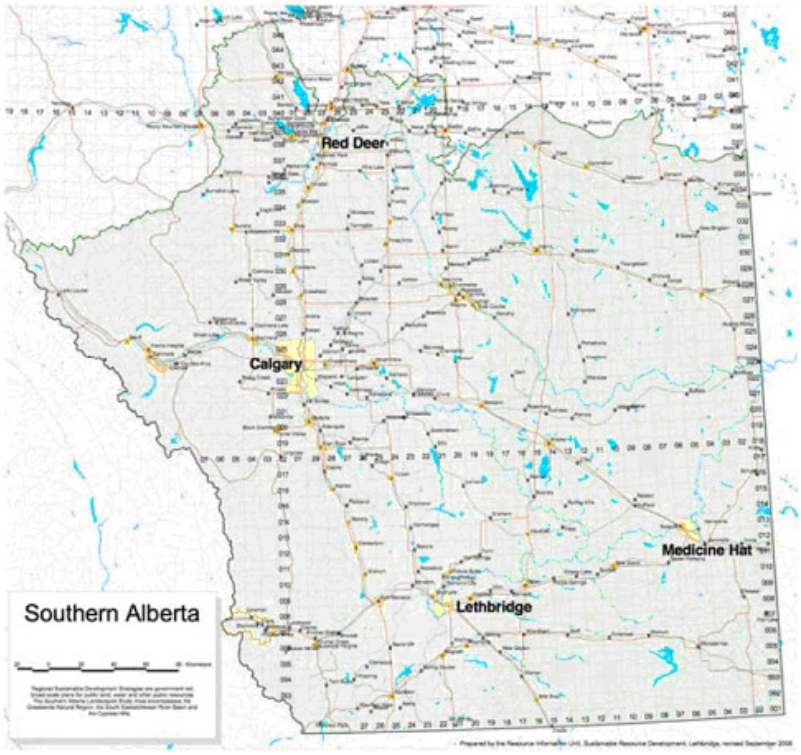


Figure 1-1 The EGS assessment area

1.1 Report Structure

Section 1.0 presents an introduction to the project and describes the theoretical background from which the literature on EGS and natural asset condition and indicators evolved. Section 2.0 summarizes a literature review and presents trends and general findings related to overall project objectives.

Natural asset condition can be evaluated across a spectrum of scales. Broad-scale components of asset condition are examined on a landscape scale, whereas fine-scale components are examined at the site level for individual patches of natural asset types. These components are discussed in Section 3.0.

Section 4.0 introduces a set of criteria for assessing the utility and ability of indicators to reflect the influences of asset condition on the ecosystem services provided by natural assets. Sections 5.0 and 6.0 identify and assess a number of broad-scale and fine-scale indicators, respectively. Cross-scale indices developed by various researchers and institutions are identified in Section 7.0. Section 8.0 discusses and summarizes how indicators of asset condition are linked to evaluating the provision of ecosystem services and provides a summary of recommended indicators for moving forward.

Further details on the project are described in the Appendices. Appendix A summarizes the literature review methodology and the database structure in which the results are organized. A list of further potential indicators of asset condition for future reference is given in Appendix B, although these are not currently recommended as priorities. Appendix C describes existing monitoring programs and data collection programs in Alberta, in order to support synergies where existing data and monitoring systems could be adapted towards measuring and monitoring ecosystem services.

1.1.1 Project Scope and Approach

The scope of the project is to develop a framework for assessing the condition of natural assets in southern Alberta with respect to their ability to provide ecosystem services.

Natural assets refer to the stock of natural resources in southern Alberta. They represent different natural land cover types, such as grasslands, forests, aquatic, and geological systems. In contrast, anthropogenic assets are defined as land cover types created by humans, the footprint of which now occupies areas of former natural assets [165]. This project only considers ecosystem services derived from natural assets. While anthropogenic assets can also provide ecosystem services (e.g., carbon sequestration in cropland), a large number of variables affect service provision (e.g., fertilizer and pesticide use, tillage practices, species planted). Therefore, for simplicity, anthropogenic assets are beyond the scope of the current project.

While the concept of EGS includes both (i) ecosystem services and (ii) ecosystem goods, this study focuses on the former. This can be justified since the production of goods is supported by ecosystem services (Figure 1-2).

This study largely conceptualizes ecosystem services as the generation of ecosystem processes or functions [46]. This is consistent with most ecological research conducted today. However, in environmental economics, 'ecosystem function' refers strictly to an environmental process (e.g., water flow), whereas an 'ecosystem service' relates a given process to a human beneficiary (e.g., water use). This study does not assess the more complex problem of relating ecosystem services to human beneficiaries.

To initiate the process of a framework for assessment as described above, a literature review was conducted. Topics researched included (Section 2.0):

- indicators of ecosystem services provided by natural assets, with a focus on the eight 'priority' services identified in the *Phase Two Report* (climate regulation, disturbance regulation, erosion control/sediment retention, biological control, nutrient cycling, primary productivity, water supply, and recreation);
- how drivers of ecosystem change alter the condition of natural assets and how this directly affects the supply and delivery of ecosystem services; and,
- threshold and/or desirable conditions of ecosystem service provision for different natural asset types.

The following ideas were then extracted, analyzed, and discussed in subsequent sections:

- the scale at which natural asset condition is measured (Section 3.0);
- desirable qualities of measurable indicators (Section 4.0);
- types of indicators that can measure natural asset conditions (Sections 5.0, 6.0 and 7.0);
- relationships between natural asset conditions and ecosystem services (Sections 5.0, 6.0 and 7.0);
- thresholds or targets for indicators (Sections 5.0, 6.0 and 7.0).

A framework for assessment was then developed that integrated these components into a suggested operational methodology for application in southern Alberta (Sections 3.0 and 8.0).

1.2 Ecosystem Goods and Services

A recent review of biodiversity monitoring programs noted that "many proposed and existing indicators do not connect clearly with human welfare and are unlikely to engage the interest of governments, businesses, and the public until they do so" [25]. To address this problem, better linkages between conservation strategies and implications for human welfare are necessary. The Ecosystem Good and Services (EGS) concept provides a means for this to occur.

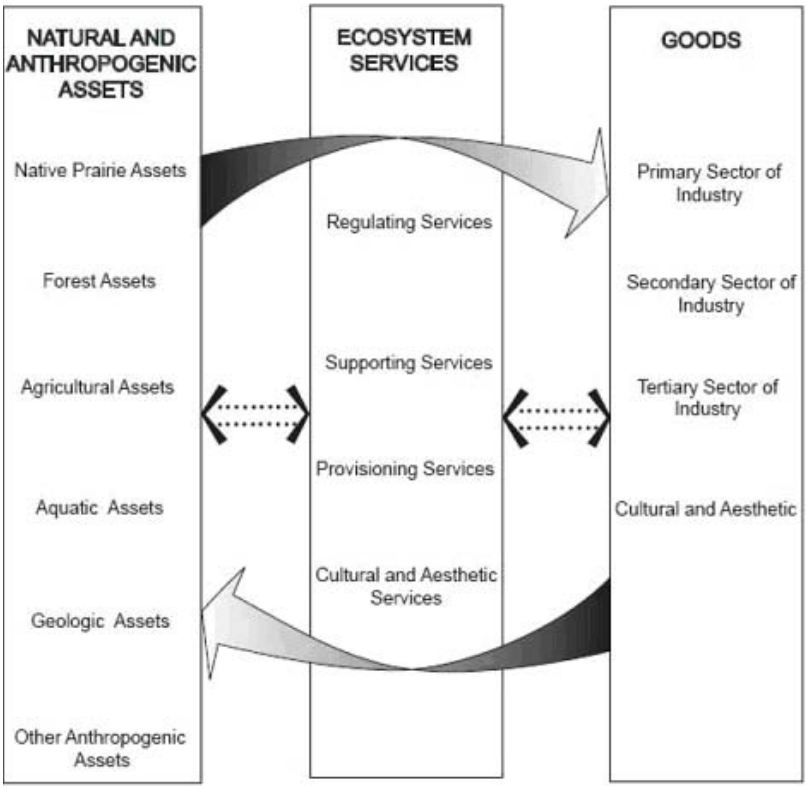


Figure 1-2 Conceptual representation of ecosystem services

Ecosystems, and the biodiversity contained within them, provide a stream of goods and services which are essential for society's wellbeing. Ecosystem goods and services (EGS)[1] are the benefits people obtain from nature. Examples of goods and services include:

- provision of food and fibre;
- provision of clean air and water;
- water storage and flood control;
- pollination of crops and native vegetation; and,
- fulfilment of people's cultural, spiritual, and educational needs.

EGS can be broken down into two distinct components: 'ecosystem goods' and 'ecosystem services'. Ecosystem goods are the products or outputs obtained and consumed from the environment. Ecosystem services are the conditions, functions, and processes through which natural ecosystems, and the species which comprise them, sustain and fulfill human life [39, 98, 100, 227, 352]. These services are critical inputs to the production of economic goods, are essential for the ongoing maintenance of critical life-support systems, and confer a wide range of highly valued non-market benefits. They provide the essential, low-level infrastructure upon which human activities and built systems rest [153].

1 Terms such as environmental or ecosystem goods and services are often used to describe EGS. Consistent terminology does not exist in the literature. For Alberta's purpose, it is assumed that all of these terms refer to the same concept that society's wellbeing is dependent on the provision of goods and services from the environment.

In 1997, a landmark study by Costanza et al. [85] calculated the approximate value of ecosystem services worldwide at approximately US $33 trillion per year. More recently, the Millennium Ecosystem Assessment [228] refined and applied the ecosystem services framework to assess the consequences of ecosystem change for human wellbeing. Although some ecosystem services can be partially replaced by technology, engineered solutions are temporary and often less cost-effective than those considering EGS [46]. For example, New York City calculated over $6 billion in savings from a strategy of maintaining forests and agricultural buffers in its' watersheds as opposed to building a new water-filtration plant [86].

The ecosystem services framework is increasingly applied by regulatory agencies [71]. For example, the USEPA is conducting a multi-year research program to contribute to a "comprehensive theory and practice for characterizing, quantifying and valuing ecosystem services" so that these services are considered appropriately in decision-making [354]. Long-term goals of their research program include:

- effective decision support;
- mapping, modelling, and monitoring of ecosystem services at multiple scales;
- pollutant-specific studies (nitrogen pollution);
- ecosystem-based demonstration projects for wetlands and coral reefs; and,
- place-based demonstration projects in several regions.

The ecosystem services framework is starting to be applied by regulatory agencies in multiple regions. In Australia, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) is coordinating an ecosystem project to study the services people obtain from their environments, and the economic and social values of these services. The ultimate aim is for scientists and communities to learn how to deliver the right information to policy developers and decision makers and move towards more sustainable land management practices [95].

In China, the Natural Forest Conservation Program and the Grain to Green Program are major ecosystem service programs designed to restore erosion control, water supply, and flood control services to degraded landscapes, with total planned investments exceeding 700 billion Yuan (approximately US $95 billion) [207]. The scale of these investments illustrates the high costs associated with restoring degraded ecosystem services.

In summary, the ecosystem services concept allows decision-makers to explain how conservation strategies are linked to the economy and human welfare. The concept provides a way to frame resource management and land use planning issues in a manner that increases our understanding of these linkages. In addition, most of the examples of regulatory agencies applying the concept do so as a reaction, partial or otherwise, to ecosystem degradation.

1.2.1 Natural Assets and Ecosystem Services in Southern Alberta

Land use is inherently linked to the characteristics of natural assets, their management, and the ecosystem services they provide. Many studies have noted how ecosystem functions are altered by land use change [148, 279, 292]. Other studies have examined the links between asset condition and ecosystem service provision [68, 139].

Southern Alberta contains a variety of natural assets which reflect the diversity of climate, landforms, and vegetation in several Natural Regions, including the Grasslands, Parkland, Rocky Mountain, Foothills, and Boreal Forest Natural Regions [250]. For the purposes of this study, the 18 natural assets identified in the *Phase 2 Report* [164] were grouped into 11 natural asset types as follows:

- Grasslands (including: Needle and Thread Dry Mixed Grass, Northern Wheat Dry Mixed Grass, Needle and Threat Sand Grass – Dry, Mixed Grass, Fescue Grasslands, and Rocky Mountain / Parkland Fescue)
- Prairie Shrub
- Badlands and Thin Breaks
- Forest Shrub
- Deciduous and Mixed Forest (includes two natural assets: Hardwood Forest and Mixed Wood Forest)
- Coniferous Forest (includes two natural assets: Spruce / Fir Forest and Pine Forest)
- Riparian (includes one natural asset: Prairie Treed / Riparian Cottonwood)
- Lentic
- Lotic
- Wetlands
- Geological (includes two natural assets: Bare Soil / Rock and Ice).

A list of ecosystem services in southern Alberta is provided in Table 1-1.

Table 1-1 Ecosystem services in Southern Alberta [165]

Regulating Services	Supporting Services	Provisioning Services	Cultural and Aesthetic Services
Gas Regulation	Soil Formation	Water Supply	Aesthetic
Climate Regulation	Primary Production	Food Production	Spiritual and Traditional Use
Disturbance Regulation	Nutrient Cycling	Raw Materials	Science and Education
Water Regulation	Pollination	Genetic Resources	Recreation
Erosion Control and Sediment Retention	Habitat/refugia		
Waste Treatment			
Biological Control			

As per the assessment of ecosystem service importance undertaken in the *Phase 2 Report*, the services defined and outlined below were chosen as priorities for the current study.

Climate regulation refers to the regulation of temperature, precipitation and other climatic processes at both global and local levels. Climate regulation has a close relationship with gas regulation through the regulation of greenhouse gases in the atmosphere, notably carbon dioxide. The importance of local climate in southern Alberta to agricultural production has a significant economic effect.

Disturbance regulation refers to the dampening of environmental disturbances and perturbations that can result in significant loss of human life and economic consequences. This includes the services of flood prevention (regulation by forests and wetlands) and storm protection. Forests on the Eastern Slopes of Alberta are important in controlling spring runoff and minimizing flood damage.

Erosion control and sediment retention refers to the process of minimizing soil loss by wind and runoff processes through the role of the vegetative root matrix and soil biota in soil retention. In southern Alberta, this is important for maintaining the fertility of arable land. The process is also important for controlling the release of sediment to aquatic systems and avoiding increased sedimentation in lakes and rivers.

Biological control refers to the maintenance of predator prey relationships and control of pests and diseases through species interactions. An example of the importance of this service in southern Alberta is research into the biological control of grasshopper populations as an alternative to chemical pesticides.

Nutrient cycling refers to the storage, internal cycling, processing and acquisition of nutrients through the various biogeochemical cycles (e.g. nitrogen, oxygen, sulphur, phosphorus, carbon, and other cycles). In southern Alberta, these 'unseen' processes are important for the maintenance of healthy and productive soils and ecosystems.

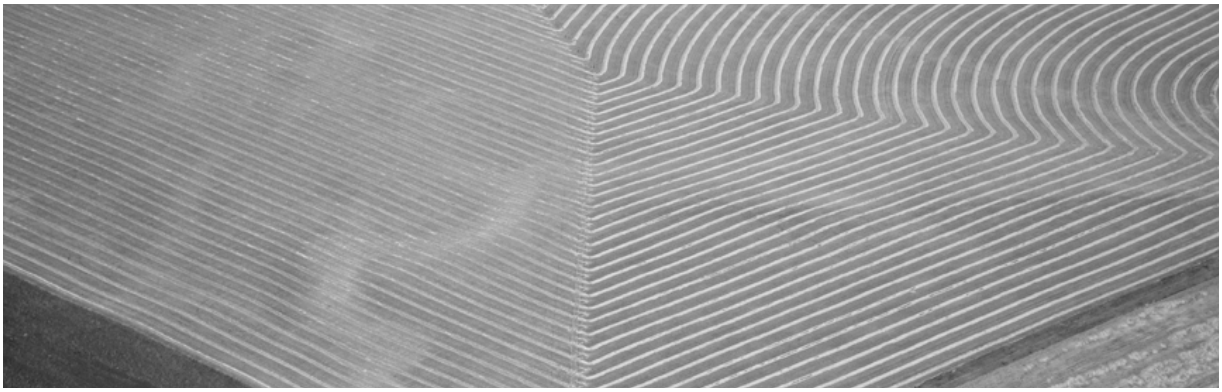
Primary production refers to the conversion of sunlight and CO_2 into biomass. In southern Alberta, primary production is essential to the growth of agricultural crops and the maintenance of healthy grasslands vital for livestock grazing.

Water supply refers to the storage and retention of water by watersheds, reservoirs and aquifers. In southern Alberta, a dependable supply of fresh water is vital for industry (e.g., food manufacturing/processing, oil and gas), agriculture (e.g., irrigation), human consumption (e.g., drinking, bathing, cooking, and watering), and power production (e.g., Spray Lakes reservoir).

Recreation services are those that provide opportunities for rest, refreshment, and recreation. These services provide non-market recreational benefits and include activities such as eco-tourism, bird and nature watching, hiking, boating, climbing, and sportfishing. A wide variety of recreational benefits are provided by lakes in southern Alberta, such as those available at Kinbrook Island and Beauvais Lake Provincial Parks.

Ecosystem services are critical to maintaining society's well-being, yet are rarely fully considered in making land use decisions. The ecosystem services framework provides a means of integrating a greater consideration of these services into land use decision-making in order to help maximize benefits to people as well as the environment. Natural assets provide a number of key ecosystem services, which are increased when the natural assets are in good condition. Defining asset conditions with respect to ecosystem services and operationalizing their assessment across southern Alberta are the goals of the current study.

2.0 LITERATURE REVIEW



This section summarizes some key findings from the literature, including an overview of broad- and fine-scale measures of asset condition, quantification of ecosystem services, scales of analysis, and ecosystem changes that affect service provision. Existing research gaps are also noted.

2.1 Assessment and Monitoring of Natural Asset Condition

Exploring the spatial characteristics of natural assets in the landscape is a necessary first step for understanding the condition of assets. Geographic landscape metrics of natural asset configurations have been developed in several fields of study, including landscape ecology [111, 133] and forest management [135, 379]. Landscape ecological patterns (e.g., connectivity, patch sizes, configuration of cover types) affect natural asset condition as well as the services ultimately provided by those assets. Literature analyzing the spatial context of natural assets includes:

- analysis of how the configuration of natural cover types provides flood mitigation benefits [68];
- the importance of scale and landscape setting to the service value of a wetland [43, 235];
- spatial and temporal patterns of change in wetland and vegetation patches across the Prairie Pothole Region (PPR) [176];
- patterns and characteristics of forests in the western US in the context of large-scale ecosystem processes, including area, stand age, forest type, and carbon stocks [158];
- patterns of forest disturbance and recovery in Canada's boreal forests [52];
- the amount and configuration of forests and wetlands within a watershed and their effect on hydrological services [279]; and,
- urban development fragmenting natural assets in the landscape [12].

However, the presence and landscape context of a natural asset is not sufficient for defining its condition; management practices within that asset and the surrounding landscape may have a profound effect on both asset condition and its ability to provide ecosystem services. For example, fire suppression practices in a fire-driven landscape may lead to a uniform, mature forest stand that may provide less disturbance regulation and primary production than a forest experiencing a regular, mild fire regime.

Geographic Information Systems (GIS) applications are used with increasing accuracy for assessing and monitoring landscape composition as well as some aspects of ecosystem conditions. For example, Bork and Su [41] integrated LIDAR (Light Detection and Ranging) data with multispectral imagery for enhanced classification of rangeland vegetation in the Aspen Parkland ecosystem of Alberta, including quantification of condition aspects such as vegetation height, cover, and biomass. Their method had high classification accuracy for bare ground, shrubland, grassland, and riparian meadows.

Some researchers have also used simple area-based metrics as landscape indicators to detect human impacts on riverine ecosystems. For example, Gergel et al. [139] reviewed common chemical, biotic, hydrologic and physical habitat assessment approaches and contrasted these with landscape-level indicator approaches. Landscape indicator approaches included quantifying the amount and arrangement of human-altered land in a watershed (e.g., percent impervious surface), delineating the spatial pattern of riparian habitats including riparian buffer length, width and gaps, and considering historical land use.

At a finer scale, a multitude of site-specific indicators of natural asset condition have been developed for a wide variety of applications. Selected examples include:

- indicators developed for biodiversity monitoring of terrestrial vegetation [293];
- the Alberta Biodiversity Monitoring Program's terrestrial, aquatic, and remote sensing indicators of biodiversity status within habitat types[8];
- aerial surveys of forest health/insect infestations [21];
- rangeland health indicators [3];
- river health indicators [139, 290];
- water quality indicators [47, 291];
- algal indicators of aquatic environmental health [224];
- indicators of riparian buffer strip effectiveness [26]; and,
- soil quality indicators [186].

Numerous methods are available to assess the condition of natural assets. Since complete and comprehensive assessments of asset condition are impractical, careful selection of indicators tied to specific objectives is required. Assessments of asset condition should be user-friendly and information-rich to facilitate translation and application into policy-oriented frameworks. The level of detail and complexity in assessments will depend on the relative importance of simplicity vs. scientific validity. The best indicators are simple yet rigorously tested in the literature against more detailed indicators to provide a measure of scientific quality.

2.2 Quantification of Ecosystem Services

A major challenge when incorporating ecosystem service values into planning and decision-making is the quantification of service provision by ecosystems, so that the structure and function of ecosystems can be

translated into a tangible value [99, 216, 230]. What is often required are standardized techniques, indicators and metrics to value and monitor ecosystem services [334].

The capacity of natural assets to provide ecosystem services depends on many factors, including the amount, location, spatial configuration, composition, and ecological quality of each natural asset (see Section 2.1), and also on more complex variables related to how asset conditions are linked to the provision of ecosystem services. Although most indicators of asset condition ultimately have some relationship with one or more ecosystem services, the relationship is rarely linear or direct and assessments focused on condition may not necessarily assess the magnitude of ecosystem services. Quantifying how much of each service is generated from a parcel of a natural asset and from a network of natural assets is explored by few studies [68].

A key challenge is understanding how much area of natural assets is necessary to sustain different ecosystem services at a variety of scales [46, 193]. However, ecosystem service evaluations should also consider the landscape ecological context of parcels of natural assets, as well as site-specific condition indicators of ecological quality. In addition, since the ecosystem services concept implies human beneficiaries, comprehensive quantification of ecosystem services ideally should also trace who benefits from a particular service [302]. Complicating matters further, a natural asset's provision of services is inconsistent and subject to change in response to environmental conditions[2]. Efforts to accurately quantify ecosystem services also face pervasive uncertainties over precisely how ecosystem conditions and ecosystem services are interrelated [129, 193, 203]. Therefore, linking natural asset conditions to a quantified amount of ecosystem services is not a straightforward task.

2.2.1 Use of Indicators

Indicators or surrogates of ecosystem services can be based on measuring the generation of ecosystem processes, by quantifying the magnitude of attributes or intermediate service levels, or by assessing the amount of final service benefit [46]. Although ideal metrics will vary with the context and location of each specific natural asset, institutionalized uniform measures can facilitate comparisons among services and between places [46]. As a necessary first step to conducting more detailed analyses, this study focuses on identifying indicators that reflect the generation of ecosystem processes.

Indicators of ecosystem services range from the simple to the complex. Although simple indicators may not adequately represent the complexity of the underlying services, they may confer advantages such as ease of communication and relative simplicity of analysis. At a broad scale, for

2 For example, flood regulation by a wetland occurs only during extreme precipitation events, and the magnitude of flood regulation service benefits depends on the presence of vulnerable human infrastructure.

example, more forest cover in a landscape generally implies more forest-related services [230]. Although this type of measure is somewhat subjective, researchers are applying this approach in mapping and planning exercises. For example, Sutton and Costanza (2002) undertook a spatially explicit global estimate of ecosystem services by combining 1 km resolution land cover maps with estimated monetary ecosystem service values for different natural assets [329] (Figure 2-1).

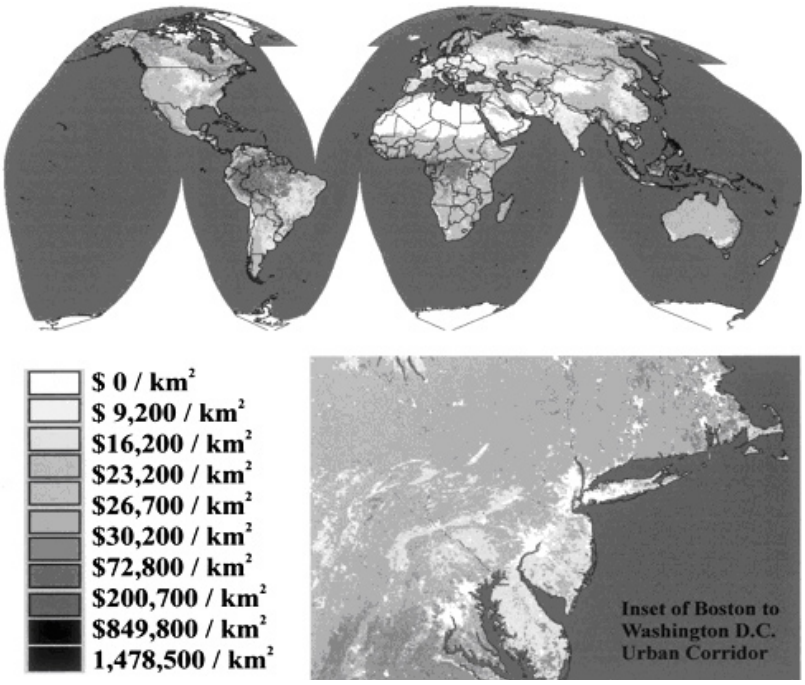


Figure 2-1 Global Map of Ecosystem Services, Sutton & Costanza (2002)

Combining land cover maps with ecosystem service valuation estimates has also been applied at the regional scale in the Del Plata basin of South America [356], and at the landscape scale in China in the Sanjian Plain [362] and for Chongming Island [385]. The method is relatively straightforward and only requires expertise in geomatics. In addition, the output GIS product maps can be highly visually appealing.

In other studies, more complex, locally derived valuation coefficients were assigned to ecosystem services associated with specific land cover types [345]. Once mapping is complete, data can be aggregated to geographies with management significance (e.g., property parcels, watershed boundaries, etc.), and subjected to scenario modelling to analyze the consequences of land use change [345]. For example, Figure 2-2 depicts the estimated annual ecosystem service flows expected to be lost on Maury Island, Washington, USA, under conditions of full zoning buildout in each parcel [345].

Despite their appeal, the above approaches for mapping ecosystem services may be subject to criticism. One issue to consider is the effect of spatial resolution on overall ecosystem service estimates. For example, Konarska et al. [190] calculated the total value of ecosystem services

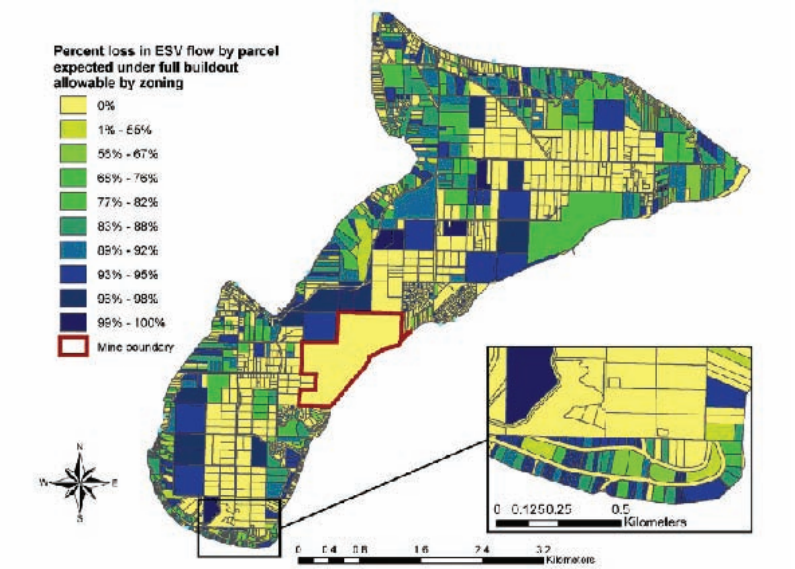


Figure 2-2 Modelled reduction in ecosystem services provided by each land parcel based on future full zoning buildout on Maury Island, Washington, USA (Source: Troy and Wilson 2006)

in the United States at $259 billion/year using the 1 km resolution IGBP data, but with finer resolution (30 m) data the total value was over $773 billion/year. There are also questions regarding the validity of applying global average service values estimated by Costanza et al. [85] to local circumstances, uncertainties associated with the absolute magnitude of econometric valuation estimates [44], and a lack of analysis of ecosystem service beneficiaries [43]. Moreover, since these sets of measures assign coefficients of value per hectare of cover type based on economic models, they do not often explicitly account for the condition or ecological quality of the asset. Generally, this approach lacks the complex local contextual analysis required for more accurate quantification.

To make land use change models more relevant to the planning process, greater linkages must be established between measurable changes in land cover and asset condition and the expected response of ecosystem services. At the same time, model outcomes, which are often complex, must be synthesized and simplified so that they are readily understandable and relevant for land managers and policy makers [198].

Examples of more detailed studies quantifying priority ecosystem services are provided below in Sections 2.2.2 to 2.2.9.

2.2.2 Climate Regulation

Climate regulation can occur on a local, regional or global scale. Examples include:

- Local scale: green areas within urban environments were studied with respect to microclimate regulation within the city [120];
- Regional scale: land cover changes were found to affect regional climate through changes in surface energy balances [128];
- Regional scale: the drainage of wetlands in Florida changed energy

balances to increase the frequency and severity of agriculturally damaging frost events in southern Florida [219]; and,
- Global scale: forests are being studied for their potential to help slow climate change through carbon sequestration [123]. Research has also been conducted on methane emissions from lakes and open water wetlands, where vegetation cover, water depth, bottom silt temperature and light intensity were all found to influence seasonal and diurnal variation in methane flux [112].

2.2.3 Disturbance Regulation

The impact of land management on disturbance regulation may be scale-dependent. For example, increased management intensity and decreased vegetation complexity in coffee plantations in Mexico was related to an increased proportion of farm area affected by landslides and an increased number and volume of roadside landslides at the landscape level [276]. However, the same study found no apparent effect of management at the plot or farm scale.

Examples of research involving disturbance regulation include:

- Mediation of flood control by cottonwood in riparian areas of the western Great Plains [312]. Impacts of late-autumn cattle grazing on riparian cottonwood biomass were assessed, and the grazing intensity threshold for riparian vegetation resilience was determined.
- Seagrasses and macroalgae were assessed in Sweden with respect to their value for control of wave and current energy [300].

2.2.4 Erosion Control and Sediment Retention

Agricultural and riparian studies tend to dominate the literature on erosion control and sediment retention. Selected examples include:

- Basic soil formation factors, characteristics and their ecosystem functions as well as how these are influenced by human decisions and management practices [181].
- An evaluation of erosion control and sediment retention services in relation to riparian and stream health [363].
- An estimate of the economic value of forest ecosystem services in China, including the value of soil conservation [149].

2.2.5 Biological Control

While many articles on biological control focused on species-specific control of agricultural pests or invasive plants, many studies addressing biological control as a natural ecosystem service considered spatial components and processes at a landscape scale. Examples include:

- Cereal aphid-parasitoid interactions in wheat fields in Germany analyzed in landscapes differing in structural complexity (ranging from 32-100% arable land). While both aphids and their predators increased with

increasing perennial habitat, they responded to different spatial scales of analysis [336].
- Similar research in central Sweden separated the influences of farming practices and landscape features on natural pest predators. Organic farming practices and landscapes with abundant field margins and perennial crops were associated with low pest establishment and persistence [263].

Spatial dynamics at a large scale can also affect biological control at a local scale:

- Patterns of ant-nest clusters based on large-scale population networks as well as local-scale variables have identified that ant species are a keystone of a larger network contributing to pest control services [355].

2.2.6 Nutrient Cycling

Nitrogen and phosphorus are key elements involved in both fertility loss and water body eutrophication. There are many potential indicators for nutrient cycling in soils:

- The nitrogen saturation index is a sensitive impact indicator [308].
- One bioindicator – phospholipid fatty acid (PLFA) profiles in soil biota – can indicate environmental stresses such as the presence of heavy metals, toxic organic compounds, tillage, nutrient starvation, and increased soil temperature [184].

2.2.7 Primary Production

Studies of primary production covered many natural asset types, as well as human influences on these assets.

- Bott et al. (2006) measured ecosystem metabolism through open-system measurements of dissolved oxygen changes in streams. Daily gross primary productivity (GPP) was found to be greater in meadow than forested riparian reaches due to riparian shading [42].
- Another indicator used to evaluate changes in ecosystem processes induced by land use change is the human appropriation of net primary production (HANPP) [378]. This indicator shows weak but significant relationships to landscape pattern indicators.

2.2.8 Water Supply

Several research articles relate to the quantity and quality of water supply as an ecosystem service.

- Meyer et al. (1999) summarized the potential effects of climate change on water supply through impacts on lake temperature (which also affects seasonal mixing regimes and fish habitat), the magnitude and seasonality of runoff (which affects nutrient loads and low-flow habitat availability), and the loss of prairie pothole wetlands [229].

- A study in New Zealand identified water yields in relation to land cover type in natural grasslands. They found that indigenous tall tussock grasslands, when in good condition, maximized water yield relative to other vegetation cover types due to minimal transpiration loss. Upper watersheds/catchments were particularly important to water supply services [218].

2.2.9 Recreation

The value of green space in urban environments is increasingly recognized.

- One index to measure green space in cities is the green plot ratio (GPR), which is the average leaf area index (LAI) on an urban site [258].
- The value of urban wetlands in providing recreation services was reviewed by Boyer and Polasky (2004) [44].
- The recreational value of potential national parks in Denmark was assessed along with biodiversity values, to determine a network of parks that maximize both recreation and species representation [197].

2.3 Scale of Analysis

Natural asset condition influences different ecosystem functions, processes and services at varying scales. An appropriate consideration of scale is critical for effective monitoring and analysis of landscape ecological patterns [350] and ecosystem services [247]. Many ecosystem services such as recreation potential, primary production, and microclimate regulation are site specific, whereas erosion control, flood control, and water supply services operate at a watershed or landscape scale, and climate regulation services related to carbon sequestration operate at a global scale [84, 302]. In general terms, the appropriate scale for analyzing ecosystem services can be defined by the spatial and temporal dimensions at which the service has the most coherence [203]. However, scales above and/or below each scale can be important to discern the context and mechanisms that govern the scale of analysis [270].

2.4 Effects of Ecosystem Change on Service Provision

When ecosystems are altered, either through land use/land cover change or a change in management regimes, associated shifts in ecosystem services often occur. As noted in Section 2.2, the relationship is rarely linear or direct.

A number of drivers of ecosystem change influence the types of services affected. The direction of change can tend towards greater human impacts on natural assets, or restoration of native ecosystems (Section 2.4.1). In either case, feedbacks and tradeoffs exist (Section 2.4.2). Some research has identified ‘optimal’ or desirable asset conditions for ecosystem service

provisioning, while others have discovered thresholds beyond which sudden, irreversible alterations in service provision occur (Section 2.4.3).

2.4.1 Drivers of Ecosystem Change

A growing human population and the need to provide food, fibre, water, and shelter are major drivers of ecosystem change on a global scale [128]. Cropland, pasture, plantations, and urban areas are expanding at the expense of natural assets. On a regional and landscape scale, forest ecosystem change can occur in response to drivers such as climate change, land use/land cover change, atmospheric pollution, and physical disturbances [158]. Raffa et al. (2008) describe the interacting natural and anthropogenic factors that drive bark beetle infestations in forests [283]. The availability of late seral stage host tree species, concentration of beetle density, favourable weather, and escape from natural enemies are all key factors, and anthropogenic influences such as reduced landscape heterogeneity and climate change have increased the risk of infestation outbreaks [283]. Postel and Thompson (2005) describe many of the alterations that degrade watershed quality in terms of its ability to provide water supply services, including deforestation, road construction, clear-cutting, and poor farming practices [279].

Ecosystem change is often the result of the cumulative effects of multiple activities and threats, including land use change. Land use change may be triggered by ultimate socio-economic drivers, including land availability, scarcity, market changes, subsidy programs or other interventions [196]. Causal relationships between individual threats and ecosystem change are rarely straightforward due to the large number of driving forces, interactions between them, and the non-linear response of ecosystems to multiple impacts [129, 300]. Cumulative effects frameworks and interdisciplinary research provides a means to address some of this complexity.

Notably, research on drivers of land use change and research on the consequences of land use change to ecosystem services have generally been conducted separately [123], although there have been recent attempts to integrate the two approaches [69, 228, 274]. Future comprehensive land use planning requires an integrated analysis of ecosystem drivers, conditions, services, and indicators, as well as sufficient treatment of feedbacks and tradeoffs.

2.4.2 Feedbacks and Tradeoffs

Applying the ecosystem services concept requires consideration of the feedbacks and tradeoffs among ecosystem services. Tradeoffs typically arise from human management decisions, which can change the type, magnitude, and relative mix of services provided by ecosystems [296]. Provision of one service may come at the expense of another, whereby increased use of one service reduces the provision of another [296]. For example, tradeoffs commonly occur when ecosystems are managed to maximize provisioning services (e.g., crop or timber production), which causes a decrease in supporting services (e.g., soil formation, pollination), regulating services (e.g., climate regulation, flood control), or cultural/aesthetic services (e.g.,

recreation). Interactions may be synergistic or competitive, and different processes may dominate at different times or spatial scales [46, 296]. Interactions may also differ in their reversibility. For example, overgrazing of native fescue pasture can shift the plant community to a degraded plant community which provides lower biological control, sediment retention, and water supply services. This type of shift is unlikely to be reversible. In contrast, the impacts of cattle grazing in a wetland (i.e., soil compaction, erosion, water supply degradation) can potentially be reversed by fencing the wetland and allowing it to regenerate over time.

Managing ecosystems to maximize carbon sequestration can also have detrimental effects on other ecosystem services. A study in Oregon found that policies designed to increase carbon sequestration did not necessarily increase species conservation and vice versa [251]. For example, biophysical models showed that species conservation was maximized when landowners restored relatively rare natural habitats (e.g., oak savanna, prairie, emergent marsh), whereas carbon sequestration was maximized when landowners restored forests (e.g., old growth, mixed and riparian forest) [251]. Similarly, Naidoo et al. (2008) provided a global analysis of how biodiversity (measured as species representation) was related to potential ecosystem service provision, including carbon sequestration [247]. They found that regions selected to maximize biodiversity conservation were not always the best regions for maximizing ecosystem service provision. Spatial agreement among different ecosystem services, and between services and other

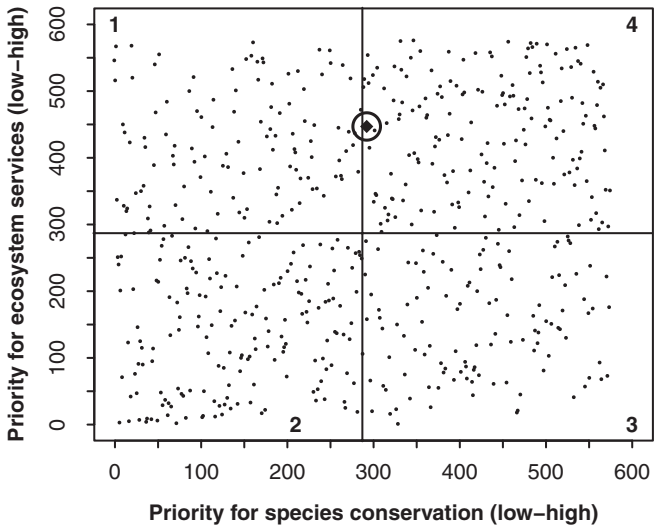


Figure 2-3 Global relationship between carbon storage potential (y axis) and biodiversity importance (x axis) across 574 terrestrial ecoregions (Source: Naidoo et al. 2008)

conservation priorities, varied considerably (Figure 2-3). However, “win-win” areas meeting both biodiversity and ecosystem services objectives could be identified as well (upper right quadrant in Figure 2-3). The amount and location of concordance between biodiversity conservation and ecosystem service priorities will vary depending on the region and the types of services considered [351]. Moreover, the effect of spatial scale on the areas of overlap between biodiversity and various ecosystem services objectives requires careful consideration [154, 345].

Figure 2-4 provides a conceptual framework for comparing land use and ecosystem service tradeoffs [128]. To illustrate differences between land use choices, qualitative star-shaped diagrams of multiple ecosystem services are provided for different land use types (e.g., natural ecosystem, intensive cropland, cropland with restored ecosystem services) (Figure 2-4). While some land uses provide relatively balanced diagrams, others (e.g., intensive cropland) are heavily weighted towards the provision of a single service (e.g., crop production).

While tradeoffs can be the result of an explicit choice, they may also occur without awareness that they exist. One analysis found that tradeoff decisions favoured provisioning, and regulating respectively, while supporting services and cultural services were less likely to be considered by decision-makers [296].

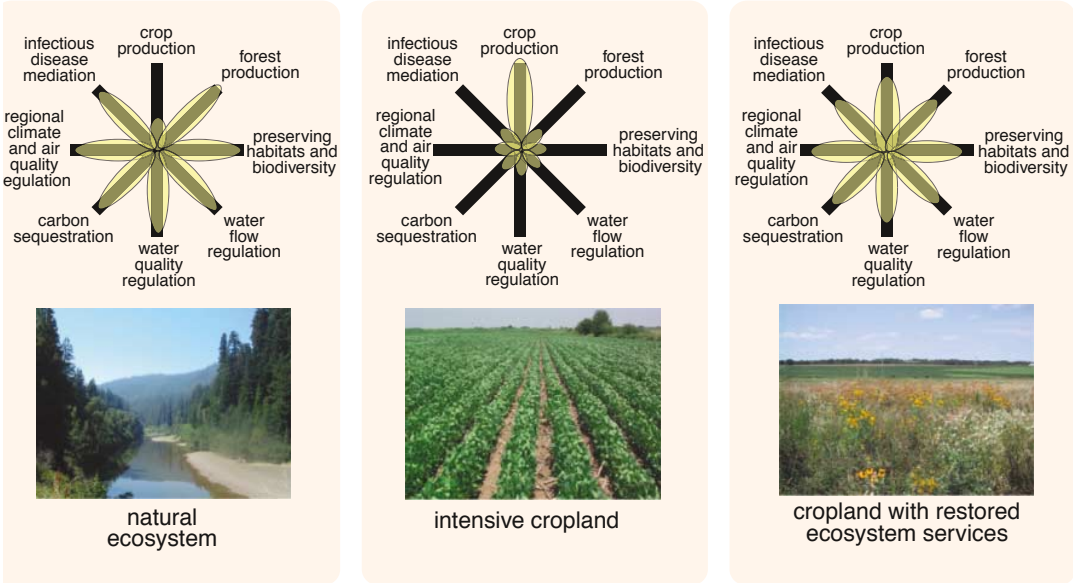


Figure 2-4 Conceptual diagrams for comparing ecosystem service tradeoffs (Source: Foley et al. (2005)).

However, new tools can enable progress towards multiple competing objectives [99]. One study applied a spatially explicit conservation planning model to California to explore tradeoffs and opportunities for aligning biodiversity conservation goals with six ecosystem services (carbon storage, flood control, forage production, outdoor recreation, crop pollination and water provision) [68]. Figure 2-5 provides a map of their analysis for the State of California. Average spatial correlations among the six ecosystem services as well as biodiversity conservation goals were low. Weak negative correlations were also observed between biodiversity goals and two agriculture-related services: crop pollination and forage production. Despite these potential tradeoffs, the systematic planning framework offered scope for identifying important synergies between multiple ecosystem services and biodiversity conservation goals. In particular, lands that were important for water provisioning, flood control, and recreation were also likely to provide significant biodiversity benefits. Future planning and research applications recommended by Chan et al. [68] included identifying hotspots where high values of multiple benefits coincide, and exploring how conservation networks can be configured to maximize the full suite of benefits [68].

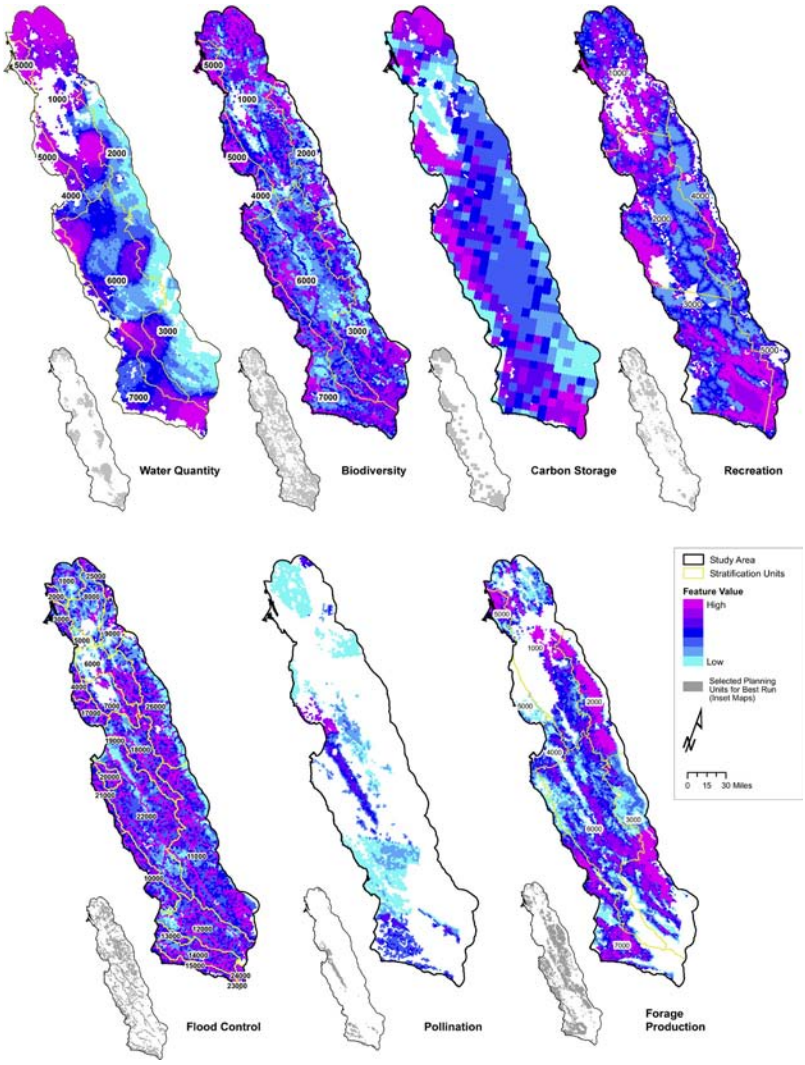


Figure 2-5 Mapping Ecosystem Services in California (Source: Chan et al. (2006))

2.4.3 Conditions and Thresholds

Generally, there is a lack of published research on thresholds and optimal conditions with respect to landscapes and ecosystem services. Only two articles in the database referred to quantitative values for 'optimal' conditions.

Mitsch and Gosselink (2000) synthesized the existing research to specify an optimal value for wetlands in temperate watersheds at 3-7% in order to maintain water quality and flood control ecosystem services [235]. In addition, this paper summarized regional studies conducted at a variety of scales to present a series of landscape-level thresholds for water quality improvements (5-9% wetlands), nitrogen control (3.4-8.8% wetlands), phosphorus retention (15% wetlands), and flood control (7% wetlands) (See Table 5-4).

Chan et al. (2006) also specifies 'Optimal' conditions selecting targets for ecosystem service flows that should be represented in an optimal conservation network [68]. Targets were expressed as a percentage of the total estimated service produced in the study area (e.g., 50% of total carbon stored in the region, 75% of total pollination service). However, they provided the important caveat that targets in their model "serve as initial hypotheses for testing the necessary level of replication and abundance to ensure feature persistence" [68].

The lack of published information on optimal conditions suggests that the complexity of ecosystem services and the multiple tradeoffs involved (Section 2.4.2) make it exceedingly difficult to define any type of optimum condition. Clearly, what is 'optimal' is likely both (a) incomprehensible due to the complexity of natural systems, and (b) a matter of political choice.

Neither of these issues can be resolved with a technocratic solution. Some recent thinking on adaptive resource management provides a framework for grappling with these issues in a systematic, scientifically defensible, and inclusive framework [129, 212].

On the other hand, although quantitative optimal solutions were generally absent from the literature review, many researchers did refer in one way or another to more general 'desirable' conditions, including targets such as:

- comparable or better than adjacent catchments [104, 105];
- similar to natural conditions [73, 146, 206];
- benefits outweighing costs [145, 162, 284];
- resource-efficient city structure and design [39];
- non-degraded ecosystem regimes [300];
- wetland compensation sites should provide equal or greater benefits than the impacted site [43];
- wetland or riparian sequestration of nitrate [170, 331];
- non-eutrophic status of water bodies [60, 146, 150, 239];
- maintenance of urban riparian vegetation [265];
- effective flood mitigation [174];
- less damage and loss of life during disturbances (tsunami) [78];
- high landscape diversity [249, 263, 378];
- high insect predator diversity [319, 374]; and,
- landscape functioning as a carbon sink [231, 384].

Related to the idea of optimal conditions is the concept of ecological thresholds. This area of research links non-linear dynamics, multiple cumulative impacts, and observed shifts in condition across a range of ecosystems [129]. The central idea of this theory suggests that gradual changes are not typical in ecosystems, and that surprise and rapid change are more common. Well documented examples of non-linear ecosystem regime shifts include the shift from clear water to turbid water conditions in temperate lakes [63], the shift from hard corals to macroalgae in coral reefs [163, 189], and shifts in marine ecosystem structure and productivity [300, 326] (Figure 2-6). Similar corollaries exist in temperate forests. For example, in some parts of central Saskatchewan, a shift from mixed forests

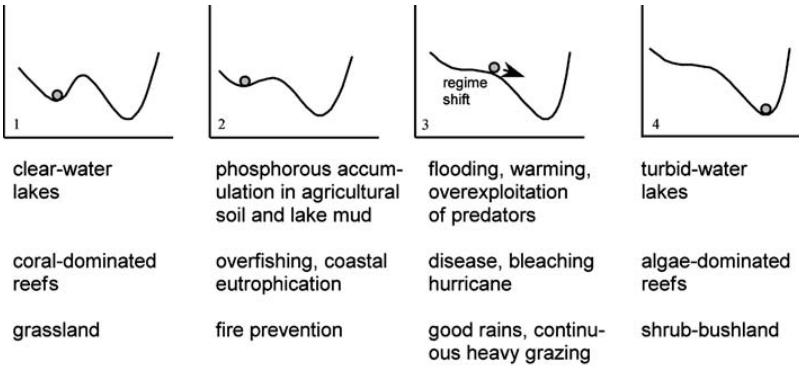


Figure 2-6 Ecosystem Regime Shifts (Source: Folke et al. 2004). 1=Original Ecosystem State, 2=Stressors, 3=Sudden Triggers, 4= Alternate Stable State

dominated by white spruce (*Picea glauca*) and balsam fir (*Abies balsamea*) to deciduous forests dominated by trembling aspen (*Populus tremuloides*) has been documented as a response to land clearing, changes in fire frequency, and logging [266, 366]. Many more studies on ecosystem thresholds have been documented and compiled by the Resilience Alliance and are available on-line on the world wide web [289].

Of particular appeal regarding this type of research is the potential for identifying quantitative biophysical thresholds, beyond which possible irreversible changes to ecosystem structure, function, and service provision may occur[3]. Interesting results on thresholds have emerged through recent research.

Holland et al. (2004) analyzed the effects of impervious surface (% IS) on water quality in several tidal creek watersheds of the South Carolina coast [161]. The integrative indicator (% IS) was examined along with more specific indicators, including human population density, land use, creek physical characteristics, sediment chemical contamination and grain size characteristics, benthic chlorophyll-a levels, porewater ammonia concentration, faecal coliform concentration, and macrobenthic and nekton population and community characteristics. At 10-20% IS in watersheds, they observed altered hydrography, upland erosion, increased chemical contamination and salinity, and increased bacterial loading. At 20-30% IS, they observed significant biological degradation, few stress-sensitive taxa, altered food webs, and shellfish bed harvesting closures. At >40% IS, there was a substantial increase in sediment contamination, while at 30-50% IS, there were major increases in faecal coliforms.

A similar study in Rhode Island watersheds observed that with increasing % IS, nitrogen pollution generally increased linearly, and stress-tolerant aquatic species replaced sensitive species at anywhere from 8-47% IS [213]. Several other studies have shown alterations in macroinvertebrate stream communities when IS exceeds 8-10% [369].

3 However, in many cases this is difficult to achieve due to the complexity of the underlying systems being studied, as well as cases where more gradual changes occur in response to interacting processes.

In a different type of study, riparian wetlands in Virginia were found to filter more phosphorus from watersheds with 8.6-13.3% IS than those with 25.1-29.1% IS, indicating how rapid movement of stormwater through engineering infrastructure results in a loss of ecosystem services performed by slower movement of water through wetlands [160].

Additional notable research on thresholds involves the use of "leading indicators" to predict non-linear regime shifts of lakes. Carpenter and Brock (2006) found that prior to threshold transitions, variance of total phosphorus during summer increased suddenly, predicting eutrophication a decade in advance [61]. Carpenter et al. (2008) found that changes in phytoplankton time series signal regime shifts in fish populations long before they occur, even with added noise to the system [62]. Other researchers have determined that changing skewness of indicator data sets can also predict regime shifts in advance [150]. This type of research has focused on lakes in Wisconsin, and future research should help determine if it is applicable in other ecosystems as well.

Excluding the examples above, the majority of existing research does not address the issue of thresholds. In the literature review, only 16% of all papers retrieved deal specifically with assessing thresholds. This may be partly due to difficulties involved with studying and quantifying thresholds. For example, Alcamo et al. (2005) noted that their model of global ecosystem services could not include ecological thresholds because data deficiencies made it difficult to include non-linear dynamics [13].

In many cases, existing insights on thresholds from the natural sciences must be integrated with planning exercises where indicators are linked to desirable outcomes based on social and biophysical criteria. Examples of this approach include:

- defining "thresholds of probable concern" for geomorphic and riparian indicators in rivers within Kruger National Park, South Africa [297];
- specifying "limits of acceptable change" associated with natural asset conditions and tourism/recreation experiences [151, 298];
- identifying a potential "critical threshold" where land use in the Argentine Pampas results in ecosystem service values dropping below the value of agricultural production [356]; and,
- aiming for intermediate land use intensities in Austria, where Human Appropriated Net Primary Productivity (HANPP) occupies less than 50% of primary productivity in landscapes as a surrogate for spatially explicit indicators of the degree of landscape naturalness [378].

A relevant example for regional landscape planning is a scenario planning exercise conducted within the 600,000 ha New York/New Jersey Highlands area [198]. Researchers established targets for various landscape indicators based on a review of the literature on the biophysical effects of land use change, combined with strategic objectives related to conserving ecosystem services such as natural water filtration, soil stabilization, groundwater recharge, and wildlife habitat support. They selected the following

'unacceptable' thresholds for application to scenario planning exercises: (i) >50% altered land, (ii) >10% impervious surface, (iii) >50% altered riparian zone, and (iv) <40% interior forest habitat (defined as greater than 90 m from forest edges). The particular strength of this approach is that the selected thresholds were based on "relationships between selected landscape indicators and independently measured environmental parameters", and thus provide a scientifically defensible basis for environmental planning. It is recommended that a similar approach be followed for selecting appropriate asset condition targets for regional planning in Alberta.

2.5 Data Gaps in the Literature

Defining ecosystem services and the processes and functions through which they contribute to human populations is inherently interdisciplinary [302]. Balmford et al. (2005) noted that our understanding of the mechanisms linking biodiversity, earth system processes, human actions, and ecosystem services remains crude, and that collaborative interdisciplinary research to elucidate these mechanisms should be a high priority [25]. Understanding thresholds and resiliency of ecosystem service provision is also a challenge [32] (Section 2.4.3).

Currently, research quantifying the magnitude of ecosystem services is relatively sparse, although the need for such information is pressing and research in this area is growing. Systematic planning methodologies incorporating ecosystem services are not common in the literature. Although it is relatively easy to identify which services an ecosystem provides, the degree or rate of provision of that service is usually difficult to quantify [46]. To date, most quantification studies utilize economic valuation techniques.

Tradeoffs between ecosystem services under different land uses and management regimes also complicates matters. Understanding the connections between management regimes, ecosystem structures, and multiple ecosystem services are challenges in the literature [32].

Other knowledge and research gaps exist with respect to the location and scale of service delivery. Ecosystem service provision is inherently spatial. Therefore, a proper understanding of scale and connections between supply and demand areas is valuable. Important supply areas need to be identified in order for policy to most effectively protect service provision [6, 247]. Since the concept of ecosystem services (as opposed to ecosystem functions) explicitly involves beneficiaries, the location of demand areas will also affect the amount of services provided (e.g., adjacent vs. remote natural areas) [68]. From a scientific perspective, there has been too little synthesis of the issue of scale in ecology, and even less effort devoted to synthesizing this knowledge into management applications [270]. However, the development of effective ecosystem service law and policy will require accurate descriptions of the chain of delivery of ecosystem services from natural assets to service user groups [302].

3.0 A FRAMEWORK FOR ASSESSING ASSET CONDITION

The condition of natural assets influences their ability to provide ecosystem goods and services (EGS). The asset condition is a result of pressures brought to bear through a variety of stressors including, among others, urbanization, linear disturbances (roads, pipelines transmission lines etc.), agriculture, oil and gas development, mining and forestry. These often alter landscape composition and ecological patterns, and can contribute to the loss, attrition or fragmentation of natural assets, thereby affecting their ability to provide goods and services. The ecological quality at the local site level may be further affected by specific land management activities.

Asset condition needs to be assessed at different scales as the provision of EGS is related both to the specifics of the asset patch itself, as well as the condition of its landscape ecological context. The condition of localized assets is, at least in part, influenced by the configuration or pattern of the surrounding mosaic of which it is part. Measurable indicators of asset condition are therefore needed at both of these scales.

Indicators can be defined as “measurable surrogates for environmental end points of value to the public” [254]. Indicators are important for synthesizing information on complex systems with many variables and for crafting feasible monitoring and management programs that can be implemented under the constraints of limited resources. There are hundreds of potential indicators of ecosystem services. To avoid paralysis by complexity, this report focuses on assessing the most promising composite indicators of ecosystem services (Sections 4.0 - 7.0). Moreover, this report focuses on *condition* indicators, and does not address *pressure* or *response* indicators (although the focus is on indicators sensitive to changes in pressure).

Broad scale indicators of natural asset condition are grouped into the categories of landscape composition as well as landscape pattern/ configuration. These are typically applied at broader scales such as entire landscapes or regions. These indicators may also be used to prioritize areas for finer scale studies. The ecological quality indicators are more feasibly measured at finer scales and at specific locations.

Broad Scale Indicators
1. Landscape Composition - refers to the amounts and proportions of land cover types in the landscape mosaic.
2. Landscape Pattern or Configuration - refers to spatial characteristics such as the size, distribution, and juxtaposition of land cover types.

Fine Scale Indicators
3. Ecological quality refers to the specific biological, chemical, or physical attributes of a natural asset at a given location.

3.1 A Hierarchy of Scales

It is useful to clarify the hierarchy of scales assessed in this report together with their relationship to the three components of asset condition listed above. Natural assets, as defined in this report, consist of individual habitat patches or land cover types that occupy the lowest level in the hierarchy of scales addressed in this report (Table 3-1). Scales at the patch or natural asset level can range from square meters up to several square kilometres for larger patches of natural assets. Assessing natural asset condition at these fine scales typically requires site visits and sampling environmental parameters. Measurement of condition at this scale examines the ecological quality of the asset.

Landscapes occupy an intermediate level in the hierarchy of scale. Landscapes can be defined as “a mosaic where the mix of local ecosystems or land uses is repeated in similar form” [131]. Landscapes reflect both human use of the area and underlying biophysical conditions. These areas tend to have similar underlying physiographic conditions including climate, land forms and soil types. The pattern of vegetation and local landscape elements is the result of the interaction of the physiographic conditions, natural disturbance regimes, and human use of the area. Landscape scales can range in size from thousands of square kilometres down to a few square kilometres [133]. Watersheds also occupy intermediate scales in the hierarchy[4]. Watersheds consist of a topographically delineated area drained by a stream or river system [49]. Although watersheds are the most logical geographic unit for analyzing water resources and water-related ecosystem services, landscapes and watershed boundaries do not always coincide. Classification systems can address this by defining “landscape units”, created by overlaying watershed boundaries with other ecological patterns (e.g., soil ecoregions or natural subregions) [255] (Figure 3-1).

Regions occur above landscapes in the hierarchy of scales. A region can be defined as a broad geographical area with a common macroclimate and sphere of human activity and interest [131]. Generally, regions are larger than several thousand square kilometres. Regions should be viewed

4 Watersheds in this category can also be subdivided by area, stream order, or specific stream reaches.

as aggregates of multiple landscape types. Larger river basins (i.e., South Saskatchewan River basin) are more appropriately considered as a region since these typically traverse many different landscapes. In some cases, it is appropriate to report condition metrics at the scale of the entire region. However, spatially explicit analysis and synthesis of information from lower levels in the spatial hierarchy is required to properly understand both the condition of assets and their influence on services.

Table 3-1 Classification of scales and associated condition indicators

Scale (Units)	Term	Examples	Application for Condition Indicators
> 10^4 km^2	Region	southern Alberta, South Saskatchewan River Basin	Synthesis from lower levels in the hierarchy
km^2 - 10^4 km^2	Landscape	Alberta Natural Subregion	Broad-Scale: Landscape Composition & Pattern
m^2 - km^2	Site / Patch	Forest stand, wetland, natural fescue patch	Fine-Scale: Ecological Quality

3.1.1 Broad-Scale Conditions

Broad-scale conditions refer to landscape characteristics which represent the setting in which a natural asset is placed. The broad scale is more meaningful for analyzing indicators of asset condition related to landscape composition and landscape pattern. In addition, it is useful in assessing *sets* of asset types.

Landscape composition is the simplest broad-scale measure of condition. Analysis of landscape composition over time under varying land use scenarios can provide useful information on natural asset condition and ecosystem service provisioning. For example, the loss of forest cover in a landscape implies the loss of forest-related ecosystem services.

Landscape pattern metrics provide a more detailed level of information by explicitly measuring spatial relationships, including the size, shape, and distribution of natural asset patches in a landscape [12]. Connectivity, the relationship of a patch to the surrounding landscape mosaic, and the juxtaposition of different patch types are all critical components of landscape pattern. The spatial arrangement and context of a natural asset affects the ecosystem functions and services it provides. Metrics for assessing these broad-scale conditions can help evaluate the provision of these services in the landscape and region.

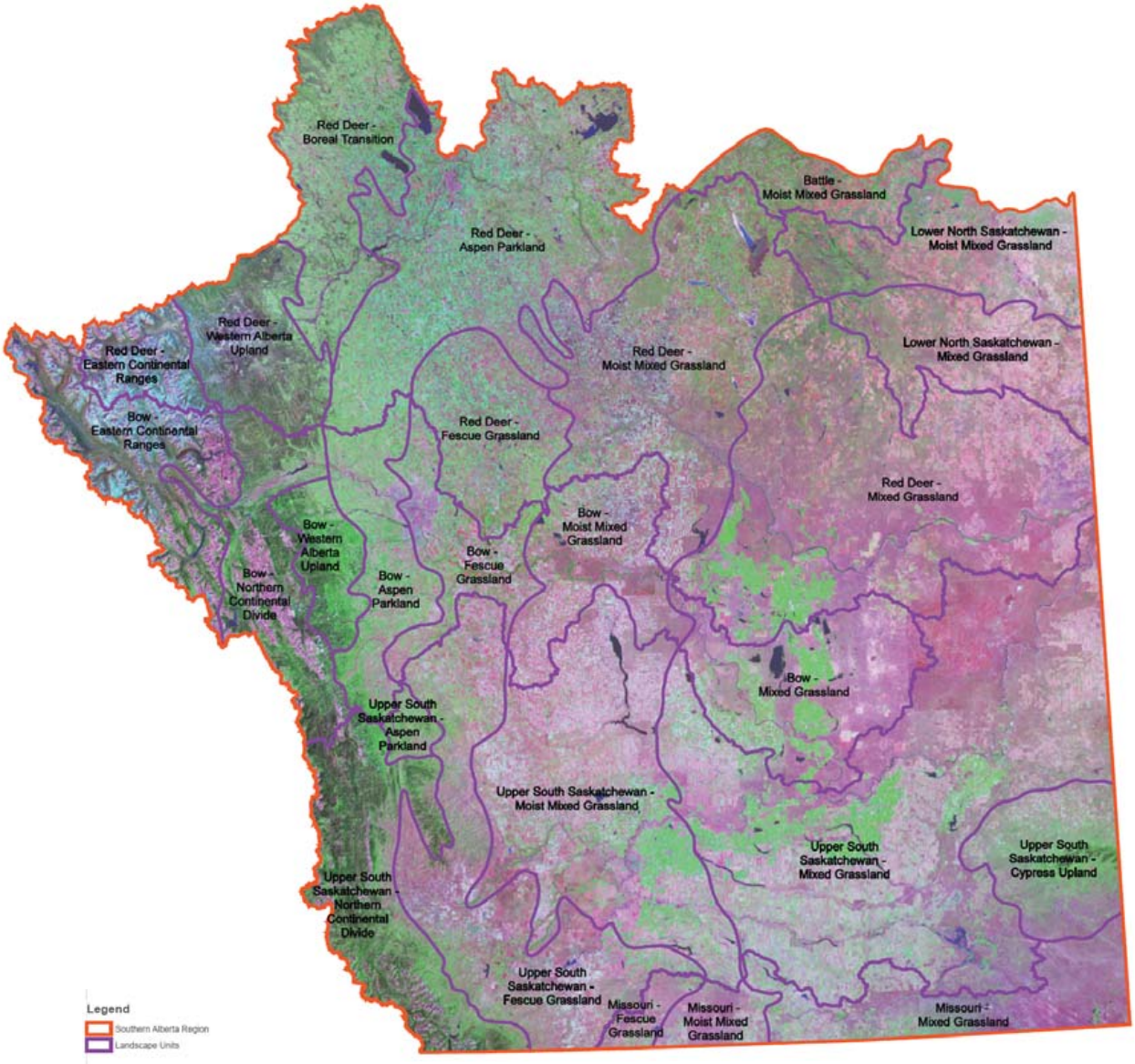


Figure 3-1 Landscape Units in southern Alberta defined by soil ecoregions and watershed sub-basins [255]

Several landscape patterns are considered “indispensable” if biodiversity and ecosystem services are to be conserved, including (Figure 3-2) [131]:

- Large patches of natural vegetation that provide the benefits of species richness, habitat for interior species and viable ecological processes;
- Well-vegetated riparian corridors to provide for species movement, erosion and sedimentation control and protection of aquatic habitats. In addition, headwater seepage areas and first order streams should receive protection in the form of near-contiguous vegetative cover;
- Corridors providing connectivity between large patches, and,
- Stepping stones of heterogeneous remnants of natural patches scattered throughout highly disturbed areas.

These patterns form a *Green Network of natural assets that provide a set of important ecosystem goods and services.*

3.1.2 Fine-Scale Conditions

Fine-scale condition assessments measure ecological conditions in specific natural asset types. Analysis of the ecological quality of an asset typically requires site-specific visits and discipline-specific expertise. There are many potential biological, chemical and physical indicators for measuring condition and ecological quality in each natural asset type. These may include:

- biological indices such as species richness or diversity at the site;
- chemical indices (nitrogen, phosphorus, metals, organic pollutants);
- physical indicators such as soil compaction, erosion potential, or evapotranspiration.

However, it is necessary to narrow down the scope of indicators to those directly related to ecosystem services. Therefore, the fine-scale measures of asset condition selected for assessment in this report can be viewed as proxies for ecosystem services.

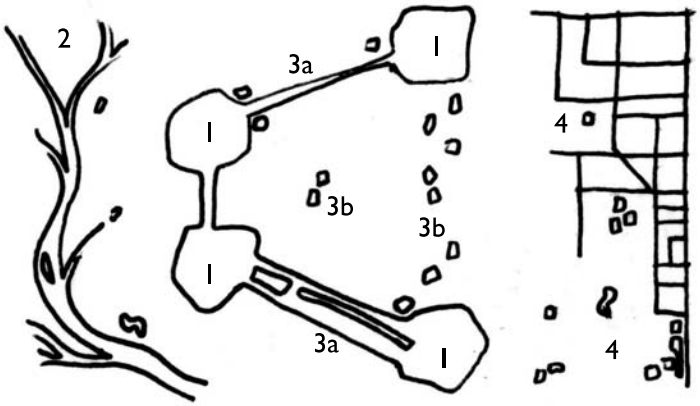


Figure 3-2 Indispensable landscape patterns (Source: Forman 1995 [131])
1=a few large patches of natural vegetation
2=major stream or river corridor
3a=connectivity through corridors
3b=connectivity through stepping stones
4=heterogeneous bits of nature in the matrix

3.2 A Framework for Assessment

Ecosystem services are tied to the condition of natural assets. At the finest scale, the ecological quality of a natural asset defines, to a large degree, the type and amount of services it provides. However, the context of the asset within its larger landscape also greatly impacts the ecosystem services provided. For example, a small isolated patch of native grassland provides fewer services than one embedded within a very large patch of natural vegetation. The proximity of the grassland to other patch types (e.g., forest cover or water) will also influence its importance as habitat. In addition, when linked with other patches, the grassland patch may form part of a critical wildlife corridor. In landscape ecology, the importance of the whole is often greater than the sum of the individual parts.

Defining a framework for condition assessment thus involves developing a methodology to link asset condition across scales, and identifying thresholds or targets against which to evaluate condition indicators. In this manner, one can comprehensively assess indicators of ecosystem services across the site, landscape, and regional scales (Figure 3-3).

3.2.1 Cross-Scale Linkages

Natural asset condition influences different ecosystem functions, processes and services at varying scales. Consequently, indicators of ecosystem services tied to asset condition must cover multiple scales. Figure 3-3 shows broad scale indicator assessments on the left and fine scale site indicator assessments on the right. While broad-scale indicators are useful and pragmatic for assessing regional and landscape scale conditions, they can miss important site-specific details [1]. In contrast, fine-scale indicators can provide more accurate site-specific data on ecological quality, yet associated costs are often prohibitive for assessing entire regions or landscapes. Achieving the appropriate balance of broad-scale and fine-scale assessment requires clear links between scales and a mechanism for prioritizing data collection efforts.

As a first priority, broad-scale indicators should be assessed in landscapes across the region (Figure 3-3, left boxes). This assessment can provide a relatively cost-effective and efficient overview of where ecosystem services are likely strong and thriving, and where they may be threatened. The broad scale assessment will identify the condition of the patterns of assets that form the Green Network of natural assets. A wide range of ecosystem goods and services are provided by this network. A broad scale assessment of the amounts and patterns of sets of assets that form the Green Network is an important first step in determining the general condition of the Green Network and associated ecosystem services. It can also assist in identifying what has been lost and what gaps exist in the Green Network, in order to identify appropriate locations for targeted restoration projects. The broad-scale analysis also provides a way to distill some of the complexity of ecosystem service assessments into something saliable for planning purposes.

Section 3.2.2 describes the selection of thresholds and target values. Selection of appropriate targets for each landscape is important for defining 'healthy' or 'threatened' areas (Figure 3-3, centre box 'Landscape Indicator Review: Assessment vs. Targets'). In landscapes where the assessment shows that selected targets are close to or being exceeded, more intensive site sampling may be warranted to obtain a better picture of the changing status of ecosystem conditions and services. This assessment of fine-scale condition indicators represents the second priority in evaluating ecosystem service provision (Figure 3-3, right boxes).

As a third priority, data collected on fine-scale indicators can also be used as part of a long-term adaptive management process. Fine-scale data can improve understanding of the relationship between fine and broad scale indicators in the region of assessment, which is important since existing thresholds for many indicators have been derived from regions with a different climate and geography from Alberta [1, 13]. Over time, studies examining how fine scale indicators are related to broad-scale indicators could be used to reassess appropriate management targets. Site indicator assessments can also be used to establish reference conditions for specific natural assets.

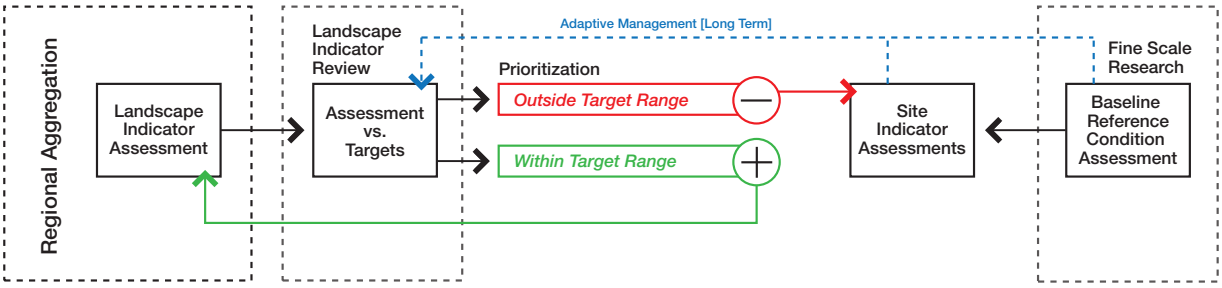


Figure 3-3 Graphic representation of the framework for asset condition assessment

3.2.2 Thresholds and Targets

An ecological threshold can be defined as a critical value at which sudden, non-linear and often irreversible change occurs. The particular appeal of thresholds is the potential to identify quantitative values for indicators, beyond which irreversible changes to ecosystem structure, function, and service provision may occur. If thresholds for indicators are defined quantitatively, managers can set targets to avoid crossing these thresholds. Yet defining quantitative thresholds is a difficult task rarely achieved in practice. The potential for sudden and irreversible change exists [129], but scientists and managers often struggle to quantify where these thresholds lie.

Planning exercises still require management thresholds and targets to be set, even in the absence of scientific knowledge. In these cases, targets must be set by integrating existing knowledge, expert analysis, and socioeconomic considerations. Knowledge of the natural range of variability (NRV) is valuable for conditions with no easily defined ecological threshold (e.g., depth of water in a mountain lake, or amount of disturbance in a landscape). In the absence of known thresholds, adaptive management frameworks are also useful in situations of complexity and uncertainty. In adaptive management, management targets are subject to explicit testing of assumptions and iterative analysis over time to refine or change targets as necessary.

Context is also particularly important when specifying desirable targets for indicators. There are no ‘right’ targets that can be applied across all of southern Alberta’s landscapes. The forested, grassland, parkland, and mountain landscapes of southern Alberta all differ substantially from one another, and consequently require different targets. In addition, more pristine areas with intact natural assets require different targets than landscapes containing substantial urban, agricultural, or industrial activity. Finally, southern Alberta’s watersheds require different land use and land management approaches that are capable of meeting instream flow needs and water quality objectives [47].

For planners and resource managers, targets are desirable conditions, whereas thresholds are limits of acceptable change that should not be exceeded.

4.0 INDICATOR ASSESSMENT CRITERIA

To ensure recommended indicators are valid, reliable, and useful for decision-making processes, a consistent set of criteria must be applied. This section describes the criteria used to assess the selected indicators, including how low, medium, or high values are assigned.

A large number of potential indicators identified in the literature were screened against these criteria. Only indicators best suited to these criteria are described in detail in this report; others with potential utility but lacking in some areas (e.g., measurability and cost-effectiveness) are listed in Appendix B. As the knowledge base grows and more data becomes available, these indicators may be appropriate for future review and use.

4.1 Understandable

The utility of each indicator in the decision-making process is affected by the degree to which it is comprehended by both professionals and the lay public. The ability of the public to understand an indicator is crucial for any planning involving diverse stakeholder groups. Indicators considered highly understandable to the public were assigned a ‘high’ score. Indicators that could potentially be understood by the public, but only after considerable explanation, were assigned a ‘moderate’ score. Indicators considered to be understandable only to technical specialists were assigned a ‘low’ score. However, it is acknowledged that some indicators of high scientific importance that are more difficult to communicate warrant consideration.

4.2 Ecosystem Service Linkages

This criterion assessed the degree to which an indicator bears a relationship to the eight priority ecosystem services assessed in this report. Although a comprehensive analysis of ecosystem services must consider human beneficiaries and demand areas, it is assumed that ecosystem functions or processes are all potential ecosystem services. For evaluating this criterion, those services with evidence supporting a strong direct relationship with the indicator were scored. Identifying a direct relationship was important since most services could actually be related indirectly to all indicators. These indirect relationships were not considered when scoring this criterion.

Indicators relevant to more than three ecosystem services were scored as ‘high’. Indicators relevant to two ecosystem services were scored as ‘moderate’. Indicators relevant to only a single ecosystem service were scored as ‘low’. Indicators bearing no apparent relationship to ecosystem services were not assessed further.

4.3 Responsiveness to Management Practices

Some indicators are highly sensitive to changes in land use or management. However, others have high natural variation and/or lag times, making it difficult to detect management influences.

Indicators with good potential for responding directly to management practices, with detection possible over short time scales, were scored as ‘high’. For those indicators where the detection of a response to management is likely to be more difficult due to high natural variation and/or significant time lags in the natural system, the indicator was scored as ‘moderate’. Indicators with very low responsiveness to management practices were not assessed further.

4.4 Measurability and Cost-Effectiveness

Indicators should be relatively easy to measure and quantify in a practical sense. The effectiveness of measurement tools and costs associated with using those tools should both be considered. One must also consider that expensive data acquisition can be justified if the importance or value of the information is high.

Indicators that are easily measurable with relatively simple and cost-effective tools were scored as ‘high’. Indicators requiring more sophisticated tools and higher associated costs were scored as ‘moderate’. Indicators where costs associated with data collection were high but the relative value of the information was not apparent were not assessed further.

4.5 Relationship to Existing Programs and Data

This criterion considered the availability of the anticipated data source, both presently and over future time horizons. If data from existing monitoring programs were available and could be directly applied towards ecosystem services, a ‘high’ score was assigned. If data were available but required significant additional analysis or data collection, a ‘moderate’ score was assigned. If no existing data or monitoring programs existed, a ‘low’ score was assigned. Appendix C summarizes existing programs and data in Alberta.

4.6 Relevance to Land Use Planning

Ultimately, this report is intended to contribute towards regional planning under the LUF. In this context, a comparison of land use and/or land management options can provide important inputs to land use planning and decision-making. To help determine an indicator's relevancy to land management decisions, two factors were considered: predictability, and the availability of defensible threshold values.

4.6.1 Predictability

The predictability of the future state of the indicator is a key component of how readily it can be incorporated into scenario modelling. If the future condition of an indicator can be reasonably forecasted using a simple modelling approach and available data, this criterion was scored as 'high'. If modelling approaches are relatively complex and/or require some assumptions, this criterion was scored as 'moderate'. If modelling approaches were complex and/or required a multitude of assumptions, this criterion was scored as 'low'. Indicators requiring a large number of questionable assumptions to predict their response were not assessed further.

4.6.2 Existing Thresholds

An additional factor affecting an indicator's utility for decision-making is the availability of any established relationships from the literature on ecological thresholds. Although the scientific validation of such relationships remains rare in the literature, when thresholds have been shown to exist, these can provide highly useful guidance for establishing management targets. If a threshold in the literature was published by several independent researchers, this criterion was scored as 'high'. If a threshold was found in the literature but required significant additional analysis or validation by other research, this criterion was scored as 'moderate'. If no thresholds were found in the literature this criterion was scored as 'low'.

5.0 BROAD-SCALE INDICATORS ASSESSMENT

This section provides a review of indicators at the broad landscape scale. The criteria outlined in Section 4.0 have been applied to analyze the suitability of a suite of indicators for addressing ecosystem services. Measurement techniques are briefly addressed under the criterion of "measurability". Typically, broad-scale conditions are more effectively measured and analyzed using Geographic Information Systems (GIS) and remote sensing platforms, which is reflected within the following assessment of the broad-scale indicators. Note that the detailed assessment below only addresses the most promising indicators for the purposes of this project, based on a screening process that eliminated a large number of possible metrics. Landscape pattern metrics are especially prone to correlation, which may make the use of multiple metrics redundant.

5.1 Landscape Composition

The mosaic of land uses and habitat types within landscapes can all potentially influence ecosystem service supplies within a defined area [33]. Aspects of landscape composition such as the percentage of forests, wetlands, and impervious surfaces can function as useful indicators of the condition of the landscape and its consequent ability to provide ecosystem services [139]. Generally, landscape composition can be monitored relatively inexpensively using remote sensing and GIS techniques [135].

5.1.1 Total Proportion of Natural Assets

The total amount of natural assets in a landscape affects ecosystem services in numerous ways. Generally, natural assets are critical for protecting watershed integrity, biodiversity-related services, and natural disturbance regimes. Although anthropogenic assets (e.g., seeded pasture, cropland) also provide some degree of ecosystem services, the scope of this study is limited to natural assets (refer to Section 1.0). Table 5-1 summarizes the assessment of this indicator.

Table 5-1 Indicator assessment: % natural assets

Criterion	Rating	Justification / Examples
Understandability	HIGH	Highly understandable Maps can facilitate communication
Ecosystem Service Linkages	HIGH	Natural assets tend to provide greater ecosystem services than anthropogenically dominated landscapes
Climate regulation	✓	Forests provide local shade and windbreaks [131] Most natural assets sequester atmospheric carbon
Disturbance regulation	✓	Wetlands & forests mitigate floods & droughts [131, 141, 257]
Biological control	✓	Natural assets provide habitat for birds, bats, and insects that prey upon pests [34, 321]
Erosion/sediment control	✓	Natural assets provide higher erosion control, water supply replenishment, and water quality services [102, 139]
Water supply	✓	
Nutrient cycling	✓	Natural assets play key roles in nutrient cycles
Primary production	✗[1]	
Recreation	✓	Natural areas provide recreational opportunities Water supply and erosion control services of natural assets improve aquatic recreational experiences [102]
Responsiveness to Management Practices	HIGH	Persistence of natural assets depends on: forest, farm, and rangeland management, energy industry reclamation success, land use decisions, policy and legislation
Measurability/ Cost Effectiveness	HIGH	Remote sensing / GIS techniques Provides key information at reasonable cost
Existing Programs	MED	GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover Mapping, Provincial Wetland Inventory However, no seamless coverage exists for the region
Predictability	HIGH	Land use choices have predictable impacts
Thresholds	MED	Political choices are required However, 50% appears to be a threshold [198, 322, 378]

[1]The proportion of natural assets on the landscape may or may not contribute to primary production. In a landscape with forests and urban land, a greater proportion of natural assets (forest) will increase primary production. However, in a landscape consisting of grasslands, badlands and irrigated cropland, primary production will tend to increase along with the amount of irrigated cropland.

Potential Targets

Several studies in widely varying regions show 50% as an appropriate target. In forested highlands of New York/ New Jersey, a loss of >50% forest cover was identified as a potential threshold for increased risk of environmental degradation and ecosystem service loss [198]. In Austrian agricultural landscapes, 50% human-dominated land was identified as a threshold for maintaining landscape diversity and ecosystem services [378]. In South Africa, models show 50% an effective target for conserving a full assemblage of herbivore populations [322]. Therefore, 50% appears to be an appropriate target value for ecosystem service provision. However, in highly altered landscapes, lower, more pragmatic targets may be required. Conversely, in landscapes with a high proportion of protected areas, higher targets are more appropriate for protecting ecosystem service provision. Table 5-2 summarizes potential targets for this indicator based on scale and context.

Table 5-2 Potential targets: % natural assets

Scale	Setting	Target (% of landscape)	Example Areas
Regional	southern Alberta	>50%	southern Alberta
Landscape	Prairie / parkland	>50%	Bow-Mixed Grassland LU Red Deer-Aspen Parkland LU
Landscape	Highly altered prairie landscape	e.g., 20%	Bow-Fescue Grassland LU Red Deer-Moist Mixed Grassland LU
Landscape	High value protected landscapes	e.g., 95%	Bow-Eastern Continental Ranges LU Upper South Saskatchewan-Cypress Upland LU

5.1.2 Proportion of Wetlands

Wetlands provide diverse and valuable ecosystem services on a per hectare basis [85]. In the prairie and parkland of southern Alberta, many wetlands have been lost to drainage. Remaining wetlands are thus increasingly critical for maintaining watershed health and ecosystem services. Therefore, the proportion (%) of wetlands is a key indicator of ecosystem services. Table 5-3 summarizes the assessment of this indicator.

Table 5-3 Indicator assessment: % wetlands

Criterion	Rating	Justification / Examples
Understandability	HIGH	Highly understandable Maps can facilitate communication
Ecosystem Service Linkages	HIGH	Relevant for multiple services
Climate regulation	✓	Wetlands regulate local climate including reduced risk of frost damage [219] Wetlands store carbon [287]. Although wetlands also produce CH_4 (methane), greenhouse gas forcing of CO_2 sequestration is often comparable [236]
Disturbance regulation	✓	Wetlands mitigate floods and droughts [48, 141]
Erosion/sediment control	✓	Wetlands capture and retain sediments [102, 139, 141]
Biological control	✓	Wetlands provide habitat for birds and insects that prey upon pests [34, 321]
Nutrient cycling	✓	Wetlands provide key roles in nutrient cycling [287]
Primary production	✓	Wetlands are often hotspots of primary production [287]
Water supply	✓	Wetlands provide groundwater recharge and help maintain baseflow in rivers and streams [48, 141] Wetlands can reduce nitrate by 80% and phosphorus by up to 94 % [65, 234, 257, 313]
Recreation	✓	Wetlands provide direct recreational and scenic opportunities [44] Wetlands indirectly influence recreation in other locations in the watershed by improving water quality
Responsiveness to Management Practices	MED	Responds to wetland policies and legislation, including degree of enforcement and compensation success Directly related to drainage or dewatering of wetlands However, non-permanent wetlands exhibit natural seasonal and inter-annual variability
Measurability/ Cost Effectiveness	MED	Remote sensing / GIS techniques (but seasonal and inter-annual changes pose classification challenges) Provides key information at reasonable cost
Existing Programs	MED	Provincial Wetland Inventory, GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover Mapping However, wetland definitions and mapping criteria used in various inventory projects differ, and no simple crosswalking methodology is available
Predictability	HIGH	Development scenarios can predict the consequences of land use decisions on wetland persistence Climate change scenarios, though more uncertain, can be used to predict wetland responses [229]
Thresholds	HIGH	3-7% wetland cover in temperate watersheds is critical to maintain water quality and flood control services [235]

Potential Targets

Previous research identifies potential targets for this indicator depending on the ecosystem service of interest and the location of the study (Table 5-4). Potential targets for the percentage of wetland land cover on the landscape thus depend on the service of interest, as well as scale and landscape context, as summarized below in Table 5-5.

Table 5-4 Potential targets: % wetlands (After Mitch & Gosselink (2000) [235])

Ecosystem Service	Location	Scale (km^2) / Watershed Area (km2)	Target (% of landscape)
Water quality and flood control	Temperate latitudes	10^2 - 10^6	3-7% [235]
Water supply: Phosphorus retention	Great Lakes, Michigan, USA	208	15% [360]
Water supply: General water quality improvement	Illinois, USA	378	1-5% [156]
Water supply: nitrogen control	Southeastern Sweden	882	5% [18]
Water supply: nitrogen control	Mississippi Basin, USA	3.0 x 10^6	3.4-8.8% [233]
Flood control	Upper Mississippi Basin, USA	1.9 x 10^6	7%[a] [157]

Table 5-5 Potential targets: % wetlands in southern Alberta

Scale	Setting	Target (% of landscape)	Example Areas
Regional	Large higher-order watershed	5-7%	South Saskatchewan River Basin
Landscape	Watershed with high phosphorus loading & eutrophication	>15%	Pine Lake watershed Red Deer-Aspen Parkland LU
Landscape	Watershed prone to flooding	>7%	Highwood River watershed Bow-Aspen Parkland LU
Landscape	Semi-arid climate & wetland-poor landscape	1-3%	Upper South Saskatchewan-Mixed Grassland LU
Landscape	Part of Mississippi River basin	>7%	Missouri-Moist Mixed Grassland LU

The potential targets presented in Table 5.5 could be used as either conservation or restoration goals. Restoration should target areas of high potential for service performance, including areas of drainage tile discharge in farmland, or floodplains [48, 234]. Targets should also consider natural surficial geology and baseline wetland cover; for example, glacial moraines contain a high density of prairie pothole wetlands, whereas lacustrine deposits contain lower wetland densities. Knowledge of the NRV for the percentage of wetlands in different southern Alberta landscapes would be useful for setting targets.

5.1.3 Proportion of Landscape-Specific Natural Assets

Individual natural assets should be reported in a disaggregated fashion from total natural asset cover. Types of natural assets that should be examined depend on the landscape setting. For example, in parkland ecosystems, forests and shrublands affect ecosystem services in multiple ways (Table 5-6). In the mountains, ice cover is important. In grasslands, scarce assets such as badlands and fescue grasslands should be monitored. At the regional scale, all natural assets should be monitored, but sub-regional landscape analyses are required for setting appropriate management targets.

Table 5-6 Indicator assessment: % of landscape-specific natural assets

Criterion	Rating	Justification
Understandability	HIGH	Highly understandable Maps can facilitate communication
Ecosystem Service Linkages	HIGH	Each natural asset has a different relationship to specific ecosystem services A few illustrative examples are described below
Climate regulation	✓	Forest loss changes carbon budgets & GHG fluxes [183]
Disturbance regulation	✓	Forests can mitigate droughts and floods [116, 131]
Biological control	✓	Loss of natural grasslands affects the ability of landscape to control pests [321]
Erosion/sediment control	✓	Increases of bare rock and soil (geological assets) indicate losses of erosion control and primary production services
Nutrient cycling	✓	
Primary production	✓	
Water supply	✓	Ice cover affects water supply services during summer months [307]
Recreation	✓	Loss of lakes / glaciers / forests diminish recreational opportunities
Responsiveness to Management Practices	HIGH	Persistence of natural assets depends on: forest, farm, and rangeland management, energy industry reclamation success, land use decisions, policy and legislation
Measurability/ Cost Effectiveness	HIGH	Remote sensing / GIS techniques Provides key information at reasonable cost
Existing Programs	MED	GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover Mapping However, no seamless coverage exists for the region
Predictability	HIGH	Development scenarios can predict the consequences of land use decisions on natural asset persistence
Thresholds	MED	A threshold for grassland persistence has been estimated at between 10-30% of the landscape [87]

Potential Targets

Potential targets for the percentage of individual natural assets on the landscape are best defined for specific landscapes, as illustrated below in Table 5-7.

Table 5-7 Potential targets: % landscape-specific natural assets for different southern Alberta landscapes

Landscape Setting	Natural Asset Type	Target (% of landscape)	Example Areas
Foothills	Coniferous Forests	>80%	Bow-Western Alberta Upland LU
Foothills/Montane headwaters in water supply source areas	Coniferous Forests	>90%	Elbow River Watershed
Parkland	Forests & Grassland & Shrubland	50%[a]	Red Deer-Aspen Parkland LU
	Grassland	10-30% [b]	
Fescue Grassland	Fescue Grassland	>20% [b]	Bow-Fescue Grassland LU
Mixed Grassland	Mixed Grass	30%[b]	Upper South Saskatchewan-Mixed Grassland LU
	Forests	<5% [c]	
	Shrubland	<20% [c]	
All landscapes	Lotic	Existing baseline	Bow-Mixed Grassland LU

a Published threshold of 50% for total natural assets considered [198, 378]
b Published threshold of 30% for grassland persistence considered [87]
c Tree and shrub establishment in upland grassland ecosystems outside of riparian and naturally wetter areas is undesirable from a biodiversity/ecosystem services standpoint [82, 208]

One issue requiring close monitoring in Alberta is the expansion of prairie shrub ecosystems at the expense of grasslands. Observations have shown that incursions of woody plants into grasslands have been increasing worldwide [45, 188]. There is good experimental evidence indicating this occurs because woody plants respond better to the increasing concentrations of atmospheric CO_2, due to photosynthetic metabolism and carbon allocation patterns that enable woody plants to take greater advantage of CO_2 fertilization than grasses [242]. Outside riparian zones and naturally wetter areas, shrub and tree cover should be maintained at levels that enable a balance between grassland obligate species and those species that benefit from woody habitats. The encroachment of shrubs into grasslands is an important problem because shrubs replace the preferred forage of domestic livestock (grass) with species unsuitable for livestock grazing [242]. However, encroachment of shrubs into grassland does not diminish soil organic carbon [79]. Monitoring for this change will require

data on the amount of shrub-type species in grasslands (an ecological quality aspect within grasslands), as well as possible shifts in cover types between grasslands and prairie shrubs. However, the ability of remote sensing classification schemes to distinguish between these two natural asset types requires further research.

5.1.4 Proportion of Impervious Surfaces

The amount of impervious surface (IS) such as concrete, asphalt, and roofs reflects the intensity of urban and industrial development in a watershed. IS is an inverse indicator of watershed integrity since increasing IS is strongly associated with high peak stormwater discharges and pollutant loadings from non-point sources [1, 67, 139, 202]. Table 5-8 below summarizes the assessment of this indicator.

Table 5-8 Indicator assessment: % impervious surfaces

Criterion	Rating	Justification
Understandability	HIGH	Understandable to all stakeholders
Ecosystem Service Linkages	HIGH	Can be related to all priority services
Climate regulation	✓	Carbon sequestration lacking in paved areas [167]
Disturbance regulation	✓	Increase in peak flood risk [19, 30, 67, 139] Drought aggravation [264]
Erosion/sediment control	✓	Channel erosion [67, 139]
Biological control	✓	Stream biodiversity / insect predator habitat [67, 139]
Nutrient cycling	✓	Litter decomposition [64]
Primary production	✓	Loss of productive soils [167]
Water supply	✓	Water supply degradation [12, 139, 217] Reduced groundwater storage and dry season flows
Recreation	✓	Eutrophication and pollution reduce recreational opportunities
Responsiveness to Management Practices	HIGH	Responds to growth management strategies, urban planning, low impact site development, etc.
Measurability/ Cost Effectiveness	HIGH	Remote sensing / GIS techniques [1, 72, 75, 172, 200, 320] Provides key information at reasonable cost
Existing Programs	MED	No direct program in Alberta exists However, GVI & AVI could potentially be used to estimate IS from linear relationships between developed land and IS (e.g., urban residential=35-50% IS, urban commercial/business=75-85% IS [285])
Predictability	HIGH	Urban growth forecasting
Thresholds	HIGH	10% and 25% are possible key thresholds [67, 160, 161, 213, 369]

Potential Targets

Several studies identify thresholds for IS in a watershed [67, 160, 161, 213, 369]. General relationships are summarized in Table 5-9. However, these thresholds are derived from studies throughout the United States, and their applicability in Alberta requires validation through research.

Table 5-9 Effects of impervious surfaces on watersheds

Variable	Corresponding Ecosystem Service (s)	Stream Classification			
		Unstressed	Stressed	Impacted	Degraded
Impervious-ness	Multiple	0 %	0-10%	11-25%	26-100%
Channel Stability	Erosion Control	Stable	Stable	Unstable	Highly Unstable
Water Quality	Water Supply, Recreation	Good	Good	Fair	Typically Poor
Stream Biodiversity	Disturbance regulation, Biological Control	Good-Excellent	Good-Excellent	Fair-Poor	Poor

Adapted from: Leitao et al. (2006) [202] and CWP (2001) [67]

There is strong evidence of thresholds for this indicator. Watersheds are impacted considerably when IS >10%, and watersheds with IS >25% provide very low ecosystem services (Table 5-10). However, there is no clear threshold of *no* effect, and some degree of resource degradation can occur at virtually all levels of development [40]. For example, as impervious surfaces in the watershed increase, linear increases in aquatic nitrogen pollution are observed [213]. Accordingly, suitable planning targets for this indicator are scale and context dependent, depending on the importance of the water body and pragmatic considerations, as illustrated in Table 5-10.

Table 5-10 Potential targets: % impervious surface

Scale	Context	Target (% IS)	Example Areas
Regional	Large higher-order watershed	<1%	Bow River Basin
Landscape	Heavily urbanizing watershed	<25%	Nose Creek watershed, Calgary Piper Creek watershed, Red Deer
Landscape	Moderately urbanizing watershed	<10%	7-Persons Creek watershed, Medicine Hat Bow-Fescue Grassland Landscape Unit
Landscape	Headwaters in water supply source areas	<0.5%	Upper Elbow River watershed

5.2 Landscape Pattern

The landscape composition indicators discussed above do not provide information on spatial characteristics, patterns, and relationships between natural asset patches. For example, consider a landscape that is 20% forested. These forests can consist of a few large, contiguous forest patches, or many smaller patches. Forest patterns may be dispersed or aggregated, highly fragmented or interconnected. These different patterns have implications for the flow of ecosystem services in the landscape. The majority of published studies on landscape patterns examine how these patterns affect biodiversity and wildlife abundance [94, 259, 323]. Increasingly, studies are also examining how landscape patterns affect ecosystem services such as nutrient cycling, primary productivity, disturbance regulation (i.e., fire control), erosion control, and water supply [12, 131, 248, 299].

A very large number of metrics for assessing landscape patterns exist [96, 137, 226, 347, 348]. However, since many of these metrics are correlated with one another, a universal and parsimonious subset of indicators can be defined with principal components analysis [96]. This universal subset [96] was combined with Forman's list of indispensable landscape patterns (see Section 3.1.1) [131] to eliminate the vast number of landscape pattern metrics and provide a list of five key landscape pattern indicators assessed below.

5.2.1 Patch Size

Large patches of natural vegetation are a critical landscape pattern [111, 131, 226]. The simplest metric of patch size within landscapes is the mean patch size of cover types [202]. Patch size distribution should also be interpreted by considering statistical outliers. For example, the largest patches in a landscape should be identified and described.

Table 5-11 Indicator assessment: patch size

Criterion	Rating	Justification / Examples
Understandability	HIGH	Highly salient and understandable Can be visualized with maps, charts, graphs, etc.
Ecosystem Service Linkages	HIGH	Directly related to many ecosystem services Also *indirectly* linked to ecosystem services through biodiversity [193]. Large patches support biodiversity by providing microhabitat diversity, higher population sizes, core habitat for large animals and keystone predators, and a buffer against extinction [131, 136, 214]
Climate regulation	✓	
Disturbance regulation	✓	Large patches maintain natural fire dynamics and other disturbance regimes [131, 210, 349] Large patches decrease windthrow of trees [131, 357] Large patches prevent floodwaters from moving rapidly downstream [116] *Indirect:* plant diversity mitigates drought [342]
Erosion/sediment control	✓	Large forest patches prevent wind and water erosion [131]
Biological control	✓	*Indirect:* higher insect predator diversity lowers the risk of pest outbreaks [58, 131, 211, 373]
Nutrient cycling	✗	
Primary production	✓	*Indirect:* plant diversity is related to high primary productivity, particularly in grasslands [59, 244, 338]
Water supply	✓	Large patches slow surface runoff and increase water infiltration [24, 116, 147] Smaller forest patches degrade water supplies by breaking hydrological connectivity and reducing retention of sediment, nutrients, and pollutants [131]
Recreation	✓	Large patches contain a full spectrum of recreational opportunities, ranging from the developed and accessible to the remote and wild [76]
Responsiveness to Management Practices	HIGH	Land use and resource management policies and legislation lead directly to attrition, loss, fragmentation, conservation, or restoration of large patches
Measurability/ Cost Effectiveness	HIGH	Even poor resolution mapping can identify the largest patches in a landscape Important information obtained at relatively cheap cost
Existing Programs	HIGH	GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover Mapping, ABMI data
Predictability	HIGH	Large patches are easily modelled and tracked over time
Thresholds	MED	Thresholds are complicated & highly context-dependent Future research is recommended to define “minimum area point” thresholds for species-area relationships and/or “minimum dynamic areas” to prevent natural disturbances from eliminating species [131]

Potential Targets

Defining scientific targets for this indicator requires significant technical analysis. When considering requirements for biodiversity conservation, targets for patch sizes are highly species-specific, and can range from 0.0004 ha (for some invertebrates) to 220 000 ha for wide ranging mammals such as bears and cougars [185] (Table 5-13). In addition, appropriate management targets can be set by applying the concepts of minimum area point and minimum dynamic area.

Table 5-12 Summary of patch size targets from the literature

Target	Species / Processes Affected
0.0004 ha (4 m^2)	invertebrates [185]
1-10 ha	small mammals [185, 315] less sensitive grassland birds [155, 353]
2 ha	prairie butterflies
20-100 ha	more sensitive grassland birds, nesting wetland species [126, 155]
100-1000 ha	preserves interior grassland habitat [126]
>1000 ha	species with large home ranges [110, 126]
10 000 ha	viable ecological processes over time [15]

Minimum Area Point

Minimum area point refers to the patch size where an abrupt change in slope takes place on a plot of a species-area curve (Figure 5-1). To define minimum area points, data on species groups directly linked to ecosystem services could be the focus for these analyses (e.g., insect-eating birds and bats). Presumably, ABMI will generate data to enable this analysis in the future.

Over shorter time horizons, information from other jurisdictions could be analyzed and applied. For example, in New Jersey, forest patches >40 ha and >5.5 ha are required to conserve >90% and >50% of insect-eating birds, respectively (Figure 5-2) [131]. This type of information can be applied to set interim targets. For example, for forest patches in parkland ecosystems, a target of >5.5 ha mean patch size, with at least 1 patch >40 ha within each 5 km^2 may be an appropriate interim target for Alberta.

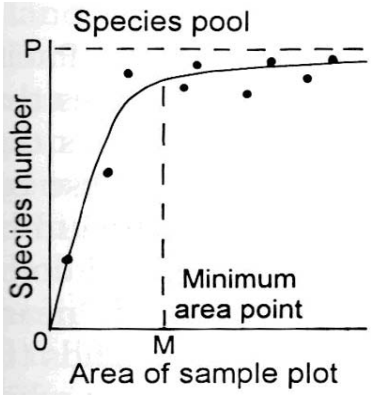
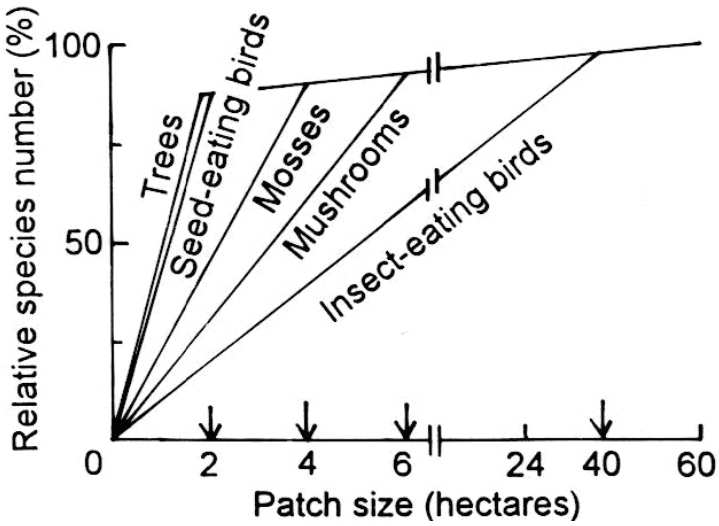


Figure 5-1 Species-area curve (after Forman 1995 [131])

Figure 5-2 Sensitivity of different species groups to patch size (after Forman 1995 [131])



In forested and mountainous ecoregions, desirable target patch sizes should be larger in order to protect headwaters, preserve interior habitat, and maintain wilderness recreation experiences. A good indicator of the intensity of wilderness experiences is the presence of large mammals (e.g., grizzly bears). Based on the average female grizzly bear range and other considerations, potential targets for patch size in these areas might be defined as >300 km^2 mean patch size, with at least 1 patch >1000 km^2 in each landscape unit.

Minimum Dynamic Area

The concept of minimum dynamic area considers patch size requirements for the persistence of natural disturbance dynamics [131, 349]. This can be conceptualized in an ecosystem services framework as reducing the risk of large 'unnatural' fire regimes, as well as reducing the risk that a disturbance will extirpate a species from a given landscape. Data collected by ASRD on fire frequencies and sizes can define minimum dynamic areas. This data should be interpreted in the context of disturbance intervals, recovery intervals, disturbance extent, and landscape extent to define desirable minimum dynamic areas (Figure 5-3) [349]. This would also enable tracking changes over time towards 'unstable' system dynamics characterized by major crashes-which is a highly undesirable and potentially irreversible threshold (Figure 5-3).

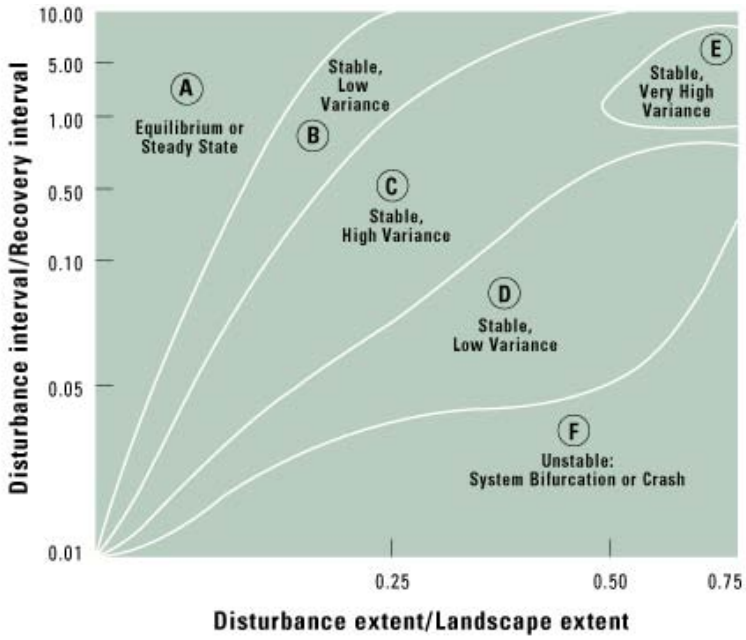


Figure 5-3 State-space diagram of landscape dynamics in response to natural disturbance [349]

Location of Large Patches

Patch size should also be interpreted and discussed in the context of the location and number of large patches in relation to valued ecosystem components and services. For example, the location of large patches should ideally coincide with the location of alluvial aquifers susceptible to contamination to maximize water supply services in the landscape.

The total number of large patches that are appropriate is also landscape-specific. In a scenario aiming to conserve species diversity and related services (e.g., biological control, primary production), two large patches in some landscapes may contain most species associated with that ecoregion. However, in landscapes where one patch contains a limited portion of the species pool for that asset, four or five large patches may be required to conserve the same number of species (Figure 5-4) [111].

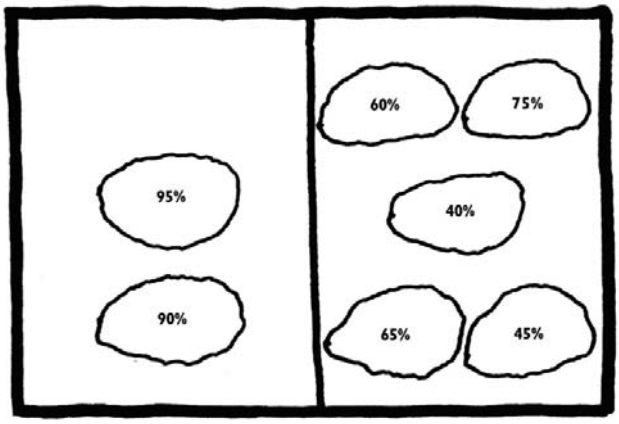


Figure 5-4 Number of large patches required to conserve species (from Dramstad 1996 [111])
Percentages indicate % of species pool captured in each patch for two scenarios.

5.2.2 Road Density and Other Anthropogenic Edge Types

Anthropogenic fragmentation of landscapes increases the edge density of landscapes and has many ecological implications, including alterations to species and fire dynamics as well as colonization by invasive species. Limiting edge and fragmentation is generally a desirable landscape objective. Activities which cause higher densities of anthropogenic edge include construction of roads, pipelines, transmission corridors, and seismic exploration, clearing land for agriculture, and forest clear-cutting.

Fragmented patches with many linear and dispersed anthropogenic features have higher edge density [103, 131]. This is illustrated by Figure 5-5, which conceptually illustrates six potential landscape transformation scenarios; the scenario with the highest anthropogenic edge density is the "dispersed" pattern.

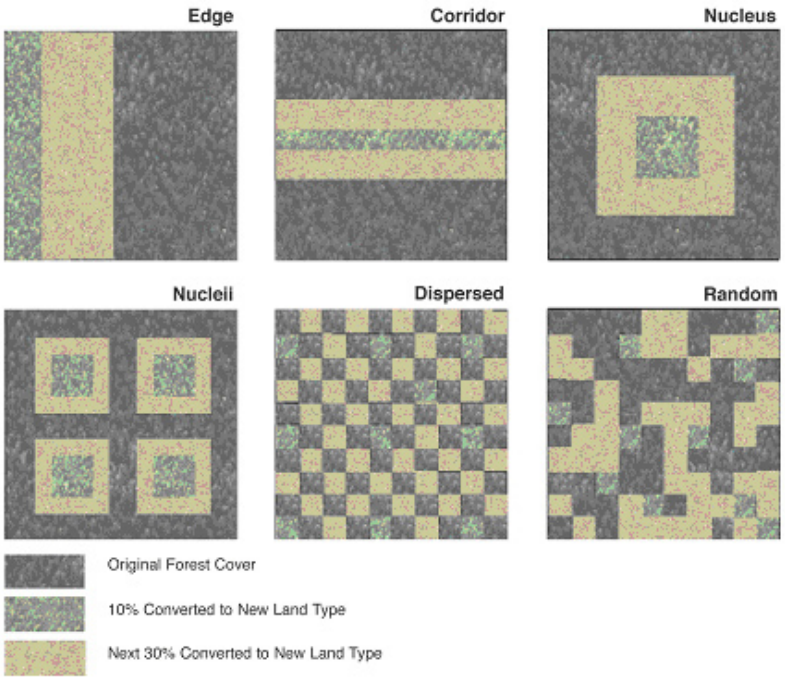


Figure 5-5 Conceptual land transformation sequence models (after Forman 1995 [131]).

Any analysis of anthropogenic edge should divide edge types into distinct categories, such as well site edges, total linear disturbance density (e.g., roads, pipelines), total vegetated anthropogenic edges (e.g., reclaimed pipelines, cropland), density of major roadways (e.g., paved highways), and total road density (including gravelled roads). Each of these edge types differ substantially from one another; thus, grouping them together may cause considerable confusion. Edge density for each of these categories can be calculated in km/km^2 as the sum of the lengths (m) of the edge type in the landscape, divided by the total landscape area (m^2), and multiplied by 10,000 to convert units.

Edges differ in structure and function from interior habitats due to changes in light penetration, wind conditions, snow depth, and species composition [122, 204]. Although edge density impacts are highly species-specific, lower edge densities tend to provide the following benefits to habitat and biodiversity [103, 131, 132, 260, 273, 382]:

- Improved habitat for species of conservation concern;
- Habitat for wide-ranging species associated with wilderness areas, such as wolves;
- Habitat for sensitive, specialized species such as salamanders;
- Lower risk of predation and brood parasitism for bird species;
- Lower probability that exotic species will invade and spread; and,
- A buffer against extinctions when core area is increased.

Table 5-13 Indicator assessment: anthropogenic edge density

Criterion	Rating	Justification / Examples
Understandability	MED	Edge density can be illustrated in a relatively simple fashion (e.g., Figure 5-5)
Ecosystem Service Linkages	HIGH	Lower anthropogenic edge density is related directly or indirectly to many ecosystem services, including:
Climate regulation	✓	Effects on wind and snow conditions
Disturbance regulation	✓	Less tree windthrow [131, 357] Natural fire frequency regime [131, 357] Lower peak floods
Erosion/sediment control	✓	Less linear conduits for sediment runoff [46, 93, 134, 288, 301, 377]
Biological control	✓	Linear anthropogenic features provide vectors for insects, diseases, and exotic plants [138, 237, 344, 364]
Nutrient cycling	✓	Maintenance of waste decomposition processes [187]
Primary production	✓	Dust and pollutants from roads and industrial sites can smother plants and alter pH, nutrients, and snow cover at distances ranging from 10-500 m from edges [17, 23, 119, 256, 335, 358, 382]
Water supply	✓	Anthropogenic edges can decrease water filtration through vegetation patches [46, 93, 288, 377] Linear developments can pollute surface waters and aquifers [46, 93, 288, 377]
Recreation	✓	Wilderness experiences (lower edge densities) Access (intermediate edge densities)
Responsiveness to Management Practices	MED	Development increases edge density Requirements for forestry and energy companies to plan access concurrently reduces habitat fragmentation
Measurability/ Cost Effectiveness	MED	Remote sensing/GIS & FRAGSTATS software [226] Measurement accuracy is affected by spatial scale Some sensors do not detect narrow seismic cutlines [205]; however, vector GIS data could fill gaps Effects of edge width are difficult to measure & consider
Existing Programs	MED	GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover Mapping Classification of the new SPOT data set
Predictability	HIGH	Mining, oil/gas, forestry, agriculture, and linear developments all increase edge density in a predictable fashion Spatial patterns of development can be modelled
Thresholds	MED	Application of ABMI's "intact" landscape reference condition approach [9] Information on species dose-response relationships for road density/linear features can be adapted/translated into an edge density framework

Potential Targets

Potential targets for anthropogenic edge density must be determined at the landscape level by combining scientific information with stakeholder engagement processes and land use zoning policies.

Most existing information on thresholds and targets are related to road density. Studies examining impacts of fish communities in Alberta have identified a potential road density threshold of <0.7 km/km^2 to avoid impacts on fish communities, and a road density target of approximately 1.0 km/km^2 if some impacts on fish are acceptable [327]. A threshold of 0.7 km/km^2 also applies to the viability of large mammals (e.g., wolves) [280]. In mixed grass prairie, grassland birds and associated ecosystem services disappear from the landscape at a road density threshold of 3.7 km/km^2 (Gates, pers. comm.).

5.2.3 Connectivity

Connectivity is a critical property of landscapes that facilitates or limits the movement of resources and organisms among natural patches [347]. In landscapes where remnant natural vegetation patches lack corridors connecting one another, major alterations can be observed in hydrological regimes, nutrient cycles, radiation balance, wind patterns, and soil movement. Although connectivity is somewhat correlated with edge density, it captures independent landscape attributes [96] and therefore should be considered as a separate indicator in landscape assessments.

Connectivity between large patches can be maintained through corridors and stepping stones (Figure 5-6). A corridor is defined as a strip of land that differs in composition from the surrounding matrix [127], while a stepping stone is a habitat patch where an animal stops while moving along a heterogeneous route [131]. Corridors and stepping stones facilitate ecological processes and can alleviate habitat fragmentation problems.

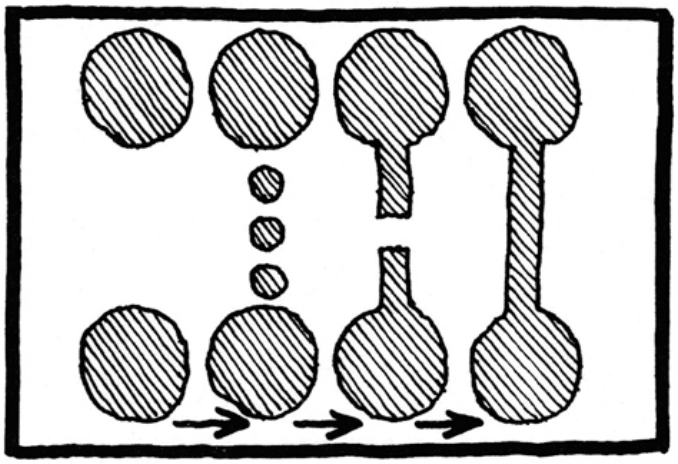


Figure 5-6 Levels of connectivity between patches: no corridor, stepping stones, fragmented corridor & complete corridor (Source: Dramstad et al. 1996 [111])

One metric used to describe inter-patch distance is the average Euclidian nearest neighbour distance (ENN) [96, 202]. This measures the degree of isolation of a patch from nearby patches of the same natural asset type,

defined as the shortest straight-line distance. FRAGSTATS is one program often used to compute ENN, and can compute additional statistics such as the mean and variability as well. Knowing the variability in nearest neighbour values can lead to derivative metrics such as patch dispersion (the standard deviation of Euclidean nearest neighbour distance) across the landscape.

Table 5-14 Indicator assessment: connectivity

Criterion	Rating	Justification / Examples
Understandability	MED	More technical and less tangible concept than other landscape condition indicators (e.g., patch size) Graphics such as colour-gradient maps can portray connectivity
Ecosystem Service Linkages	HIGH	Connectivity is highly related to those ecosystem services related to movement across the landscape
Climate regulation	✗	
Disturbance regulation	✓	Well-connected vegetated corridors mediate flood control [312]
Erosion/sediment control	✓	Riparian connectivity [367]
Biological control	✓	Dispersal of biological control agents
Nutrient cycling	✗	
Primary production	✗	
Water supply	✓	Connected patches and corridors increase water quality and quantity [218, 367]
Recreation	✓	Connectivity of natural areas/ urban parks for recreation purposes (e.g., hiking, biking trails)
Pollination	✓	Pollinator richness and visitation rate on crops decline with increasing distance from natural habitat [194, 240, 241, 247]
Responsiveness to Management Practices	HIGH	ENN is quick to respond to an increase in roads and linear development as well as isolated patches of development that fragment the landscape, as opposed to aggregated development
Measurability/ Cost Effectiveness	MED	Highly measurable using remote sensing/GIS & FRAGSTATS software [226] Computing power across large landscapes and regions may be limiting
Existing Programs	MED	GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover Mapping May require some processing to develop a common landscape and land use vocabulary Existing spatial analysis software (e.g., FRAGSTATS)
Predictability	HIGH	Linear developments and other developments that fragment natural patches all have a predictable impact on landscape connectivity that is easily modelled
Thresholds	MED	The literature on recommended inter-patch distances is available, but is very species- and process-specific, and may also depend on the landscape in question

Potential Targets

The degree of desired connectivity in terms of corridor width is dependent on the ecological process (e.g., water quality protection, wildlife habitat) and even species of interest. This determines the *functional* connectivity of the landscape. Functional corridor widths, for example, vary between 50 and 200 m [121, 324]. On a regional scale, where a corridor is intended to be used by a variety of species and persist over a long period of time, the corridor should be on the scale of kilometres in width. North-south corridors are especially important to facilitate adaptation to climate change.

Each large patch of natural vegetation should have at least two connections to other patches in order to include diverse habitat types within connected areas and minimize potential barriers to movement or unexpected events that could disrupt dispersal [127].

The effectiveness of landscape connectivity through stepping stones is usually described by the inter-patch distance. As distance increases between patches of natural assets, the ability of a patch to provide ecosystem services decreases, especially if the patch is small. Plant pollinators and other species have difficulty dispersing across large distances, which reduces the internal diversity of the natural asset and thus its ability to provide high-quality services.

Targets for inter-patch distance depend on the species (or associated ecosystem service) in question. Deer mice in prairie and badlands travel approximately 60 m to forage and have an effective distance of 140 m [243]. Other animals have larger dispersal ranges. Frogs, salamanders and small mammals often do not travel more than 300 m from a suitable habitat patch, and reptiles travel only slightly further than 500 m distance [140]. Flying animals tend to have greater thresholds for inter-patch distances, although many small birds will not travel more than 200 m to neighbouring habitat [180]. Schultz and Crone (2005) recommend that suitable habitat patches remain within 1 km of each other to conserve prairie butterfly species [311]. In Alberta, pollinator species and related services in adjacent cropland increase in abundance when uncultivated, natural land is within 750 m of cropped fields [240].

Connectivity in riparian habitats is particularly important and should be maximized to the highest extent feasible to prevent perforations that can degrade riparian services by providing conduits for runoff and water pollution as well as habitat changes (Figure 5-7).

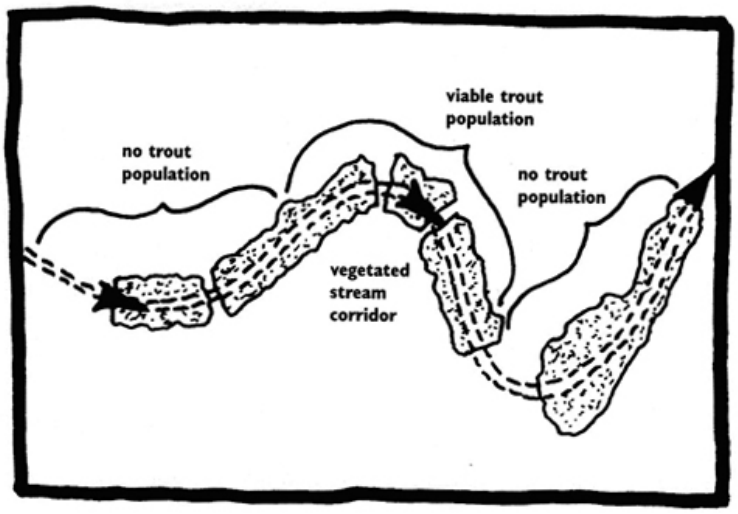


Figure 5-7 Connectivity of a stream corridor (Source: Dramstad et al. 1996 [111])

Table 5-15 Potential targets for connectivity (nearest neighbour distance)

Target	Species / Processes Affected
100 m	small walking and flying insects [180]
200 m	small birds and mammals [180]
300 m	frogs, salamanders, small mammals [140]
500 m	reptiles, medium-sized birds [140, 180]
750 m	foraging of pollinating bumblebees in Alberta [240, 241]
1 km	prairie butterflies, large birds and mammals [180, 311]

5.2.4 Riparian Buffers

Vegetated riparian buffers are particularly important. The width of riparian buffers affects their form, function, and capability to provide ecosystem services. Several metrics of riparian buffer width should be examined, including average width, width variability (e.g., standard deviation), and minimum width. Mapping natural riparian widths is particularly useful for identifying gaps in the riparian network.

Table 5-16 Indicator assessment: riparian buffer width

Criterion	Rating	Justification / Examples
Understandability	HIGH	Highly understandable Maps can facilitate communication
Ecosystem Service Linkages	HIGH	Directly relevant to many services, including pollination Indirectly related to services by providing effective linkages for communities and species [31, 271]
Climate regulation	✓	Regulation of stream temperatures
Disturbance regulation	✓	Flood control functions [312]
Biological control	✓	Increased habitat for insect predators
Erosion/sediment control	✓	Wider buffers are more effective filters providing erosion control and water supply [46, 377]
Water supply	✓	
Nutrient cycling	✓	Riparian nutrient cycling functions
Primary production	✓	Riparian areas are hotspots of primary production
Recreation	✓	Trail networks and recreational opportunities
Responsiveness to Management Practices	HIGH	Responds to development setback distances Responds to landowner cultivation practices
Measurability / Cost Effectiveness	HIGH	Readily measurable and highly important information
Existing Programs	MED	AENV 2008 Assessment of Riparian Zones in Southern Alberta using aerial video could be used to infer widths ASRD will be mapping riparian areas in forested regions of Alberta during 2008/09 GVI, etc.
Predictability	HIGH	Directly related to cultivation practices, land use bylaws (required setback distances), etc.
Thresholds	MED	Thresholds of acceptability can be defined by quantifying water filtration or flood control services Desirable thresholds are highly context specific

Potential Targets

Scientifically and socially acceptable riparian widths depend on many biophysical and human factors. For example, consider the service of filtering nutrient runoff from adjacent cropland. Studies indicate that nitrogen reductions of 5%-30% per meter of riparian buffer width are typically achieved [46, 109, 303]. The EPA has analyzed nitrogen removal by riparian buffers in over 40 studies throughout the USA and Canada (Figure 5-8)

[222]. Their statistical analysis indicates that for 90% nitrogen removal, riparian buffers should be 100-110 m wide, whereas targets of 75% and 50% nitrogen removal generally require 25 m or 5 m buffers, respectively (Figure 5-8). Variability among sites was influenced primarily by vegetation type (grassland, forest), soil permeability, and whether subsurface or surface flows dominated.

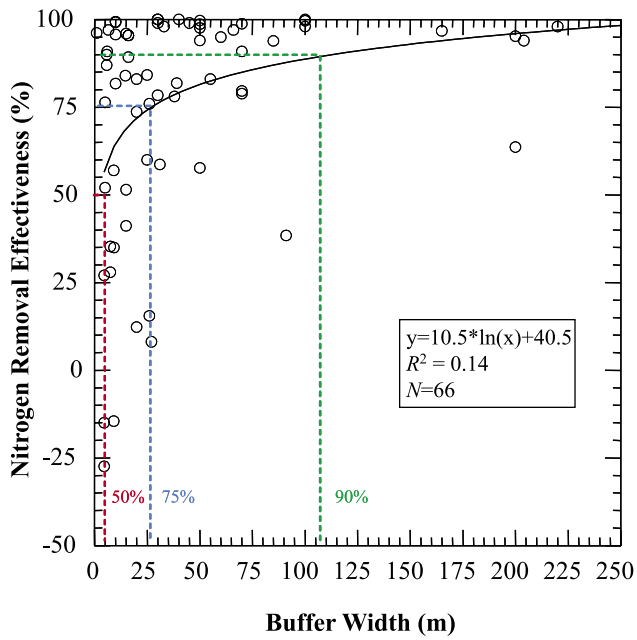


Figure 5-8 Nitrogen removal vs. riparian buffer width: a fitted non-linear model [222]. Coloured lines indicate probable 50%, 75%, and 90% removal efficiencies. Note that in a few studies, buffers <10m actually added to nitrogen levels.

Studies in diverse landscapes indicate that riparian areas are effective at performing not only nitrogen removal, but also phosphorus and biocide removal, as well as sediment and erosion control. In Maryland cornfields (USA), 50 m forested riparian buffers substantially reduced particulate matter and nutrient runoff into streams [272]. Similar results were found in agricultural landscapes of Illinois[5] [261]. In forested landscapes, vegetation width, especially above hillslopes, is a key controller of sediment input to streams [51, 131]. As a broad guideline for water quality considerations, Castelle et al. (1994) recommends a 15-30 m buffer width [66], while Environment Canada recommends a 30 m minimum buffer along at least 75% of a stream's length [121].

Desirable targets for riparian buffers are generally wider when biodiversity conservation and biological control services are considered. In Vermont, riparian corridors between 75-175 m width were recommended to meet the requirements of 90% of avian species [324]. Kennedy et al.'s (2003) literature review found that the majority of researchers recommend 100 m as a minimum riparian buffer to conserve both water quality and wildlife habitat [185].

5 In this study treed riparian areas retained more nitrogen, whereas grassy riparian buffers retained more phosphorus.

Despite these broad guidelines, the importance of context is paramount. At some sites, the functional riparian zone may be narrow (e.g., 3 m) and the transition to upland habitat can be rapid and abrupt. Conversely, riparian zones are often very wide along low-gradient meandering streams with prominent oxbows, or unconfined alluvial segments of streams underlain by gravel, where groundwater-surface water interactions often extend under the floodplain for several hundreds of metres [325].

In other cases, human infrastructure needs to be considered. In farmland with tile drainage systems, riparian buffers will be ineffective for nutrient retention, particularly if pipes bypass the riparian zone and discharge directly into streams. Wetland retention ponds are more appropriate in these locations.

Table 5-17 lists potential vegetated riparian buffer widths based on the literature review. These targets can be applied in both forested and grassland ecosystems of southern Alberta.

Table 5-17 Potential targets for riparian buffer width

Context	Target (m)	Example Areas
Streams with a narrow natural riparian zone	6	Intermittent channels & small streams with poor potential for riparian habitat development
Streams & creeks	30	Small prairie coulee streams
Streams in drinking water supply areas	100	Mountain/foothill headwater streams
Moderately sized rivers	100	Elbow River Ghost River
Larger rivers	100-200	Oldman River Red Deer River
Zones of extensive floodplains	Size of floodplain	Portions of Oldman River, Bow River Nose Creek's floodplain is up to 670 m wide [88]

5.2.5 Habitat Diversity

Diverse habitats are critical for maintaining species-rich communities [35, 131, 348]. An extensive statistical analysis of European landscapes found habitat diversity to be a highly significant predictor of species richness [34]. Species richness in turn can be linked with many ecosystem services (Table 5-18) [193].

Several metrics for assessing habitat diversity exist, including: (i) richness of natural asset types in a landscape boundary; (ii) natural asset richness density calculated as the number of different natural patch types present in a moving window with a radius of 1 km; (iii) Simpson's diversity index.

Table 5-18 Indicator assessment: habitat diversity

Criterion	Rating	Justification / Examples
Understandability	MED	Concept is relatively understandable Metrics are somewhat technical
Ecosystem Service Linkages	HIGH	Qualitatively related to several ecosystem services Quantitative diversity-ecosystem service links are difficult to establish [113, 193] Literature quoted below examines species diversity at the site scale, not habitat diversity at the landscape scale
Climate regulation	✗	
Disturbance regulation	✓	Diversity regulates disturbances such as drought [342]
Erosion / sediment control	?	Plant diversity of sites can assist with erosion control [113, 193], and landscape level effects are possible
Biological control	✓	Diverse habitats support many birds, bats, and insects, which can decrease insect outbreaks [249, 263, 283]
Nutrient cycling	✓	Diversity increases nutrient cycling efficiency [177, 193]
Primary production	✓	Diversity increases primary productivity [338]
Water supply	✗	
Recreation	✓	Diverse habitats provide better aesthetic, wildlife and birdwatching opportunities
Responsiveness to Management Practices	MED	Although habitat mosaics shift naturally over time [131], land use and management exerts a strong influence
Measurability/ Cost Effectiveness	MED	GIS & remote sensing techniques Fine spatial scale and detailed classification schemes are required (e.g., ecosite phase level is ideal, ecosections would be acceptable)
	MED	Detailed habitat diversity monitoring at the regional scale is expensive, but important
Existing Programs	MED	ABMI is mapping 130 natural landscape elements for forested areas using 1:20,000 air photos [9] Recent ecosite mapping has been completed in the Spray Lakes Sawmills FMA on the Eastern Slopes [314]
Predictability	MED	Moderately predictable in response to future scenarios
Thresholds	LOW	No particular thresholds have been identified

Potential Targets

Current baseline levels or NRV for habitat diversity in specific landscapes could be set as targets. Retaining current diversity is a desirable and prudent target for maintaining ecosystem resiliency and a stable output of ecosystem services.

Detailed habitat diversity data may be unavailable in many landscapes, especially for applications on short time horizons. Where ecosite mapping has already been completed, these are information sources that can be applied in the near future, providing that scale issues and landscape boundary definitions are addressed. For example, the Spray Lakes Sawmills FMA boundary does not correspond with natural ecosystem units or watershed boundaries, although it does overlap to a significant degree with, for example, the Bow-Western Alberta Upland LU (Figure 3-1).

One source of information that does exist is the data collected by the Alberta Biodiversity Monitoring Institute (ABMI; Appendix C). ABMI conducts habitat monitoring through remote sensing, tracking changes in habitat area for 130 natural landscape elements and changes in landscape configuration for major vegetation types. ABMI also reports on habitat status, as defined by the degree of 'intactness', or deviation from reference conditions. These reference conditions may be helpful in determining a NRV for setting management targets.

6.0 FINE-SCALE INDICATORS

This section reviews indicators at the fine scale for specific types of natural assets. The criteria outlined in Section 4.0 have been applied to assess the indicators. While many of these indicators are linked to existing data collection programs, they likely involve some measure of field sampling.

6.1 Grasslands

Within the Grassland Natural Region, there are four natural subregions (NS): Dry Mixedgrass, Mixedgrass, Foothills Fescue, and Northern Fescue. Grassland patches also occur within the Parkland Natural Region. Native prairie in Alberta has declined by over 61% since human settlement [304]. Although many ecosystem services are provided by grasslands, chief among them are nutrient cycling, erosion control, and climate regulation.

6.1.1 Range Health Assessment Score

ASRD's field of Range Health Assessments provide a useful indication [3]. The parameters used to measure range health reflect a set of ecosystem functions performed by healthy rangelands. The method uses a visual approach including comparisons to reference conditions. The approach and methodology is described in detail in Appendix C, Section C-2.

Table 6-1 Indicator assessment: range health

Criterion	Rating	Justification / Examples
Understandability	MED	Requires well trained surveyors (range managers or botanists), but concepts are easily understood [156]
Ecosystem Service Linkages	HIGH	Range Health effectively measures multiple ecosystem services, including productivity, erosion control and sediment retention (site stability), water supply (capture and beneficial release of water), and nutrient cycling
Climate regulation	✓	Native grasslands sequester large quantities of carbon in their roots [53, 163][74, 339, 365]
Disturbance regulation	✓	Healthy grasslands retain productivity during drought [342]
Erosion/sediment control	✓	Range Health assessments evaluate community structure, litter and human caused soil erosion [156]
Biological control	✓	Diverse insect populations can provide biological control services [249, 319, 336]
Nutrient cycling	✓	Diverse grasslands support efficient nutrient cycling [108, 340]
Primary production	✓	Diverse grasslands often have higher biomass than monocultures [70, 179, 223, 333, 340, 341, 375, 376]
Water supply	✓	Litter and organic matter influence soil-water relations [245, 246]
Recreation	✓	Native grasslands provide opportunities for bird and flower watching, horseback riding, and hunting
Responsiveness to Management Practices	HIGH - MED	Short-term changes to plant community structure, litter and the amount of human-caused bare ground are easily detected and managed Long-term changes in species composition and invasion of noxious weeds may be slower to respond to management
Measurability/ Cost Effectiveness	MED	Range Health indicators have been field tested and are relatively easy to measure providing the surveyor is adequately trained However, it is labour-intensive and relatively expensive
Existing Programs	MED	Those areas covered by GVI will have maps showing the extent of native prairie with assigned reference Ecological / Range Sites, a necessary step for Range Health Assessments However, this data is not yet available
Predictability	HIGH	Long term research on grasslands in Alberta and other regions has established a reasonably good ability to predict changes in the ecological quality of grasslands due to grazing or other impacts
Thresholds	LOW	No clear thresholds identified, but targets can be based on the score intervals (healthy, healthy with problems, etc.)

Potential Targets

Fescue grasslands are particularly sensitive to disturbances such as overgrazing, oil and gas development, road construction, logging and recreational activities [2, 101, 376]. Permanent ecosystem shifts can occur once fescue is replaced by non-native grasses. Modified plant communities often have lower drought resistance and lower suitability for winter grazing. There appears to be limited potential for recovery from this degraded community type back to native grasses [2].

Dryland ecosystems can even collapse to desert when subjected to natural perturbations or human-caused disturbances [275]. Moreover, these shifts may be irreversible [144, 275]. The risk of this type of shift is highest in the dryer semi-arid eastern and southern-most portions of Alberta.

Therefore, the target for this ecosystem should be a healthy status. For sites with considerable impairment, it may not be feasible to restore these to a 'healthy' status, particularly over shorter time scales; in these cases, interim improvements in health scores should be the target.

6.1.2 Soil Organic Matter

Soil quality is particularly important for determining the structure, function, and sustainability of grasslands. The Range Health indicators described in Section 6.1.1, reflect the influence of soils on vegetation, but do not explicitly assess soils themselves.

Although a vast number of chemical, physical, and biological indicators of soil condition exist [28, 50, 186, 238, 267], three properties underpin their ability to provide ecosystem services: texture, mineralogy, and soil organic matter [267]. Texture and mineralogy largely depend on natural factors and are unresponsive to management practices. Therefore, soil organic matter was selected as a key indicator of grassland ecosystem services.

Table 6-2 Indicator assessment: soil organic matter

Criterion	Rating	Justification / Examples
Understandability	MED.	Far more understandable than more detailed chemical or physical indices of soil quality
Ecosystem Service Linkages	HIGH	Organic matter has a major influence on soil fertility, aggregation, and infiltration [80, 267], which in turn affects many ecosystem services
Climate regulation	✓	Reflects carbon stored or sequestered in the soil
Disturbance regulation	✗	
Erosion/sediment control	✓	Aggregation and cohesion [80, 267]
Biological control	✗	
Nutrient cycling	✓	Cation Exchange Capacity, etc. [80, 267]
Primary production	✓	Fertility [80, 267]
Water supply	✓	Water holding capacity [80, 267] Pollutant filtration & attenuation [134, 173]
Recreation	✗	
Responsiveness to Management Practices	MED.	Highly responsive to plowing, overgrazing, drainage, etc. However, recovery of depleted soil carbon in Alberta can take 75-150 years [107]
Measurability/ Cost Effectiveness	MED.	Accurate measurement requires field sampling and laboratory analysis by trained personnel High spatial variability requires sophisticated sampling Munsell colour charts can be used for rough estimates Expensive to quantify for many sites
Existing Programs	MED.	ABMI will be collecting data on soil carbon [10], which could be used to approximate soil organic matter
Predictability	MED.	Modelling in scenarios requires some assumptions [267]
Thresholds	MED.	Approximately 3.4% soil organic matter is considered by many to be a critical level of organic carbon required for soil aggregate stability, adequate water storage, and productivity [80, 171]. Existing studies on grazing pressure can also be used to define thresholds [108]

Potential Targets

Approximately 3.4% soil organic matter is considered by many to be a critical level of organic carbon required for soil aggregate stability, adequate water storage, and productivity [80, 171]. However, realistic targets for soil organic matter must account for factors such as the natural range of organic matter for soil types in Alberta. This should ideally be defined at the soil series level in the Canadian System of Soil Classification. In addition, sampling, interpretation and assessment should consider the effects of local topography on soil organic matter [330].

6.2 Prairie Shrub

In grassland ecoregions, prairie shrub patches are typically located in depressions, along riparian edges, on north-facing slopes, or anywhere that retains slightly greater moisture conditions. The Prairie Shrub community has very diverse attributes. Range sites vary from loamy to blowout, and common soils include Solonetzic Brown, Cumulic Regosol and Orthic Black. Drainage is well-drained to rapidly drained and slopes range from gentle to steep. Prairie shrub communities tend to increase ecosystem stability (disturbance regulation) by including diverse species and structure in a grassland environment [342]. Sage brush is a common component of many prairie shrub communities.

Prairie shrub ecosystems are best assessed using the same indicators as the grassland indicators in Section 6.1.

6.3 Badlands and Thin Breaks

The badlands are defined as nearly barren or barren lands, with exposure to softrock, hardrock, or surficial geology. Thin breaks are areas with a veneer (<1 metre or less) of parent material overlaying softrock or bedrock. Badlands typically cover very little of the landscape in terms of area but are important for specialized, rare and often sensitive species (e.g., short-horned lizard) that contribute to regional biodiversity and ecological processes [281].

Badlands and thin breaks have an interesting relationship with ecosystem services. In terms of service provision, these areas have a detrimental to highly detrimental impact on services such as water regulation, erosion control and sediment retention, soil formation, primary production, pollination, and water supply [165]. At the same time, these areas are important to highly important to habitat/refugia, raw materials, genetic resources, aesthetics, spiritual and traditional use, science and education, and recreation [165]. For the priority services addressed in the current report, the overall impact of badlands and thin breaks on the landscape is negative or neutral for priority services other than recreation.

Invasive species and the condition of the upland buffer adjacent to the slope have been considered by many as key condition indicators for badlands and thin breaks. Invasive species may be extremely destructive to natural erosional processes and habitat for rare species. Development on adjacent upland areas, such as roads, is also extremely detrimental to badland services, through increased erosion and disturbance to rare species.

The Range Health Assessment (see Section 6.1) may be a suitable condition indicator for badlands, as it collects information on invasive species.

Excessive recreation may have negative impacts on badland environments due to soil compaction, disturbance, and increased rates of erosion; these impacts would be captured through a Range Health Assessment.

6.3.1 Potential Targets

Few potential targets exist with respect to ecological quality of badlands. However, a road within 1 km of slope breaks is detrimental to many breeding birds, as it causes some birds (e.g., prairie falcon, American kestrel) to abandon their nests [282, 316].

6.4 Forest Shrub

Forest shrub ecosystems include open or closed shrub meadows, pastures, or shrubby wetlands. Forest shrub ecosystems harbour insects which are directly related to ecosystem services such as nutrient cycling. They are also related to climate regulation (both local and global through carbon sequestration), biological control, water supply, and various forms of recreation [368].

Forest shrub ecosystems are included in the ASRD Range Health assessments, and are best assessed using the same methodology described in Section 6.1 above. An exception may occur for shrubby wetlands, which are best assessed using other indicators (see Section 6.10 for wetland indicators).

6.4.1 Potential Targets

No targets for forest shrub quality were found to date.

6.5 Deciduous and Mixed Forest

Deciduous or hardwood forest stands refer to stands in which 80% of the stand is composed of deciduous trees, such as trembling aspen or balsam poplar.

Mixed wood forest stands are characterized by low relief and level to undulating terrain. Soils are typically Gray Luvisols in well-drained upland till sites and Eutric Brunisols in coarse-textured sandy uplands.

Deciduous and mixedwood forests are highly important providers of many ecosystem services [165].

Forest composition and natural succession are important to ecosystem services in deciduous and mixedwood forests. Indicators of forest conditions therefore relate to forest structure and the health of natural succession processes.

6.5.1 Canopy Structure

Useful measures for characterizing forest canopy in a stand include the number, height, and age of canopy layers. This characterization represents a structural indicator, where canopy layers are defined as a height difference of at least 3 m between layers. Describing the vertical structure of the forest stand is important to evaluate patch complexity, micro-climates and habitat diversity. Knowing the dominant age of each canopy layer provides valuable information on stand maturity stages and potential successional processes. Where available, age can be obtained from the AVI database for each forest canopy layer, or, where surveyed, age measurements can be taken from the leading species of each height class. This provides an indication of the age-class structure within the forest stand.

Table 6-3 Deciduous and mixed wood indicator assessment: canopy structure

Criterion	Rating	Justification / Examples
Understandability	HIGH	Canopy layer characterization is comprehensible to professionals and the lay public
Ecosystem Service Linkages	HIGH	Forest canopy characteristics are highly related to ecosystem services. Forests with diverse canopy structure and stand age typically have higher resilience and can be linked to the following ecosystem services:
Climate regulation	✓	Structural complexity adds to climate regulation services, at micro-climate, local and regional scales
Disturbance regulation	✓	Complex vertical structure contributes to disturbance regulation by offering buffer or refuge layers against wind storms or flood events (e.g., controlling spring runoff)
Erosion/sediment control	✓	Greater canopy cover provides more erosion control by buffering the effects of rain and wind
Biological control	✓	Increased niches in a structurally diverse forest harbour natural predators of biological pests, while a diversity of ages ensures that pests such as mountain pine beetle that prey on single age structures cannot proliferate
Nutrient cycling	✗	
Primary production	✓	Primary production tends to be higher, since more vertical niches are occupied
Water supply	✗	
Recreation	✓	Recreational opportunities may be higher in forests with diverse canopy characteristics due to increased bird and wildlife watching opportunities
Responsiveness to Management Practices	MED	Canopy structure is sensitive to changes in use and management, especially silvicultural treatments. Over time, stands managed for forestry may exhibit less varied vertical and age structure which has impacts on the services provided by the stand.
Measurability/ Cost Effectiveness	MED	This indicator is considered moderate to highly measurable, as all indicators can be measured through AVI data or field measurement techniques. AVI information can be used to guide a stratified sampling strategy
Existing Programs	MED	AVI contains information on species composition, height and age classes A pilot study on the use of LIDAR to detect vegetation height has been conducted in the Parkland natural region of Alberta [41]
Predictability	HIGH	Detailed site-level information can be used in scenario development and planning, in order to identify those stands with valuable characteristics, such as a strong vertical structure, as important to maintain. It can also help to identify those stands where management activity may need to be revised to improve ecosystem service provision in the area
Threshold Relationships	MED	The literature on recommended stand structure is primarily qualitative and relatively vague, but it is available

Potential Targets

Forests with two to three canopy layers are common in Alberta, especially in mixedwood forests. Less than this implies an even stand forest that may be more susceptible to disease outbreaks and disturbance. Further details on healthy canopy structure will be landscape-specific, and baseline conditions may help to determine trends in indicator values.

6.5.2 Presence and Abundance of Dead Wood Resources

To measure the presence and abundance of dead wood resources in a forest patch, a number of values can be quantified. Useful measures include snag and down log density, and may be separated into two size classes: 10-20 cm diameter at breast height (DBH) and >20 cm DBH. These size classes recognize the need for larger snags by some forest species. Snags and down logs make up the largest proportion of coarse woody debris in a forest stand and provide important indications of the forest health in terms of successional processes and species diversity. Dead wood resources can be measured as part of a field sampling program.

Table 6-4 Deciduous and mixedwood indicator assessment: dead wood resources

Criterion	Rating	Justification / Examples
Understandability	MED	This indicator can be easily understood by both the lay public and professionals, although its capacity to be illustrated visually may be more difficult than some other indicators (e.g., pattern analyses).
Ecosystem Service Linkages	HIGH	The following ecosystem services are related to the presence and abundance of dead wood resources:
Climate regulation	✓	Dead wood stores carbon in the long-term, mitigating some climate change effects [380]
Disturbance regulation	✓	Forests with snags and down logs have increased resiliency and are often more resistant to disease, pests and climate change [380]
Erosion/sediment control	✓	Preserves slope and soil stability [380]
Biological control	✓	Forest stands with high snag density have a greater variety of habitat niches available, which has implications for biological control These habitats can house a wide range of species, including vertebrates, invertebrates, fungi, lichens, plants and micro-organisms
Nutrient cycling	✓	As dead trees decay, energy and nutrients are released back into the soil Forests with a higher amount of dead wood resources typically have a larger proportion of soil nutrients than stands with less or no dead wood resources
Primary production	✓	Habitats provided by down logs include regeneration sites for fungi, bryophytes and tree seedlings
Water supply	✗	
Recreation	✗	
Responsiveness to Management Practices	MED	Time periods over which dead wood resources change may be extensive, as natural disturbance processes or tree aging and senescence are long-term processes Shorter-term disturbances such as forest harvesting operations and pipeline or other linear developments may influence dead wood resources Managed stands typically have lower dead wood Land use in or adjacent to a forest patch may cause sudden increases in tree mortality (e.g., mining operations)
Measurability/ Cost Effectiveness	MED	A field sampling program can measure dead wood resources relatively simply, but accurate sampling protocol and measurement design must be implemented. Fixed plots or standard fixed areas could be used to this purpose. Region-wide datasets are not currently available.
Existing Programs		ABMI ASRD
Predictability	MED	Information can be used by planners to develop strategies to manage or protect stands with high dead wood resources This may be especially important in highly-managed forestry areas where these resources are less common In addition, if a patch undergoes a sudden increase in snag and down log abundance, this may indicate mortality due to activity in or adjacent to the forest patch or a change in landscape-scale disturbance processes
Threshold Relationships	MED	Specific amounts of dead wood required for a healthy forest depends on the landscape, forest, and forest history

Potential Targets

Excessive removal of dead wood or snags from forests exerts pressure on forest wildlife and increases biodiversity loss. In unmanaged European forests, the volume of dead wood resources ranges from 5-30% of total timber or 40-200 m^3/ha. In contrast, dead wood in managed forests may be in the range of 6 m^3/ha, while plantations contain even less [380].

6.6 Coniferous Forest

There are two types of coniferous forest in southern Alberta: pine forests and spruce/fir forests. Pine forests are pure conifer stands with lodgepole pine as the leading species. Spruce/fir forest stands are pure conifer types with white spruce, Engelmann spruce, black spruce or a balsam fir or Douglas fir constituting more then 30% of the stand. Forested riparian is also included in this category.

Coniferous forests offer a slightly different set of ecosystem services than their deciduous and mixedwood counterparts. Like the deciduous and mixedwood forests, coniferous forests are highly important providers of climate regulation services, erosion control and sediment retention, biological control, water supply and recreation; however, they are moderately important as providers of disturbance regulation services, primary production, and nutrient cycling.

Natural disturbance and developmental pathways are important to the provision of ecosystem services in coniferous forests. Indicators of forest conditions therefore relate to forest age and natural disturbance processes. Fire is the most commonly occurring natural disturbance that alters forest composition and structure [27]. Fires can vary in size from small crown fires to large ground fires that can burn many hectares of land. Insects and disease can also alter forest ecosystems, decreasing stand vigour and potentially leading to mortality [27]. This process, when in balance, allows nutrient cycling to occur. Wind, herbivory, and human disturbances also affect forest composition and structure.

6.6.1 Age Class Distribution

The dominant age of each canopy layer provides valuable information on stand maturity stages and potential successional processes occurring within the stand [27]. Where AVI data is available, age data can be obtained from the database. Where available, age can be obtained from the AVI database for each forest canopy layer, or, where surveyed, age measurements can be taken from the leading species of each height class. This provides an indication of the age-class structure within the forest stand.

Table 6-5 Coniferous indicator assessment: age class distribution

Criterion	Rating	Justification / Examples
Understandability	HIGH	Description of forest age classes is comprehensible for professionals and lay public
Ecosystem Service Linkages	HIGH	Forests with a wide age class distribution typically have higher resilience and can be related to the following ecosystem services:
Climate regulation	✗	
Disturbance regulation	✓	Uniform age-class distributions are at greater risk of large-scale fire, windthrow, or other disturbance events
Erosion/sediment control	✗	
Biological control	✓	Forests with a variety of age classes have greater resistance to insect pests (e.g., mountain pine beetle)
Nutrient cycling	✗	
Primary production	✓	Primary production tends to be higher in forests with younger and variable age-class distributions
Water supply	✓	Large-scale fires characteristic of even-aged stands result in major increases in TSS, nitrogen and phosphorus exports, whereas smaller fires do not have as great an impact [36]
Recreation	✗	
Responsiveness to Management Practices	MED	Age class distribution is sensitive to changes in use and management, especially silvicultural treatments Over time, stands managed for forestry may exhibit less varied age structure which has impacts on the services provided by the stand
Measurability/ Cost Effectiveness	MED	This indicator is considered moderate to highly measurable, as all indicators can be measured through use of AVI data or field measurement techniques AVI information can be used to guide a stratified sampling strategy
Existing Programs	MED	AVI, Montane Bioregion Landcover Mapping AVI contains information on species and age classes. If additional field measurements are required, a sampling protocol would need to be developed for field crews, and a consistent technique used
Predictability	HIGH	Detailed site-level information can be used in scenario development and planning to identify stands with valuable characteristics, such as a wide age-class distribution
Threshold Relationships	MED	The literature on recommended age-class distribution is primarily qualitative and relatively vague (e.g., narrow vs. wide age class distribution, young vs. older forests), but ongoing research is being conducted

Potential Targets

Most natural forests tend to have a wide age class distribution. Uniform age-class distributions are not representative of historical patterns, and are usually a result of management intervention. In Alberta and British Columbia, there is an increasing under-representation of forests in younger age classes, which has impacts for regional biodiversity and ecosystem services.

6.6.2 Tree Crown Condition

Because tree crowns are an important component of ecosystem structure, they directly affect the composition and processes of the forest understory. Large, dense crowns are associated with potential or previous vigorous growth rates, while small and sparse crowns are associated with poor site conditions or aging and senescent trees [106, 309]. A balanced crown diameter structure, in which a similar crown area is achieved by different age classes, leads to greater forest sustainability in terms of ecosystem service provision over time [106].

A Crown Index (CI) may be used as a surrogate of balanced diameter structure and an indicator of vertical structure [106]. For this index, the canopy area of trees in the main and upper canopy is divided by the canopy area of the lower strata. A CI of 1.0 indicates an overall balanced structure, on average, while values >1.0 indicate dominance of large tree canopy cover and values <1.0 indicate dominance of medium and small tree canopy cover. In general, greater growth and regeneration occur as the CI approaches 1.0 [106].

The U.S. Forest Services also describes a similar Tree Crown Condition Indicator that uses a set of seven different measurements [309].

Table 6-6 Coniferous indicator assessment: tree crown condition

Criterion	Rating	Justification / Examples
Understandability	MED	This indicator can be understood and explained by both the lay public and professionals, although its components may be difficult for those other than technical experts to comprehend
Ecosystem Service Linkages	HIGH	The following ecosystem services are directly related to tree crown characteristics:
Climate regulation	✓	Tree crowns are the main source of absorption of carbon dioxide [175] Tree crowns regulate forest micro-climates
Disturbance regulation	✗	
Erosion/sediment control	✓	Tree crowns intercept rainfall, slowing infiltration and reducing soil erosion
Biological control	✗	
Nutrient cycling	✗	
Primary production	✓	As a component of forest structure, tree crowns affect the composition and vigour of understorey plants and animals [309]
Water supply	✓	The size of tree crowns affects rainfall interception and soil infiltration [175]
Recreation	✓	Tree crown structure affects the aesthetics of the forest, which impacts visitation and recreation
Responsiveness to Management Practices	MED	There are many factors that affect tree crown characteristics, including air pollution, insect attack, weather extremes. Under short-term stress, trees can recover, but if the stress is prolonged, tree crown characteristics will show it There may be a time lag between management activity and tree crown response
Measurability/ Cost Effectiveness	MED	Some information may be gleaned from remote sensing programs Extensive field sampling may be required to assess this indicator, which may be expensive
Existing Programs	MED	
Predictability	MED	Information about tree crown condition can help identify which species or forest types in a region have more crown dieback or less crown density than healthy (or baseline) conditions
Threshold Relationships	LOW	No specific threshold values were found. Most studies used baselines as comparison

Potential Targets

Targets are not necessarily specific, but tend to be comparative in nature. Trends in crown characteristics for forests and forest species (e.g., pine vs. spruce/fir) can be monitored and compared to baseline conditions to assess the direction of forest health and associated ecosystem services.

6.7 Riparian

Riparian areas are the strip of transitional vegetation in between aquatic and upland ecosystems. They can also be defined as “lands adjacent to streams, rivers, lakes and wetlands, where the vegetation and soils are strongly influenced by the presence of water” [92]. Riparian systems provide many valuable ecosystem services in amounts disproportionately larger than the area they encompass, and have also been the focus of conflicts between resource users [55, 131, 348].

Primary ecosystem services provided by riparian areas include water supply and erosion control, although they contribute many other services as well. The width of riparian areas as well as connectivity has already been considered as landscape-level indicators (Section 5.2.4). However, a relatively intact riparian vegetation corridor is necessary, but not sufficient, for the protection of aquatic habitats [40]. Site-specific quality also affects the ecosystem services provided by riparian zones.

6.7.1 Riparian Health Index

The Riparian Health Index (RHI) used by Cows and Fish in Alberta combines several parameters characterizing riparian site conditions into one composite index. This indicator provides useful site-specific information on the ability of riparian systems to provide valued ecosystem functions and services.

Table 6-7 Indicator assessment: riparian health index

Criterion	Rating	Justification / Examples
Understandability	MED	Parameters which make up the RHI are based on a visual approach, and the concept of riparian health has been well articulated in products for the public [125]. However, the visual approach, while easy to communicate, may be a source of reduced accuracy due to variability in surveyor interpretations
Ecosystem Service Linkages	HIGH	All eight priority ecosystem services are reflected in one or more of the underlying parameters (in parentheses)
Climate regulation	✓	Local provision of shade (vegetative cover in the floodplain, preferred tree/ shrub vegetation, amount of dead woody material, amount of human-caused bare ground) Carbon capture and storage services (vegetative cover of the floodplain, preferred tree/shrub establishment, dead woody material, root mass protection, and human-caused bare ground)
Disturbance regulation	✓	Blocking or attenuation of floodwaters (vegetative cover of the floodplain, preferred tree/shrub establishment, amount of dead woody material, root mass protection, and human alteration to the site
Erosion/sediment control	✓	(Vegetative cover in the floodplain, root mass protection, human caused bare ground, alteration of streambanks, channel incisement) Weed roots typically have lower soil-binding capacity than native vegetation (Invasive plant parameters)
Biological control	✓	Habitat for natural insect predators (vegetative cover and dead woody material) & preventing the spread of weeds (low human-caused bare ground, low amounts of invasive and disturbance-caused plants)
Nutrient cycling	✓	(Vegetative cover in the floodplain, preferred tree/shrub vegetation, amount of dead woody material, root mass protection, human-caused bare ground)
Primary production	✓	
Water supply	✓	Filtration, capture, uptake, and breakdown of nutrients, pesticides, and other materials (vegetative cover in the floodplain, root mass protection, human caused bare ground, alteration of streambanks, channel incisement)
Recreation	✓	Quality of recreational opportunities
Responsiveness to Management Practices	HIGH	Highly responsive to farm management practices, including off-site watering (e.g., nose pumps), grazing intensity management (e.g., number of animals, seasonal timing), and exclusionary fencing for livestock [125] Legislation and policies governing how the forestry, energy, and urban development industries treat riparian buffers, as well as the effectiveness of these policies, is directly linked to riparian health.
Measurability / Cost Effectiveness	MED	A practical field method for assessing riparian health and ecosystem services However, collecting the fine-scale data is labour intensive
Existing Programs	HIGH	Cows and Fish have conducted riparian health inventories on thousands of sites across Alberta
Predictability	MED	Can be predicted if some assumptions are made
Thresholds	LOW	No clear thresholds identified, but targets can be based on the score intervals (healthy, healthy with problems, etc.)

Potential Targets

The developed health categories can serve as targets for conservation or restoration of riparian systems. A 'healthy' riparian score should be the target, as these are expected to provide a wide range of ecosystem services. However, in certain cases pragmatic targets must be set in combination with current benchmark conditions. Since many riparian sites examined in Alberta are unhealthy, it may be unfeasible to restore these to a 'healthy' status, particularly over shorter time scales; in these cases, interim improvements in health scores should be the management target.

6.8 Lentic

Lentic (standing) water bodies lack a defined channel and floodplain. These include lakes, ponds, and reservoirs. Lakes in Alberta have diverse characteristics that reflect the influences of climate, geology, and human land use in contributing watersheds.

Pristine, cold mountain lakes such as Lake Louise are found in the Rocky Mountains. Dotting the parkland and prairie are numerous shallow lakes and ponds, such as Eagle Lake east of Calgary. The semi-arid southeastern areas of the province contain few lakes, while ponds that exist here are often saline. In central parts of the province, parkland and forested landscapes are dotted with lakes of every size and description, including Sylvan Lake, Gull Lake, and Pine Lake [232].

Primary ecosystem services provided by lentic ecosystems include water supply and recreation. Secondary ecosystem services include nutrient cycling, primary production and climate regulation. The selected indicators assessed below were constructed to reflect these key services.

6.8.1 Lentic Water Levels

The depth of water bodies provides an integrated measure of water balance, including gains from runoff and groundwater inputs, and losses from evapotranspiration, outlet streams, groundwater outflow, and extractions. Water levels will remain constant over time if these factors are balanced. Over the period of record for most lakes in Alberta, water levels do not show either a downward or upward trend, although short-term variability is common [232].

Table 6-8 Indicator assessment: depth of lentic water bodies

Criterion	Rating	Justification / Examples
Understandability	HIGH	Highly understandable Appeals directly to on-the-ground experiences
Ecosystem Service Linkages	HIGH	Directly related to two services Indirectly related to two services
Climate regulation	✗	
Disturbance regulation	✓	Drought mitigation
Biological control	✗	
Erosion/sediment control	✗	
Nutrient cycling	✓	Indirectly affected by water level changes [294]
Primary production	✓	Indirectly affected by water level changes [294]
Water supply	✓	Water volume is directly related to water level changes
Recreation	✓	Docks, boating, shoreline recreational properties, and beaches are all affected
Responsiveness to Management Practices	MED	Short-term natural fluctuations are common, but over the period of record for Alberta's lakes, water levels do not show any trends [232] A sustained, prolonged trend over longer time scales indicates unsustainable water use or climate change Water level sensitivity to land use change is highly variable. If regional groundwater linkages exist, response to disturbances will show a considerable time lag
Measurability / Cost Effectiveness	HIGH	Measured using data loggers at reasonable cost
Existing Programs	HIGH	Water levels are regularly measured on many Alberta lakes
Predictability	HIGH	Changes in water levels due to land use decisions, water withdrawals, and engineering control structures can be modelled fairly readily Changes due to climate change are more difficult to model, but the rate and amount of change cannot be controlled through regional planning
Threshold	MED	A significant departure over time from a stable depth can be considered a threshold

Potential Targets

For lakes with sufficient historical records, benchmarks could be defined using the monthly mean, minimum, and maximum water levels. Plotting the seasonal distribution is particularly important for regulated water bodies affected by the operation of flow control structures. A plot of historical monthly water levels for Gull Lake at Sunnyside Marina is provided in Figure 6-1.

The minimum historical lake level is a suitable target. Alternatively, minimum and maximum targets for each month could be established (e.g., Table 6-9). Even more detailed targets could refer to mean lake levels and define acceptable statistical departures over five or ten year moving averages (e.g., NRV).

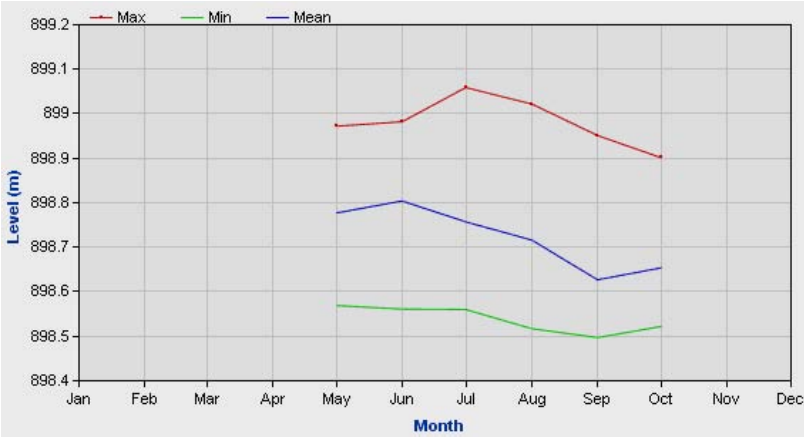


Figure 6-1 Monthly water levels for Gull Lake at Sunnyside Marina, Alberta (Statistics correspond to 66 years of seasonal data from 1924 to 2007) [117]

Table 6-9 Potential targets for water level in Gull Lake based on statistical benchmarks

Month	Minimum Water Level (m)	Maximum Water Level (m)
May	>898.569	<898.972
June	>898.561	<898.982
July	>898.560	<899.059
August	>898.517	<899.022
September	>898.497	<898.951
October	>898.522	<898.901

6.8.2 Lentic Trophic Status (Chlorophyll-a)

The addition of nutrients to lakes stimulates algal growth and can alter the balance between the production and decomposition of organic matter, leading to reduced dissolved oxygen and fish kills. Therefore, a lake's fertility level, or trophic status, is a key condition indicator related to the ability of lakes to provide ecosystem services. Trophic status is highly correlated with many other water quality variables, including nutrient concentration, total suspended solids, and dissolved oxygen regimes. Typical trophic status indicators used by limnologists include the concentration of chlorophyll-a, the ratio of algae to zooplankton, and the concentration of phosphorus [224, 239, 381]. Although phosphorus is typically the limiting nutrient in

most freshwater systems, there is evidence that many lakes in Alberta are co-limited by phosphorus and nitrogen [191]. Therefore, chlorophyll-a is the most appropriate metric of trophic status in Alberta's Lakes. Table 6-10 defines trophic states based on chlorophyll-a values.

Table 6-10 Trophic status of lakes in Alberta

Trophic Status	Appearance of Water	Maximum chlorophyll a concentration (µg/L)	% of lakes assessed in the Atlas of Alberta Lakes	Examples
oligotrophic	clear	<8	10%	Ghost Reservoir Glennifer Lake Kananaskis Lake
oligo-mesotrophic	usually clear	occasionally over 8	5%	Glenmore Reservoir
mesotrophic	sometimes green	8-25	32%	Buffalo Lake Crimson Lake Ethel Lake
eutrophic	green most of the summer	26-75	29%	Pigeon Lake Pine Lake Pinehurst Lake
hyper-eutrophic	frequent dense algal blooms	>75	24%	Eagle Lake

(Source: Mitchell and Prepas 1990, after OECD [232])

Table 6-11 Indicator assessment: lentic trophic status (chlorophyll-a)

Criterion	Rating	Justification / Examples
Understandability	MED	Understanding the chlorophyll-a metric requires some technical background Illustrations of eutrophication can be used to communicate concepts
Ecosystem Service Linkages	HIGH	Trophic status affects several ecosystem services
Climate regulation	✗	
Disturbance regulation	✗	
Erosion/sediment control	✗	
Biological control	✗	
Nutrient cycling	✓	Oxygen-depleted lakes provide a strong reducing environment which converts oxidized forms of sulphur (SO_4) to reduced species (H_2S)
Primary production	✓	Although higher trophic states are positively correlated with primary productivity, they can also cause a collapse of higher trophic levels (e.g., predatory fish)
Water supply	✓	Increased turbidity and microtoxins accompanying algal blooms decreases usability of water supplies
Recreation	✓	Algal blooms reduce opportunities for swimming, boating, fishing, or beach recreation Increased turbidity affects water clarity Unpleasant odours
Responsiveness to Management Practices	MED	Natural eutrophic status among lakes is highly variable and can change gradually over time "Cultural eutrophication" caused by fertilizer application, animal production, discharges of industrial and domestic waste, fossil fuel combustion, and nutrient mobilisation due to land clearing occurs more rapidly. Controlling the location, scale, and extent of activities with active land use planning and management influences trophic status Time lags occur between management changes and system responses, particularly for larger watersheds
Measurability / Cost Effectiveness	HIGH	Field sampling and laboratory techniques are well developed [232] Remote sensing can measure chlorophyll-a [83, 361]
Existing Programs	HIGH	Several existing as well as ongoing programs sample Alberta lakes for *Chlorophyll-a,* including: AENV (many water bodies) ABMI lake program administered by ACA Municipalities sample reservoirs used for drinking water (e.g., Glenmore Reservoir by City of Calgary) Community watershed groups (but data reliability issues) Samples reported in the *Atlas of Alberta Lakes* [232]
Predictability	MED	Eutrophication can be modeled in landscape scenarios [168, 239, 274, 306] However, models must be lake-specific since watershed size, slopes, soils, geology, and internal loading all affect lake responses to nutrient inputs Constructing accurate models to predict trophic status may be too labour and data intensive to provide rigorous scientific models for land use planning
Thresholds	MED	There is much research on thresholds and instability of lake eutrophic status [62, 129] but defining quantitative values for Alberta is difficult and may be different for each individual lake

Potential Targets

Lakes differ in their trophic status due to natural factors such as water depth [102, 262], the ratio of watershed area to lake volume [102, 305], and vertical mixing regime [191]. Lake management should aim for the natural trophic status as a target.

Targets for individual lakes can be defined with paleolimnology, which examines changes in diatoms, algae, non-biting midges, and pollen in lake sediment cores [253]. These techniques can provide hindcasts of trophic status from hundreds to thousands of years, enabling quantitative assessments of natural variability and pre-disturbance trophic status. In Alberta, a model has been developed to reconstruct lake trophic history using data from 112 lakes [191]. This model can define targets based on natural trophic states (Dr. Koster, pers. comm.). However, in highly developed landscapes with nutrient loading from agriculture and other land uses, more pragmatic targets may be required.

Statistical variance of chlorophyll-a data over time should also be examined and monitored, since it has the potential to predict non-linear regime shifts of lakes in advance [61]. In Wisconsin, a sudden increase in variance of total phosphorus predicted eutrophication a decade in advance [61]. A similar relationship would be expected for chlorophyll-a due to a close relationship between phosphorus concentration and algae and plant biomass production. Analyzing time series of chlorophyll-a within data sets generated by past and future monitoring in Alberta could determine whether this has utility for predicting a regime shift in advance. This may have great management utility since actions directed at avoiding a regime shift could intensively focus on areas likely to shift past a threshold into a eutrophic status.

6.9 Lotic

Lotic systems are running water bodies such as rivers, streams, or any other channel that periodically or continuously carries flowing water. Functions and services provided by lotic systems are diverse and critical to society. Reducing flooding, recharging aquifers, supplying irrigation water, supporting fisheries, recycling nutrients, absorbing wastes, and supporting recreation are just some of the many services provided by rivers. Many human activities alter lotic systems and potentially threaten some of these services, including dams, channelization and diversion, agriculture, forestry, and construction [131, 279].

Many types of lotic ecosystems occur in southern Alberta, reflecting landscape diversity and position in their respective watersheds. Rocky Mountain headwater streams and Prairie coulee streams are two lower-order lotic systems. Intermediate-order streams often meander through the foothills and prairies, before coalescing into higher-order mainstream branches of the Oldman River, the Bow River, the Red Deer River, the South Saskatchewan River, and the Milk River.

6.9.1 Alberta River Water Quality Sub-Indices

Hundreds of water quality parameters can be measured, including physical (e.g., electroconductivity, sediment load, temperature), chemical (e.g., dissolved substances, pH, organic chemicals), and biological (e.g., *E.coli*) parameters. The Alberta River Water Quality Index [4] combines many water quality parameters into a consistent framework that can be used as an overall indicator of river water quality. The ARWQI can also be split into four sub-indices addressing: (i) metals, (ii) nutrients and related variables (e.g., dissolved oxygen), (iii) bacteria, and (iv) pesticides. To assess ecosystem services, each of these subindices should be examined separately. However, for the purposes of the indicator assessment these have been grouped together by their similarities in measuring up against the criteria.

Table 6-12 Indicator assessment: river water quality sub-indices

Criterion	Rating	Justification / Examples
Understandability	MED	Understanding how these indicators are monitored and calculated requires a great deal of technical expertise. However, the colour-coded index ratings are a good communication tool that most people can relate to
Ecosystem Service Linkages	MED	Related to two priority ecosystem services
Climate regulation	×	
Disturbance regulation	×	
Biological control	×	
Erosion/sediment control	×	
Nutrient cycling	×	
Primary production	×	
Water supply	✓	Poor-quality water requires more treatment prior to use, while higher quality water provides supplies at lower economic cost [46, 279]
Recreation	✓	The bacteria sub-index directly affects contact recreation safety All sub-indices can affect fishing, birdwatching, and wildlife viewing opportunities
Responsiveness to Management Practices	LOW-MED	Water quality often exhibits high natural variability due to weather and other factors Long lag times between a management change and a system response are typical due to complex relationships The larger the watershed, the more complex the analysis of management effects
Measurability / Cost Effectiveness	MED	Sampling and lab techniques measure parameters to construct each of the sub-indices. Pesticide analyses are the most expensive Assessing many sites regularly is expensive Applying existing monitoring sites is cost-effective
Existing Programs	HIGH	Alberta Long Term River Network Monitoring Sites [4]
Predictability	MED	Changes due to land use changes can be difficult to reliably predict, particularly in larger watersheds However, more simple models based on correlations between key factors of interest and the four sub-indices can be developed (e.g., *E.coli* predicted based on the # of animals in feedlots within 800 m of water bodies)
Thresholds	MED	Quantities in the index have been compared to water quality guidelines based on detailed toxicological and health risk assessments In addition, the Water Quality Objectives (WQOs) that have been defined for the Bow River [47] could be adapted to define acceptable thresholds for these indicators within specific reaches of the Bow River

Potential Targets

Although the ARWQI cannot be used for year-over-year comparisons due to high natural variability, longer-term five or ten year moving average values can cancel out some of this variability and therefore make it amenable to setting targets for monitoring and assessment.

The sub-indices of the ARWQI encompass much of the scientific and social information on suitability of river water for human use, which contributes to their suitability for setting management targets. Stakeholder consultations

could be used to set target values or ranges of target values. For example, a target value of “Good or Excellent” for all four sub-indices at each stations could be set. More detailed reach-specific targets could also be developed (e.g., Excellent quality for the metals sub-index in the Red Deer River at Morrin Bridge station).

6.9.2 Indicators of Hydrological Alteration

Hydrologic regimes encompass the quantity, timing, frequency, duration, and rate of change in water flows. Quantitative evaluations of human-induced hydrologic alterations using stream gauges, wells, or model-generated data can be useful to define and predict impacts from dam operations, flow diversions, groundwater pumping, or land-use conversions [278, 290]. Richter et al. (1996) have developed a series of 32 parameters for analyzing Indicators of Hydrological Alteration (IHA) through a statistical analysis of hydrological regime [290]. Statistical parameters can be segregated into the following five groups:

- Magnitude of monthly water conditions (mean value for each calendar month);
- Magnitude and duration of annual extreme water conditions (1 day, 3 day, 7 day, 30 day, and 90 day annual maxima and minima);
- Timing of annual extreme water conditions (Julian date of each annual 1 day maxima and minima);
- Frequency and duration of high and low pulses (number and mean duration of high and low pulses within each year); and,
- Rate and frequency of water condition changes.

Table 6-13 Indicator assessment: indicators of hydrological alteration

Criterion	Rating	Justification / Examples
Understandability	MED	Generally understandable to technical specialists, but less so for the general public
Ecosystem Service Linkages	HIGH	Hydrological regimes produce much of the natural heterogeneity of habitat and vegetation across a variety of scales [131, 195] This heterogeneity, in turn, helps supply many ecosystem services to society, which may be threatened by hydrological alterations
Climate regulation	✗	
Disturbance regulation	✓	
Biological control	✓	
Erosion/sediment control	✓	
Nutrient cycling	✓	
Primary production	✓	
Water supply	✓	
Recreation	✓	
Responsiveness to Management Practices	HIGH	The degree of hydrological alteration is, by definition, directly related to the location of dams, dam operational design (e.g., seasonal distribution of outflows), channelization, land use, and other factors
Measurability / Cost Effectiveness	MED	Flow statistics can be calculated from existing data sets. A software program to facilitate calculations of IHA parameter values and deviations is available [290] Many rivers in Alberta are "regulated" by weirs and dams throughout much of the period of record, making it difficult to characterize a "natural" hydrologic regime Data collection and definition of baseline values is limited to existing monitoring stations
Existing Programs	HIGH	Flow statistics characterizing hydrological regimes are available at many monitoring stations throughout southern Alberta Extending data collection to other areas is difficult
Predictability	MED	Changes to hydrologic regimes can be modelled relatively accurately, particularly for dam construction or flow diversions Predicting effects of land use change are more uncertain
Thresholds	MED	Several studies provide information on critical minimum discharges, where habitat quality or amount decreases rapidly, or where a small decrease in flow results in large decreases in wetted perimeter [139, 178]

Potential Targets

Critical differences in post-development flows vs. naturalized flows, either modelled or recorded after physical development, can be used to develop thresholds or guidelines. Guidance on how and where to set desirable target thresholds can be provided by Water Conservation Objectives, Instream Flow Needs, or Instream Objectives [5].

6.9.3 Lotic Fish-Based Index of Biotic Integrity

A program for monitoring lotic system condition should assess biological communities. Biological communities in rivers can be impacted by the water pollution and hydrological alterations discussed above, but also by invasive species and fishing pressures. One well-documented effect of fishing on communities is a shift "down the food web" from high trophic-level piscivorous fish to short-lived low trophic-level species [269].

The Index of Biotic Integrity (IBI) provides a multi-metric index of aquatic communities that combines species richness, composition, trophic structure, abundance, and condition of fish communities [12, 139, 182]. Typically, up to 10 parameters are combined into the IBI value. A key consideration for the development and application of this index is that benchmark reference conditions are required to define expected values throughout the ecoregion or subwatershed [5, 130, 139]. Studies in Alberta by the Alberta Conservation Association (ACA) developed simplified IBI indices for fish communities that focus on parameters most sensitive to human disturbances and eliminate redundancy among parameters [327, 328].

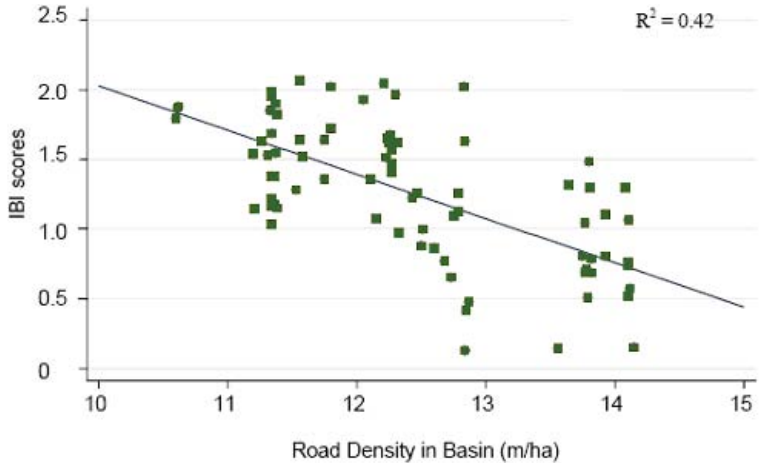


Figure 6-2 **Battle River IBI study: relationship between IBI scores and road density**

Table 6-14 Indicator assessment: fish-based Index of Biotic Integrity

Criterion	Rating	Justification / Examples
Understandability	MED	This index is not very understandable to a lay audience, but aspects of it could be explained
Ecosystem Service Linkages	MED ?	Presumably, more diverse and natural aquatic communities have greater productivity, stability, and resilience, which in turn can supply increased biological control, nutrient cycling, primary production, recreation, and water supply purification services However, there is a lack of information on how intact aquatic communities contribute towards services, although intact communities can be better related to the production of ecosystem goods (e.g., fish)
Climate regulation	✗	
Disturbance regulation	✗	
Biological control	✗	
Erosion/sediment control	✗	
Nutrient cycling	✓	
Primary production	✗	
Water supply	✓	Fish respond to impoundments & diversions
Recreation	✓	Fishing opportunities
Responsiveness to Management Practices	MED	Related to fishing pressure as well as land use decisions Land use planning can incorporate more spatially explicit fisheries management (e.g., designating areas for low, medium, and high fishing pressure) Landscape variables and land use affects IBI [328]
Measurability / Cost Effectiveness	MED	Requires intensive field sampling by technicians with fish identification skills
Existing Programs	MED	A study of the Battle River Basin developed a fish-based IBI using three parameters (percent carnivores, percent omnivores, and species richness) [327] A study in five sub-basins of the Red Deer River watershed in the Crossfield-Three Hills area developed a fish-based IBI using five parameters, including [328]: *% fish ≥ 1 year old* *occurrence of white sucker* *no. of ≥1 yr. fathead minnow* *% diseased fish* *no. of young-of-year individuals*
Predictability	MED	Some information exists for predicting the response of IBI to land use decisions [328]
Thresholds	MED	There is some indication of a disturbance threshold where environmental conditions are no longer capable of supporting systems with biotic integrity [328]

Potential Targets

In the Red Deer River ACA study, a perfect score of 50 suggests high quality conditions appropriate for maintaining biological integrity. IBI scores over 30 suggest healthy fish communities. Low-quality sites (IBI <20) are often linked to human disturbances, and are characterized by poor fish communities [328]. However, they acknowledge uncertainty in correctly identifying healthy versus unhealthy conditions for sites with mid-range IBI scores (i.e., 20-30), and recommend that resource managers, whenever possible, incorporate data on other biota and the physical and chemical attributes of a site [328]. IBI scores somewhere underneath 20-30 may prove difficult to recover, particularly if disturbances are widespread and connectivity to healthier areas is impaired. Low IBI values may exhibit threshold behaviour and aspects of irreversibility.

In the Battle River ACA study, their multi-metric IBI was highly sensitive to changes in road densities. Regression analysis indicated that cumulative disturbances associated with road densities as low as 7 m/ha (equivalent to 0.7 km/km^2) in basins impaired the integrity of fish assemblages (Figure 6-2) [327]. This analysis exhibits the kind of cross-scale adaptive management research that should be encouraged, where fine-scale condition metrics are applied to calibrate appropriate targets for landscape indicators.

Developing targets for this indicator requires additional analyses. This indicator is clearly linked to the cross-scale analytical framework, wherein fine-scale indicators are used to calibrate landscape scale targets in an adaptive management framework. Additional analyses such as the one depicted in Figure 6-2 should be performed using the suggested landscape indicators, including natural habitat in the watershed, wetlands in the contributing watershed, impervious surface in the watershed, mean patch sizes of natural habitat, connectivity metrics, riparian buffer width, etc. Validating and probing the relationship between variables within an adaptive management framework is desirable so that appropriate landscape targets are set to protect fish communities.

6.10 Wetlands

The majority of southern Alberta is in the greater Prairie Potholes region [141], where wetlands are characterized by sloughs, marshes, and ponds typical of arid and semi-arid climates [11]. Wetlands associated with lacustrine fringes (lentic) and rivers (lotic) are also common in southern Alberta [53, 55, 89, 318]. Although peatlands and groundwater springs on sloping lands are present, these are a very minor component of wetlands in the region.

Principal ecosystem services provided by wetlands include disturbance regulation (flood and drought mitigation), water supply, and recreation. Secondary services include climate regulation, biological control, primary production, and nutrient cycling. A large proportion of wetlands within the prairie and parkland regions of Alberta have been lost since European colonization; this makes the health of remaining wetlands increasingly important.

6.10.1 Wetland Water Storage Index

The US Army Corps of Engineers have developed the best indicators of wetland functions for relatively rapid assessment. Their approach quantitatively defines Functional Capacity Indices (FCIs) with equations combining multiple parameters. Parameter values are normalized to a standard reference wetland to account for natural variability [141, 318]. Specific assessment methodologies are identified for different wetland types as defined by hydrology and geomorphology (e.g., riverine, lacustrine fringe, depressional potholes). This “Hydrogeomorphic Approach” was initially designed to permit adequate environmental impact assessment under the *US Clean Water Act*. However, other uses have been identified, including wetland restoration and management [141, 318].

The Hydrogeomorphic Approach provides wetland function indicators that are rigorous yet capable of being applied with limited field work. However, familiarization with the models can be cumbersome, and the total number of FCIs is large. For Prairie Pothole wetlands, six FCIs have been developed for water storage, groundwater recharge, particulate retention, removal/conversion/sequestration of dissolved substances, plant community resilience and carbon cycling, and provision of faunal habitat [141]. For riverine wetlands, 14 FCIs have been developed [48]. Due to the large number of FCIs, analyzing each individual index is unfeasible.

For the above reasons, only the water storage FCI has been advanced as a potential ecosystem service indicator, since this indicator is easily understood, modelled, and communicated. The water storage FCI reflects the capacity of a wetland to collect and retain inflowing surface water, precipitation, and groundwater. The FCI for prairie pothole wetlands depends largely on surface and subsurface drainage outlets, contributing watershed area, and upland land use [141]. A formula and parameter definitions for this indicator is provided in Table 6-15.

Table 6-15 Pothole wetlands: Functional Capacity Index for water supply equation and definitions (based on: Gilbert et al. (2006)[141])

EQUATION			
Parameter	Definition	Examples	Rationale for Ecosystem Services Assessment
	Minimum value of Vout or Vsubout	Vout=0.3, Vsubout=0.1 Min (Vout, Vsubout)=0.1	Drainage reduces water storage capacity
Vout (Wetland outlet)	Ratio of elevation of constructed surface outlet to natural surface outlet relative to basin central elevation	Drainage ditch: 957.8 m Natural surface outlet: 958.8 m Basin Central Elevation: 957.3 m Vout=0.5/1.5=0.33	Surface drainage reduces water storage capacity
Vsubout (Subsurface outlet)	Categorical values representing whether constructed subsurface drainage exists	Vsubout=1.0 if there is no subsurface drainage <33 m from the wetland edge Vsubout=0.1 if almost all water moving through the soil profile below the wetland is intercepted by a drainage tile	Subsurface drainage reduces water storage capacity and increases peak flows downstream Effectiveness of drainage outside the wetland is also based upon distance to the drain and volume capacity of drain
Vsed (Sediment)	Extent of sedimentation into wetland from culturally accelerated sources, estimated by average depth to soil B horizon	As depth to the B-horizon decreases, a linearly decreasing value down to 0.1 is assigned to Vsed	Loss of volume from sediment infilling reduces water storage capacity
Vsource (Wetland Source Area)	Represents % change in catchment area surrounding a wetland. Categorical values are assigned based on relative amount of change.	Vsource=1.0 if >90% of catchment intact Vsource=0.25 if <25% of catchment intact and a seasonal wetland is changed to a semi-permanent or temporary wetland	Terraces, road ditches, tile drainage, or irrigation infrastructure often decrease catchment area by diverting flow away from the wetland
Vupuse (Upland land use)	Weighted average score for land use in catchment. A linear model converts runoff curve numbers to a value between 0.1-1.0	Runoff curve numbers: impervious surface=98, feedlot=90, conventional tillage row crop=79	Terrestrial land use affects runoff

The FCI for water storage in riverine wetlands applies different parameters [48]. An FCI for long-term water storage[6] in riverine wetlands can be defined as the capacity of a wetland to detain standing surface water for long durations. Sources of water include overbank flow, direct precipitation, overland flow, channel flow, or subsurface flow. The formula and parameters for this indicator in riverine wetlands is relatively simple (Table 6-16).

6 A more complex indicator of dynamic surface water storage is also defined by Brinson et al. (2005)

Table 6-16 **Riverine wetlands: Functional Capacity Index for water supply equation and parameter definitions (based on Brinson et al. (2006) [48])**

EQUATION			
Parameter	Definition	Examples	Rationale for Ecosystem Services Assessment
Vsurwat (Indications of Surface Water Presence)	Wetland is inundated by ponded or retained water for a continuous period of over 1 week	Direct (gauge data, aerial photos) or indirect (soil samples) indicators of ponding water similar to reference standard, then Vsurwat=1.0	A riverine wetland must be inundated to adequately reduce flood peaks (disturbance regulation) and store water to augment water supplies
		Ponding water present, but below reference standard, Vsurwat=0.5	
		Main indicators absent but other evidence of ponding water present, Vsurwat=0.1	
		Indicators absent, Vsurwat=0.0	
Vmacro (Macrotopo-graphic relief)	Topographic relief on the floodplain that provides restricted outlets which allow surface water to be trapped.	Oxbows, meander scrolls, backswamps, etc. similar to reference standard, Vmacro=1.0	A riverine wetland must be able to retain floodwaters effectively to reduce flood peaks (disturbance regulation) and store water to augment water supplies
		Less developed than reference standard and low surface gradient, Vmacro=0.5	
		Indicators are absent and a moderate to steep surface gradient exists, Vmacro=0.0	

Table 6-17 Indicator assessment: Functional Capacity Index for water supply

Criterion	Rating	Justification / Examples
Understandability	MED	Easy to understand for technical specialists, but more difficult for those with non-technical backgrounds
Ecosystem Service Linkages	HIGH	
Climate regulation	✓	Locally, stored water can mitigate frost damage [219] Water storage in wetlands prevents releases of sequestered CO_2 [287] Although wetlands also produce CH_4 (methane), greenhouse gas forcing of CO_2 sequestration is often comparable [236] Continuously flooded wetlands generally do not release N_2O, a very powerful greenhouse gas [287]
Disturbance regulation	✓	Water storage by wetlands tends to desynchronize water pulses and reduce downstream peak flows Riverine wetlands allow streamflow to spread out across floodplains [141]
Biological control	✗	
Erosion/sediment control	✗	
Nutrient cycling	✓	Water storage maintains anerobic soil conditions, which affects nutrient cycling
Primary production	✓	Continuously flooded wetlands are hotspots of primary production
Water supply	✓	Prairie pothole wetlands are good at storing surface runoff since they tend to lack surface water outlets and subsurface flows in till are very slow [141] Water storage also benefits crop production, since subsurface water storage is a crucial determinant of crop yields the following growing season [141, 310]
Recreation	✗	
Responsiveness to Management Practices	HIGH	Since the indicator is defined against natural reference standards, variability is directly tied to upland land use patterns and management practices such as drainage, flow diversions, and developing engineering works or urban/ industrial footprints
Measurability / Cost Effectiveness	HIGH	Measurability of all parameters that make up the water supply FCI is straightforward and amenable to interpretation from air photo data
Existing Programs	LOW	The method currently is not commonly applied in Alberta
Predictability	MED	For Prairie Pothole wetlands, upland land use, watershed source reduction, and alteration to outlet control are all clearly predictable for scenarios at the local scale For riverine wetlands, floodplain complexity and artificial changes in the flood fringe are predictable under different scenarios, and flood frequency is related to land cover which is also predictable
Thresholds	LOW	No clear thresholds identified

Potential Targets

Based on the prioritization component of the assessment framework (Section 3-2; Figure 3-3), this indicator would only be assessed locally within landscapes where the wetland landscape indicator (% wetlands in the watershed) approaches the lower threshold of 3% for the watershed.

6.10.2 Wetland Health Score

The aggregate Wetland Health Index (WHI) used by Cows and Fish in Alberta (Section C.13) provides a way to combine several parameters characterizing wetland conditions into one composite index. This indicator can provide useful site-specific information.

Parameters included in the WHI include:

- vegetative cover of the floodplain
- invasive plants: canopy cover & density distribution
- undesirable herbaceous species
- preferred tree/shrub establishment
- utilization of preferred trees/shrubs
- standing decadent & dead woody material (lotic wetlands only)
- streambank root mass protection (lotic wetlands only)
- human alteration of vegetation
- human alteration of the physical site
- human-caused bare ground
- alteration of streambanks
- human alteration to the site
- stream channel incisement (lotic wetlands only)

Table 6-18 Indicator assessment: wetland health

Criterion	Rating	Justification / Examples
Understandability	MED	Parameters making up this indicator are relatively straightforward and visually-based, but may be more difficult to communicate to a broad audience
Ecosystem Service Linkages	HIGH	All eight priority ecosystem services are reflected in one or more of the underlying parameters
Climate regulation	✓	Tree/shrub establishment (CO_2 sequestration, local shade)
Disturbance regulation	✓	Invasive or undesirable plant species: negative influence
Biological control	✓	Vegetative cover: positive influence Human-caused bare ground: negative influence
Erosion/sediment control	✓	Vegetative cover, physical habitat alteration, tree/shrub establishment, streambank root mass protection: positive influences [277] Invasive or undesirable plant species, channel incisement: negative influences
Nutrient cycling	✓	Vegetative cover, physical habitat alteration, tree/shrub establishment, standing decadent & dead woody material
Primary production	✓	Vegetative cover, physical habitat alteration
Water supply	✓	Vegetative cover, tree/shrub establishment
Recreation	✓	Vegetative cover, tree/shrub establishment: positive influence Invasive or undesirable plant species: negative influence
Responsiveness to Management Practices	HIGH	Highly responsive to physical disturbances, reclamation success, changes to local contouring and topography, chemical inputs, alterations to the water budget or watershed, grazing management, cattle access, etc. Legislation and policy governing how forestry, energy, and urban development industries are allowed to develop in the vicinity of wetlands, and the effectiveness of these policies, has a direct link to wetland health
Measurability / Cost Effectiveness	MED	A practical field method for assessing wetland health and ecosystem services However, collecting the fine-scale data is labour intensive
Existing Programs	MED	Cows and Fish have conducted inventories of wetland health for about 170 sites on 55 water bodies [14] Cows and Fish have the capacity to target specific sites in the future in response to identified priorities
Predictability	MED	Can be predicted if some assumptions are made
Thresholds	LOW	No clear thresholds identified, but targets can be based on the score intervals (healthy, healthy with problems, etc.)

Potential Targets

Health categories that have been developed can serve as targets or thresholds for conservation or restoration of wetlands. A ‘healthy’ wetland score should be the target, as these wetlands will provide a wide range of ecosystem services. However, in some cases pragmatic targets must be set in combination with current benchmark conditions. For example, less than 1/3 of wetland sites assessed by Cows and Fish in Alberta were rated as healthy [14]. For those sites with considerable impairment, it may be unfeasible to restore these to a ‘healthy’ status, particularly over shorter time scales; in these cases, interim improvements in health scores should be the management target.

6.11 Geological

Although land cover types of bare rock and soil play a role in nutrient cycling and other ecosystem services, this role is relatively minor in the landscape and is not recommended for detailed fine-scale monitoring. An exception occurs for glaciers in the mountains, which have been categorized as geological assets and may warrant some site specific sampling due to their importance for maintaining water flows during late summer months in dry years.

6.11.1 Ice Quality

The rate of melting glacier ice and glacier mass balance depends on site-specific conditions related to the integrity of the glacier. Gradual melting may occur in more intact chunks of ice, whereas more rapid melting can occur when ice is highly fragmented or water underneath the ice enables rapid non-linear advances. Existing monitoring programs carried out by geographers at the University of Alberta (e.g., Martin Sharpe) University of Calgary (e.g., Shawn Marshall), and Geological Survey of Canada (e.g., Mike Demuth) could be used to study these ice dynamics.

This indicator can be related to the following ecosystem services:

water supply: amount of late-season baseflow contributed by melting glaciers within streams and rivers;

climate regulation: high ice albedo reflects more incoming solar radiation; and,

recreation: aesthetics of glaciated mountain landscapes, safety of backcountry skiers and ice climbers (e.g., amount of ‘rotten’ ice).

6.11.2 Future Research: Groundwater

Although the conceptual framework for this project is focused on land cover, groundwater is a critical consideration in any land use plan. Sensitive groundwater units include alluvial aquifers, buried valley aquifers, shallow sand and gravel aquifers, and other areas where groundwater is under the direct influence of surface water (GUDI). Development of these areas should be avoided, particularly where the risk of a spill or contamination incident is high. Existing and ongoing county-based groundwater mapping and upcoming initiatives on mapping groundwater management units should be incorporated in land use planning.

7.0 CROSS-SCALE INDICATORS

Cross-scale indices are those that combine fine-scale local site measurements with broad-scale modelling approaches. Local measurements are used to derive average values for specific cover types. The locally-derived average values can then be incorporated in GIS models covering larger scales within the landscape, watershed, or region of interest. Scaling up the local measurements requires an accurate land cover map covering the boundaries of interest. Three key cross-scale indicators have been selected for assessment here.

7.1 Carbon Management Index

Soil organic matter, as discussed in Section 6.1.2, is an important indicator of ecosystem service provision at the fine scale. Its responsiveness to management practices was considered 'medium' because, although it was highly responsive to depletion, recovery time is slow.

A carbon management index (CMI) combines the active (biologically derived) and passive (stable) components of soil carbon to provide a sensitive indicator of carbon dynamics in response to changes in land management [37, 80]. The more active components of soil carbon (labile carbon fraction) tend to be more sensitive to changes in land management.

The CMI is defined as:

$$CMI = CPI \times LI \times 100$$

where, CPI = carbon pool index (changes in the proportion of total carbon between sampled site and a reference site)

LI = lability index (changes in the proportion of labile carbon between sampled site and a reference site)

A similar index applied at the landscape-scale (CMI_L) combines soil samples and GIS-derived spatial data on land cover types as well as management practices such as grazing or tillage. Carbon content can be expressed on

an area rather than concentration basis to compensate for differences in soil bulk density.

The CMI_L is derived by multiplying CMI values for a land use by the proportion (%) of that land use in the landscape. Values are then summed for each land use in the landscape so that:

$$CMI_L = \Sigma (CMI \times L_p)$$

where, L_p = the proportion of a given land use in the landscape

Table 7-1 Indicator assessment: Carbon Management Index

Criterion	Rating	Justification / Examples
Understandability	MED	While the details and derivation of the CMI and CMI_L are likely to be only understood by technical specialists, the value of the index (ranging from 0 to 1 in comparison to a reference site) may be communicated and understood by a variety of people
Ecosystem Service Linkages	HIGH	The CMI and CMI_L are highly related to a number of ecosystem services, including:
Climate regulation	✓	Measures carbon sequestration in the landscape [80]
Disturbance regulation	✗	
Biological control	✗	
Erosion/sediment control	✓	Higher organic carbon content is related to higher aggregate stability [80]
Water supply	✓	Labile carbon fractions are linked to physical soil properties such as infiltration [29, 80]
Nutrient cycling	✓	Labile carbon fractions are closely linked to soil microbes and nutrient turnover [80]
Primary production	✓	High soil carbon is linked to higher productivity [267]
Recreation	✗	
Responsiveness to Management Practices	HIGH	Soil organic matter declines with increasing land use and farming intensity. Short-term changes in soil organic carbon are usually difficult to detect, but labile carbon fractions have a more sensitive response. CMI, as a composite index, has an even more sensitive response [80]
Measurability/ Cost Effectiveness	MED	A soil sampling strategy needs to be determined and standardized Laboratory work is required to separate the carbon fractions and determine the CMI
Existing Programs	MED	ABMI will be collecting data on soil carbon [10] GIS land cover datasets are available at coarse resolution
Predictability	MED	Models link field-based soil measurements (CMI) to GIS systems to produce broad-scale maps of soil resources and their response to changing land-use patterns Cannot tell significant differences between edge and core sites of a natural asset, allowing values to be pooled across an asset patch [80] Providing adequate measures of carbon sequestration in the landscape is likely to be increasingly important for Alberta to develop adequate and defensible strategies for mitigating climate change through land use practices and decisions
Thresholds	MED	Some thresholds exist (e.g., 2% organic carbon). However, concentration and rate of decline of soil carbon varies widely depending on soil type, measurement depth, rainfall, vegetation and management practices [80] Research work is ongoing

Potential Targets

Two percent soil organic carbon (or approx. 3.4% soil organic matter) is considered by many to be a critical level of organic carbon required for soil aggregate stability and productivity [80, 171]. However, applying this target to different soil types is questionable [80].

The effects of soil type and soil management (e.g., tillage regime) in agricultural areas are critical considerations. Table 7-2 shows some CMI values obtained for different soil types and cropping durations in agricultural areas of Australia. Similar ideas can be applied in Alberta by leveraging the existing and ongoing work on agricultural tillage credits and afforestation credits within the Alberta Offset Registry System administered through Climate Change Central (CCC) [77].

Table 7-2 Examples of CMI values based on soil types and cropping durations (Australia) (adapted from Collard and Zammit 2006 [80])

Soil Type	Cropping Duration (yrs)	CMI*	Study (Year)
Red clay	>20	53.3	Blair and Crocker (2000) [38]
Brown earth	4	45.0	Blair et al. (1995) [37]
Black earth	7	33.0	Blair et al. (1995) [37]
Red earth	16-18	30.5	Blair et al. (1995) [37]
Red earth	15-40	28.0	Whitbread et al. (1998) [371]
Black earth	>20	26.7	Blair and Crocker (2000) [38]
Red earth	>18	23.0	Whitbread et al. (2000) [370]

*Values are expressed in reference to uncultivated sites.

It has been recommended that research efforts focus on quantifying a basis for threshold levels of total and labile carbon fractions for a range of soil types in order to strengthen the value of the CMI_L in determining soil functional capacity and the provision of ecosystem services [80].

7.2 Primary Productivity Estimated by Remote Sensing

Primary production is a fine-scale ecological condition that can be measured across broad scales. The most common remote sensing tool for measuring primary productivity across landscapes is the Normalized Difference Vegetation Index (NDVI). Remotely sensed NDVI values are often correlated with ground-based measurements to calibrate a productivity model. The NDVI can be calculated from satellites collecting data in both the infrared (IR) and red (R) bands, and has been widely applied in ecology and forestry [135, 346]. The formula for calculating NDVI is [135]:

$$\text{NDVI} = \left(\frac{\text{IR-R}}{\text{IR+R}}\right)$$

Other indicators of primary productivity exploit the same principles as NDVI, but take advantage of greater multispectral and multiangular capabilities of modern sensors [372]. The Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) is now used by the Canadian Centre for Remote Sensing across broad scales with coarse resolution [57, 81].

An intriguing application of primary productivity is a surrogate for other ecosystem services. Although several studies show low spatial congruence between different ecosystem services [68, 118, 247], a study in South Africa found that primary production was an effective surrogate indicator for five distinct ecosystem services at the regional scale (1.22 million km^2) [118].

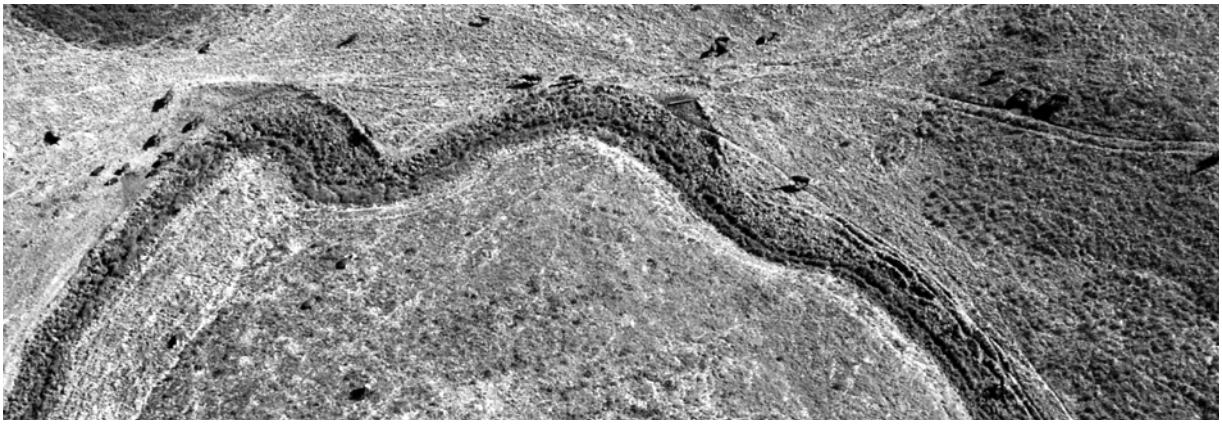


Table 7-3 Indicator assessment: NDVI / FAPAR

Criterion	Rating	Justification / Examples
Understandability	MED.	Primary production is relatively straightforward NDVI & FAPAR are more difficult to understand
Ecosystem Service Linkages	HIGH	Directly measures primary production Potential surrogate for several ecosystem services [118]
Climate regulation	× ✓	Primary production and carbon accumulation are not always closely related [118] However, models to estimate carbon sequestration from FAPAR values have been constructed [142, 317]
Disturbance regulation	✓	Regulation of water flow & mitigation of extremes [118]
Biological control	×	
Erosion/sediment control	✓	Surrogate indicator of erosion control [118]
Water supply	✓	Surrogate indicator of surface water supplies [118]
Nutrient cycling	✓	Productivity is strongly influenced by soil moisture, which affects decomposition, mineralization, and plant nutrient uptake [152, 209, 295]
Primary production	✓	Directly measures primary production
Recreation	×	
Responsiveness to Management Practices	MED.	Productivity varies over time in response to climate, weather, and internal dynamics Productivity is affected by land use (e.g., urban) [167], overgrazing [3], and loss of plant diversity [337, 338]
Measurability/ Cost Effectiveness	MED.	Remote sensing / GIS platforms Time series required due to seasonal and interannual changes and statistical analysis and interpretation is required (e.g., Principal Components Analysis) Datasets must be preprocessed by technical experts to correct for any errors associated with atmospheric effects, clouds, anisotropic, and spectral effects
Existing Programs	MED.	Spatial resolution & seamless coverage requires analysis The Canadian Centre for Remote Sensing and the Manitoba Remote Sensing Centre have produced 7-day maximum NDVI data for Western Canada since 1987, truncated to 8 bits and calibrated [57, 159] Mapping of NDVI at 250m resolution was recently completed for Grizzly Bear habitat in Alberta [268] A recent study conducted a multi-temporal analysis of FAPAR across all of Canada [81] FAPAR data is available from the Canadian Centre for Remote Sensing [57]
Predictability	MED.	Future state of the indicator can be predicted, but requires several assumptions regarding the impacts of land use and management practices, climate change effects on regional precipitation, etc.
Thresholds	LOW	None identified

Potential Targets

Targets for this indicator can be defined with a baseline covering a sufficiently long period (e.g., 1970 - 2001 average NDVI or FAPAR value). This would help smooth out seasonal and interannual trends.

The potential applicability of this indicator across entire landscapes, including anthropogenic assets, requires careful analysis. Cropland productivity depends on irrigation and fertilizer inputs. However, maximizing current productivity can gradually degrade soil and supporting services (e.g., pollination, nutrient cycling), eventually causing productivity losses decades in the future.

In addition, due to the human enhanced greenhouse effect, primary productivity over the next few decades is likely to increase in response to CO2 fertilization, a longer growing season, and possibly increased precipitation. This should be kept in mind when defining targets and interpreting data on primary productivity in relation to targets.

7.3 Evapotranspiration

Differences in evapotranspiration (ET) can be observed among different assets. Riparian, forested, and cropped lands evaporate large amounts of water through plant transpiration, which affects downstream water yield [46, 56]. Yet assets with high ET rates often provide critical erosion control, flood control, and water purification services. Without measurements and models of ET, a tradeoff analysis is very difficult. One useful way to measure ET is the proportion of total annual precipitation lost to ET. Figure 7-1 illustrates values for this measure across different land cover types.

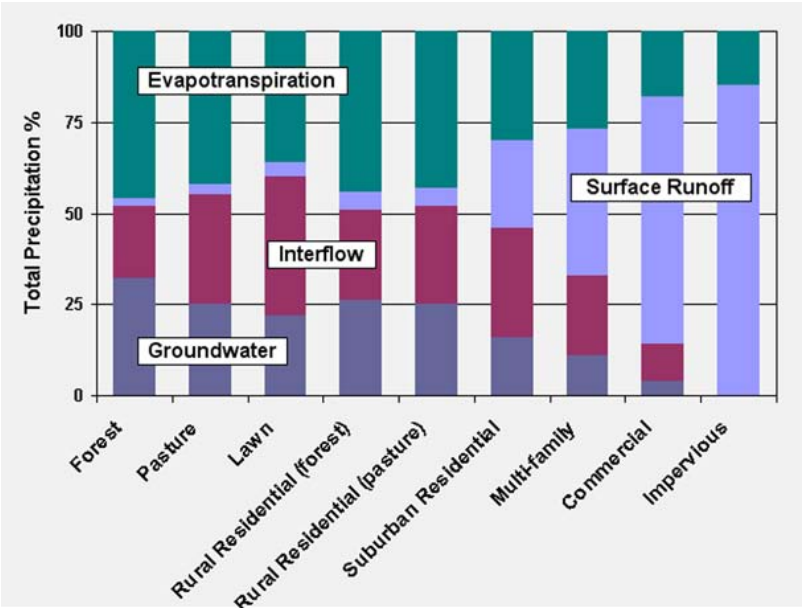


Figure 7-1 Evapotranspiration and water balance for different land cover/land use types Source: Dr. Hans Schreier, personal communication (not calibrated for Alberta)

Table 7-4 Indicator assessment: evapotranspiration

Criterion	Rating	Justification / Examples
Understandability	MED	Relatively understandable
Ecosystem Service Linkages	HIGH	Related to several ecosystem services in either positive or negative ways
Climate regulation	✓	ET moderates local humidity levels in semi-arid areas
Disturbance regulation	✓	ET can potentially mitigate floods ET can potentially exacerbate droughts
Biological control	✗	
Erosion/sediment control	✓	Land cover types with high ET also tend to provide high erosion control services
Water supply	✓	High ET reduces water quantity services, but increases water quality services
Nutrient cycling	✗	
Primary production	✓	Photosynthesis often results in high ET
Recreation	✗	
Responsiveness to Management Practices	MED	Responsive to land use and management, such as forest harvesting, shelterbelt planting, and riparian restoration strategies. Lag times are likely to be observed in system responses (e.g., due to tree age, etc.)
Measurability/ Cost Effectiveness	MED	Average ET values for assets must be calibrated locally, which may be expensive initially Once a model is calibrated costs decrease
Existing Programs	LOW	None identified
Predictability	MED	Predictions likely will require some assumptions until ET values are calibrated
Thresholds	LOW	None identified

Potential Targets

Targets for ET depend on the landscape context, including climate and characteristic natural vegetation patterns. Generally, targets for ET should aim to simulate natural landscape patterns. For example, in dryer landscapes of southern Alberta, shrub and tree cover is naturally low, and extensive tree-planting in these areas is undesirable. An example of the impacts of ignoring natural ET patterns, pine plantations in grassland watersheds of Fiji reduced dry season flows by 50-60%, threatening drinking water supplies and the operation of a hydroelectric plant [115, 279].

8.0 DISCUSSION AND SUMMARY OF RECOMMENDATIONS

This section summarizes the suggested indicators of asset condition at both broad and fine scales, and discusses a suggested framework for analysis as well as cross-scale linkages (introduced in Section 3.2) in greater detail. Finally, the main conclusions of the study are summarized.

8.1 Summary of Indicators

Tables 8-1 to 8-3 summarize the recommended indicators and composite indices according to the evaluation criteria described in Section 4.0. While the ratings are helpful in prioritizing indicators for monitoring programs, note that indicators with low ratings for some criteria and/or moderate ratings for several criteria may nonetheless have high potential for the evaluation of specific ecological services and should *not* be screened out without due consideration of their utility.

The indicators with the highest overall rankings according to the criteria include: proportion of impervious surfaces, proportion of natural assets, proportion of landscape-specific natural assets, patch size, and riparian buffer. Proportion of wetlands in the area, as well as the fine-scale indicators 'depth of water bodies' and 'indices of hydrologic alteration' also scored highly on the assessment criteria. Recommended indicators at the lower end of the criteria ranking scheme included habitat diversity, tree crown condition, the ARWQI, IBI and the cross-scale indices 'NDVI' and 'evapotranspiration rates'. These lower-ranked indicators may require further research, development, or data collection prior to becoming cost-effective and practical.

Tables 8-4 to 8-6 summarize the condition indicators according to the most relevant ecosystem services to which they apply. These tables summarize which indicators can be used as proxies for specific ecosystem services, and can be used as tools for decision-making and stakeholder communication.

Table 8-1 Summary of assessment criteria: broad-scale condition indicators

	Broad-Scale Indicators								
	Landscape Composition				Landscape Pattern				
Indicator Assessment Criteria	#1 Proportion of Natural Assets	#2 Proportion of Wetlands	#3 Proportion of Landscape-Specific Natural Assets	#4 Proportion of Impervious Surfaces	#1 Patch Size	#2 Road Density	#3 Connectivity	#4 Riparian Buffers	#5 Habitat Diversity
Understandability	3	3	3	3	3	2	2	3	2
Ecosystem Service Linkages	3	3	3	3	3	3	3	3	3
Responsiveness to Management	3	2	3	3	3	2	3	3	2
Measurability / Cost-Effectiveness	3	2	3	3	3	2	2	3	2
Existing Programs and Data	2	2	2	2	2	2	2	2	2
Predictability	3	3	3	3	3	3	3	3	2
Thresholds	2	3	2	3	2	2	2	2	1
	Legend								
	High	3							
	Medium	2							
	Low	1							

Table 8-2 Summary of assessment criteria: fine-scale condition indicators

	Fine-Scale Indicators													
	Grasslands and Shrubland		Deciduous / Mixed Forest		Coniferous Forest		Riparian	Lentic		Lotic			Wetlands	
Indicator Assessment Criteria	#1 Range Health Assessment Score	#2 Soil Organic Matter	#1 Canopy Structure	#2 Presence / Abundance of Dead Wood	#1 Age Class Distribution	#2 Tree Crown Condition	#1 Riparian Health Index	#1 Depth of Water Bodies	#2 Trophic Status	#1 Alberta River Water Quality Indices	#2 Indices of Hydrological Alteration	#3 Index of Biotic Integrity	#1 Water Storage Function Capacity Index	#2 Cows and Fish Wetland Health Score
Understandability	2	2	3	2	3	2	2	3	2	2	2	2	2	2
Ecosystem Service Linkages	3	3	3	3	3	3	3	3	3	2	3	2	3	3
Responsiveness to Management	2	2	2	2	2	2	2	2	2	1	3	2	3	3
Measurability / Cost-Effectiveness	2	2	2	2	2	2	2	3	3	2	3	2	3	2
Existing Programs and Data	3	2	2	2	2	2	3	3	3	3	3	2	1	2
Predictability	3	2	3	2	3	2	2	3	2	2	2	2	2	2
Thresholds	1	2	2	2	2	1	1	2	2	2	2	2	1	1
Legend														
High		3												
Medium		2												
Low		1												

Table 8-3 Summary of assessment criteria: cross-scale indicators

	Cross-Scale Indicators		
Indicator Assessment Criteria	#1 Carbon Management Index	#2 Primary Productivity (NDVI)	#3 Evapo-transpiration Rates
Understandability	2	2	2
Ecosystem Service Linkages	3	3	3
Responsiveness to Management	3	2	2
Measurability / Cost-Effectiveness	2	2	2
Existing Programs and Data	2	2	1
Predictability	2	2	2
Thresholds	2	1	1
	Legend		
	High	3	
	Medium	2	
	Low	1	

Table 8-4 Applicability of broad-scale condition indicators to priority ecosystem services

	Broad-Scale Indicators								
	Landscape Composition				Landscape Pattern				
Ecosystem Functions and Services	#1 Proportion of Natural Assets	#2 Proportion of Wetlands	#3 Proportion of Landscape-Specific Natural Assets	#4 Proportion of Impervious Surfaces	#1 Patch Size	#2 Road Density	#3 Connectivity	#4 Riparian Buffers	#5 Habitat Diversity
Regulating Services									
1. Climate regulation	✓	✓	✓	✓	✓	✓	✗	✓	✗
2. Disturbance regulation	✓	✓	✓	✓	✓	✓	✓	✓	✓
3. Erosion control and sediment retention	✓	✓	✓	✓	✓	✓	✓	✓	?
4. Biological control	✓	✓	✓	✓	✓	✓	✓	✓	✓
Supporting Services									
5. Nutrient cycling	✓	✓	✓	✓	✗	✓	✗	✓	✓
6. Primary production	✗	✓	✓	✓	✓	✓	✗	✓	✓
Provisioning Services									
7. Water supply	✓	✓	✓	✓	✓	✓	✓	✓	✗
Cultural and Aesthetic Services									
8. Recreation	✓	✓	✓	✓	✓	✓	✓	✓	✓
Legend									
Relevant	✓								
Not Relevant	✗								

Table 8-5 Applicability of fine-scale condition indicators to priority ecosystem services

	Fine-Scale Indicators														
	Grasslands and Shrubland		Deciduous / Mixed Forest		Coniferous Forest		Riparian	Lentic		Lotic			Wetlands		Geo-logical
Ecosystem Services	#1 Range Health Assessment Score	#2 Soil Organic Matter	#1 Canopy Structure	#2 Presence / Abundance of Dead Wood	#1 Age Class Distribution	#2 Tree Crown Condition	#1 Riparian Health Index	#1 Depth of Water Bodies	#2 Trophic Status	#1 Alberta River Water Quality Indices	#2 Indices of Hydrological Alteration	#3 Index of Biotic Integrity	#1 Water Storage Function Capacity Index	#2 Cows and Fish Wetland Health Score	#1 Ice Quality
Regulating Services															
1. Climate regulation	✓	✓	✓	✓	✗	✓	✓	✗	✗	✗	✗	✗	✓	✓	✓
2. Disturbance regulation	✓	✗	✓	✓	✓	✗	✓	✓	✗	✗	✓	✗	✓	✓	✗
3. Erosion control and sediment retention	✓	✓	✓	✓	✗	✓	✓	✗	✗	✗	✓	✗	✗	✓	✗
4. Biological control	✓	✗	✓	✓	✓	✗	✓	✗	✗	✗	✓	✗	✗	✓	✗
Supporting Services															
5. Nutrient cycling	✓	✓	✗	✓	✗	✗	✓	✓	✓	✗	✓	✓	✓	✓	✗
6. Primary production	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✓	✓	✗
Provisioning Services															
7. Water supply	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cultural / Aesthetic Services															
8. Recreation	✓	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓
Legend															
Relevant	✓														
Not Relevant	✗														

Table 8-6 Applicability of cross-scale indicators to priority ecosystem services

	Cross-Scale Indicators		
Ecosystem Services	#1 Carbon Management Index	#2 Primary Productivity (NDVI)	#3 Evapo-transpiration Rates
Regulating Services			
1. Climate regulation	✓	✓	✓
2. Disturbance regulation	✗	✓	✓
3. Erosion control	✓	✓	✓
4. Biological control	✗	✗	✗
Supporting Services			
5. Nutrient cycling	✓	✓	✗
6. Primary production	✓	✓	✓
Provisioning Services			
7. Water supply	✓	✓	✓
Cultural and Aesthetic Services			
8. Recreation	✗	✗	✗
Legend			
Relevant	✓		
Not Relevant	✗		

8.2 A Framework for Applying EGS in Land Use Planning

A framework for analysis is needed to implement the assessment of ecosystem goods and services (EGS). Most natural assets, as defined in this report, provide EGS to some degree. However, the reality of land use allocation requires prioritization and cost-benefit analysis to support decision making. All areas are not of equal importance and priority areas for long term protection of EGS need to be established. The following is a potential methodology to assess and prioritize the protection of EGS within the land use planning process [143].

Step 1. Define Boundaries

Stratify the Region into geographic sub-units (i.e., Landscapes, Sub-basins, Landscape Units)

Step 2. Assess and Map Broad-Scale Indicators of EGS

Assess broad-scale indicators at the regional scale, and report and map data within:

- The region (e.g., South Saskatchewan Region)
- Landscapes (e.g., Lower Foothills Natural Subregion)
- Major Sub-basins (e.g., Bow River)
- Landscape Units (Landscapes x Major Sub-basins) (e.g., Bow-Mixed Grassland LU)

Step 3. Assess and Map Potential EGS Based on Land Cover

Utilizing the methods identified in the Phase II EGS Report [165], generate EGS maps of:

- Important areas for individual goods and services
- Important areas for multiple goods and services (EGS “hotspots”)

Step 4. Mapping Synthesis: The Existing Green Network

Integrate maps from Steps 2 and 3 to identify the existing Green Network of Natural Assets that provides critical EGS. This network will include the following indispensable patterns:

- The largest patches of natural assets,
- Stepping stones of natural assets large enough and close enough together to provide landscape connectivity;
- Major regional corridors that provide landscape connectivity;
- Riparian corridors in permanent vegetative cover;
- Other special features (i.e., badlands, wetlands, ecologically significant areas)

NOTE: The vast majority of EGS hotspots are captured within the above landscape patterns. However, any missed hotspots will be included in the Green Network.

Step 5. Set Targets for Broad-Scale Indicators

Set future management targets and, where applicable, thresholds for broad-scale indicators by integrating:

- Data and maps from Steps 2-4 above;
- Available scientific information;
- Land use planning tradeoff analyses;
- Desired land use outcomes as identified through land use planning

Step 6. Gap Analysis and Desired Future Green Network

Identify gaps in the existing Green Network that would be required to meet targets and future land use outcomes identified in Step 5. These may include:

- Areas where restoration is required to improve the network (e.g. riparian buffers not in permanent cover);
- Areas identified in other studies or through expert or stakeholder consultation.

Step 7. Identify Threats

As part of the planning process, identify potential future land use threats or stressors to the Green Network.

Step 8. Prioritization

Prioritize areas within the Green Network that are highly valued *and* potentially threatened by existing or contemplated land uses.

Within prioritized areas, conduct finer scale condition analysis to confirm asset condition and importance to EGS, particularly where compensation is considered.

Step 9. Management Actions

Develop a management and conservation strategy for high priority lands. This may include best management practices for operating within the Green Network, and/or protection incentives (e.g., zoning, conservation easements, transfer of development credits, etc.)

An illustrative example of the concept using the Bow-Mixed Grassland LU is provided below.

STEP 1: DEFINE BOUNDARIES

A logical way to stratify regions of Alberta into smaller geographic units is to overlay watershed boundaries for large rivers (e.g., Bow River) on top of the province's Natural Subregions (e.g., Mixed Grassland) [250]. The intersection between these two geographic classification schemes can be used to define "Landscape Unit" (LU) boundaries [255]. To illustrate the concept, consider the Bow-Mixed Grassland LU, which includes that portion of the Bow River watershed that intersects the Mixed Grassland Natural Region (Figure 8-1). This LU includes approximately 5384 km^2 south of the Town of Brooks and upstream from the confluence of the Bow and Oldman rivers (Figure 8-2).

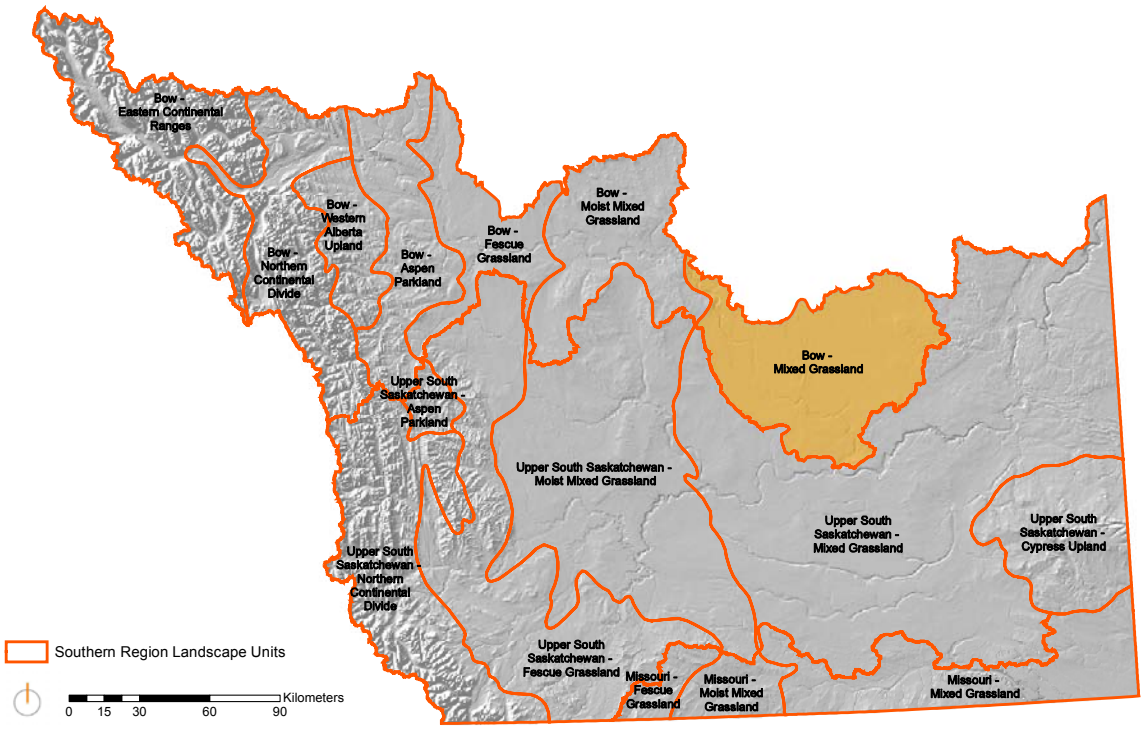


Figure 8-1 **Regional Context of the Bow-Mixed Grassland Landscape Unit**

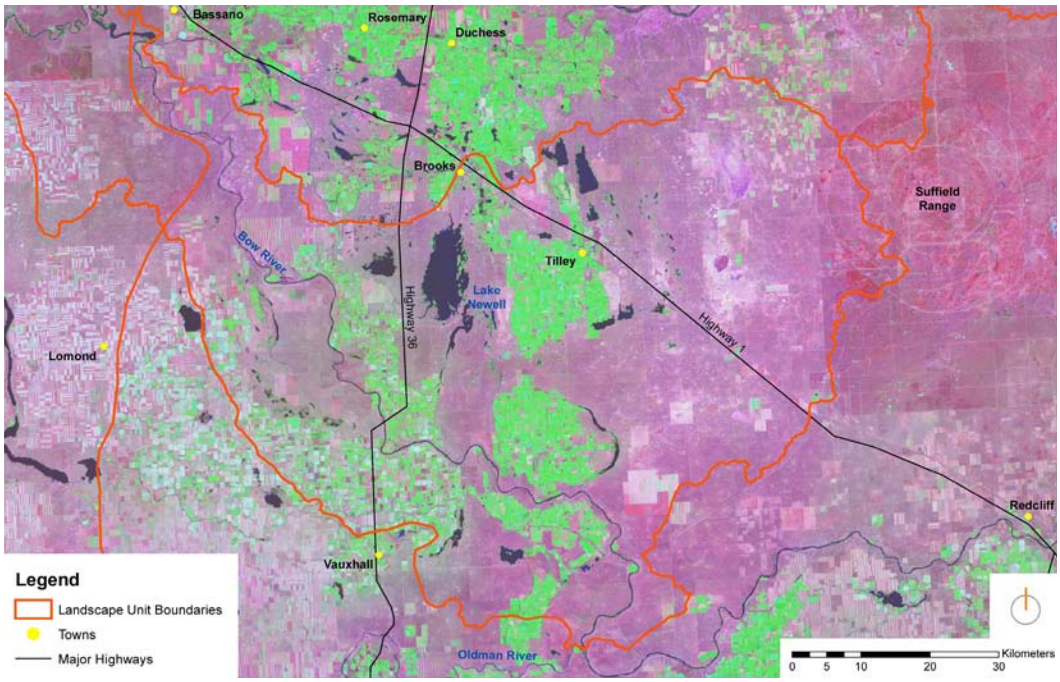


Figure 8-2 **Infrared image of the Bow-Mixed Grassland LU and adjacent areas**

STEP 2: ASSESS AND MAP BROAD-SCALE INDICATORS OF EGS

The next step of the assessment framework is to analyze and map broad-scale indicators. A general assessment of ecosystem services at the regional scale tends to over-generalize results and lose the context required for defining targets and zoning within individual landscapes. Therefore, assessments at the landscape and watershed scales should be initiated.

To assess landscape indicators, GIS vector data from the Southern Alberta Landscapes (SAL) project were queried with ArcGIS 9.2 software. Note that this mapping is for example purposes and may lack accuracy and precision. Other data sets and detailed models may be required in practice. Results for landscape composition are summarized in Table 8-7 and Figure 8-3.

Table 8-7 **Summary of landscape composition indicators in the Bow-Mixed Grassland LU**

Landscape Composition Indicator	Measured Value for Bow-Mixed Grassland Landscape Unit
% natural assets	65%
% wetlands	0.13-1.9%[a]
% grasslands	63%
% badlands	0.76%
% shrubland	0.05%
% reservoirs + lakes (grouped)	3.6%
% impervious	3.0%

[a]Wetlands were underestimated by the SAL dataset (0.13%); the Prairie Farm Rehabilitation Administration (PFRA) land cover data set estimates wetlands as 1.85% for this area.

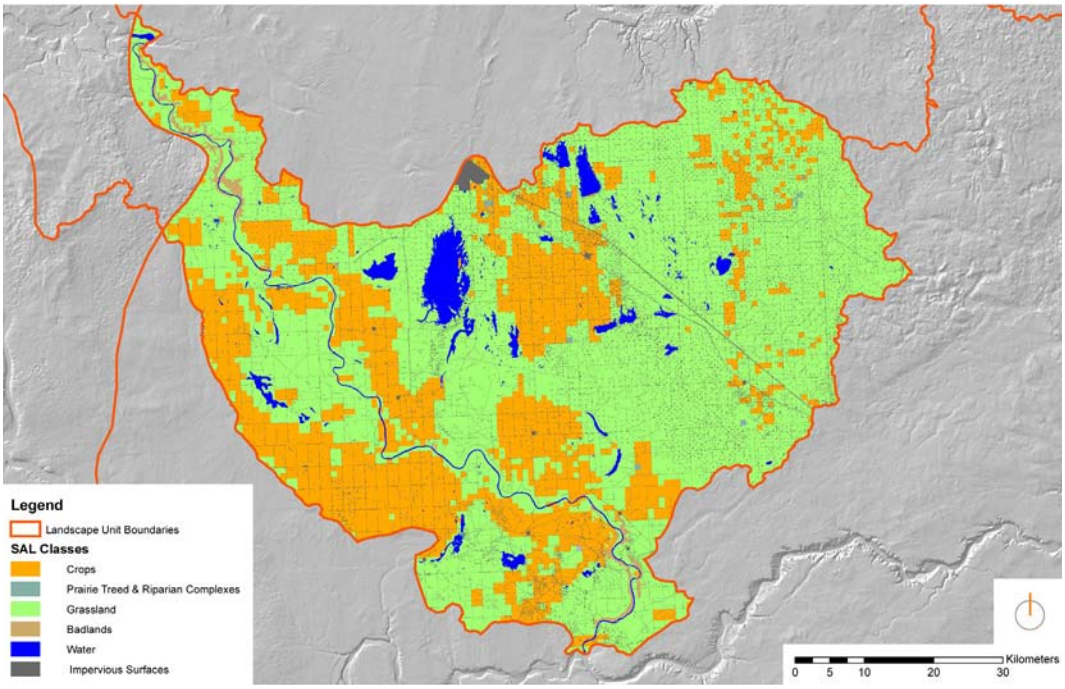


Figure 8-3 **Land Cover in the Bow-Mixed Grassland LU**

Each of the landscape composition indicators in Table 8-7 are strongly linked to ecosystem services. The more wetlands, grasslands, and badlands a landscape contains, the higher the associated ecosystem services provided by each of these respective cover types. For example, the loss of natural grasslands affects pest control ecosystem services, as well as water supply and erosion control services (Table 5.6). Conversely, lower amounts of impervious surfaces in a watershed are related to a greater supply of ecosystem services such as climate regulation, flood regulation, erosion control, biological control, and water supply (See Table 5-8).

The landscape pattern analysis is illustrated with maps. Mapping the "patch size" indicator provides the important spatial context necessary to support management strategies such as zoning. Large patches are a key broad-scale indicator of several ecosystem services, including disturbance regulation (flood, fire, and drought regulation), erosion control, water supply, and a range of biodiversity-related services (i.e., insect pest control) (See Table 5-11). Generally, the condition of a large intact habitat patch is better than the same habitat distributed widely across small patches. Moreover, patch sizes >1000 ha are important to conserve species with large home ranges [110, 126], and patch sizes >100 ha have been identified as necessary to preserve interior grassland habitat [126]. Mapping large patches based on these two size classes indicates high priority locations for conserving ecosystem services (Figure 8-4). The locations of natural habitat patches <100 ha may also be important for conserving site-specific ecosystem services. Note that due to high fragmentation by roads, smaller habitat patches may be difficult to distinguish from one another.

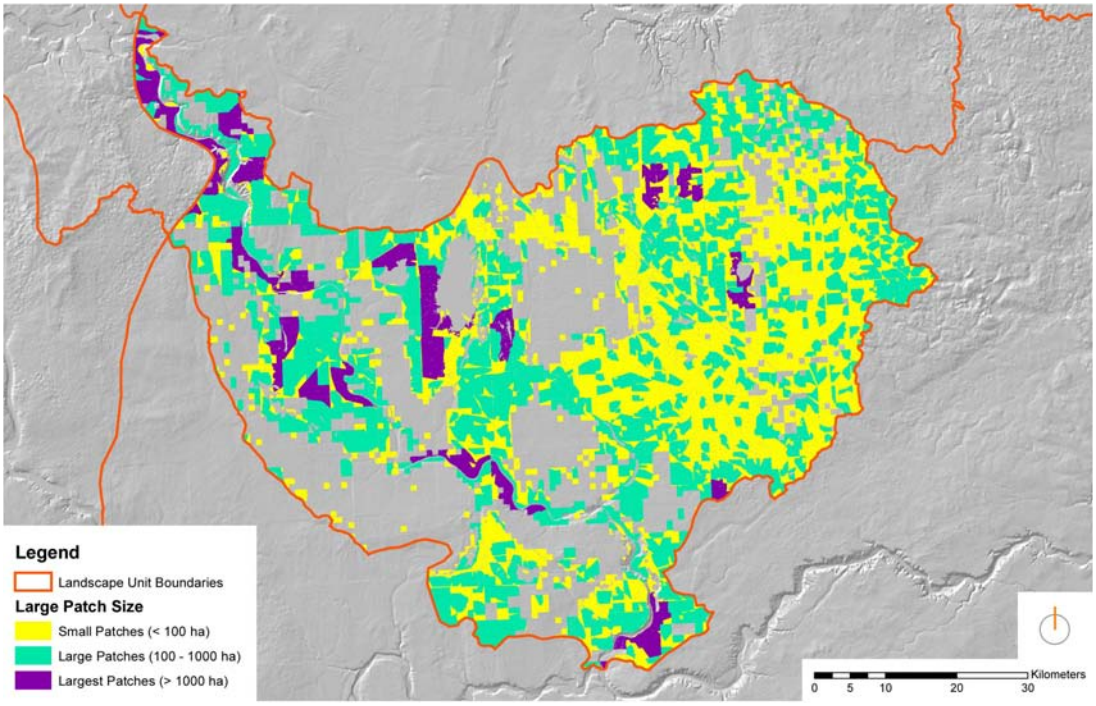


Figure 8-4 Large Patches of Natural Vegetation in the Bow-Mixed Grassland LU

The mean patch size in the landscape can be a useful summary statistic. Mean patch size for natural vegetation in the Bow-Mixed Grassland LU is 28.5 ha. However, this value should be combined with and interpreted in the context of mapping (Figure 8-4) as well as patch size distribution summaries such as histograms.

Another key broad-scale indicator of ecosystem services is landscape connectivity. Figure 8-5 illustrates connectivity in the Bow-Mixed Grassland LU based on the Euclidean Nearest Neighbour (ENN) distance between natural patches. Notably, natural habitats are particularly highly connected when they constitute the background landscape matrix. This is evident in the eastern half of the Bow-Mixed Grassland LU (Figure 8-5), where natural grasslands form the landscape matrix within which well sites, roads, pipelines, residences, and some cropland are located. In other areas, the reverse applies, with arable agriculture as the background matrix and connectivity provided by natural corridors and stepping stones.

More detailed spatial methods to measure landscape connectivity are also required, such as connectivity provided through stepping stones. Stepping stones were considered as natural asset patches larger than 2 ha and closer than 200m from the closest adjacent patch. Stepping stones that met these contiguity requirements are mapped in Figure 8-6. Stepping stones in the western half of the study area are particularly important since this heavily altered portion of the landscape contains fewer natural patches to provide landscape connectivity. Stepping stone complexes - aggregates of stepping stones 200 m for one another - were also provided with a unique identifier and classed by area within the GIS.

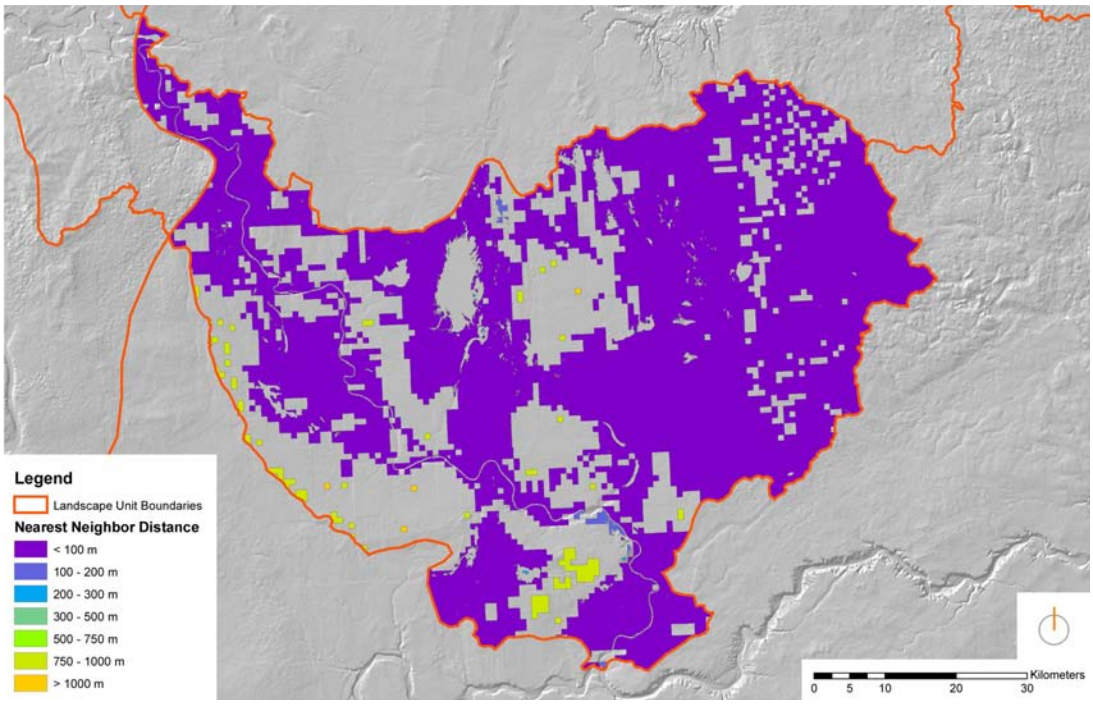


Figure 8-5 Connectivity between patches in the Bow-Mixed Grassland LU

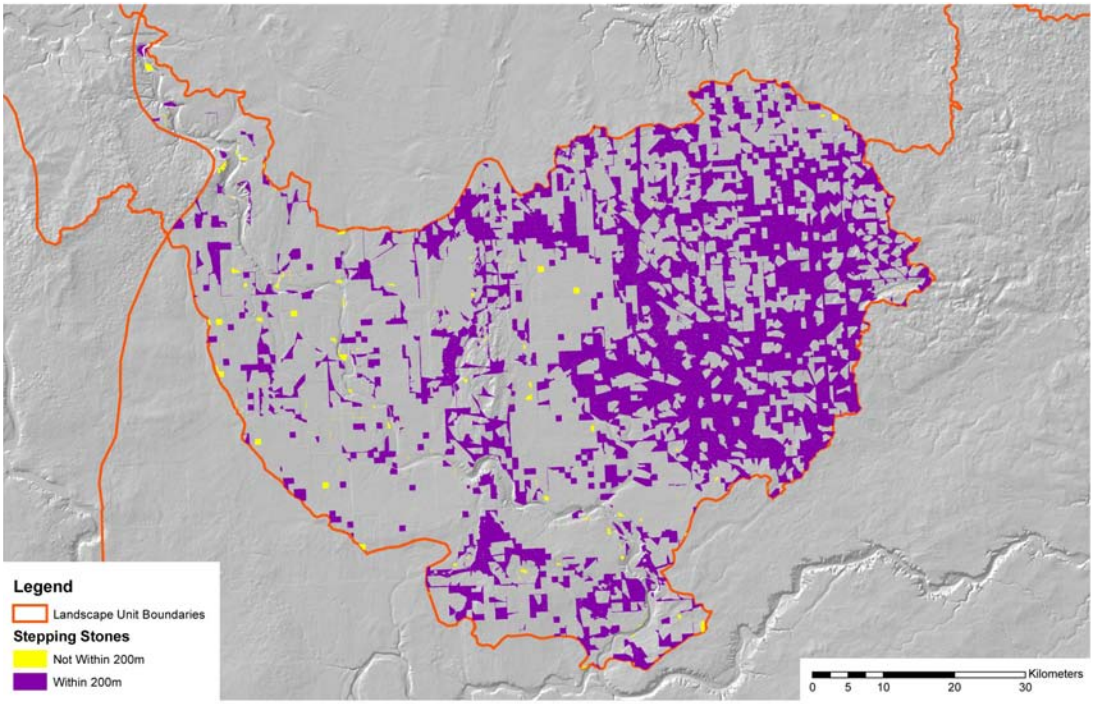


Figure 8-6 Landscape Connectivity through Stepping Stones in the Bow-Mixed Grassland LU

Regional corridors provide key landscape and regional connectivity functions. Therefore, a natural patch of vegetation within a regional corridor will tend to provide more ecosystem services than a natural patch outside of the corridor. For the purposes of this example, only the Bow River valley was considered as a major regional corridor, although a more detailed analysis may reveal other important corridors (i.e., a north-south regional corridor east of Lake Newell (Figure 8-4)).

Figure 8-7 maps the existing condition of the Bow River valley regional corridor with respect to natural vs. anthropogenic land cover types within 500m of the Bow River. In total, 71% of the regional corridor is currently naturally vegetated, whereas 29% of the regional corridor is occupied by crops and other anthropogenic land cover types.

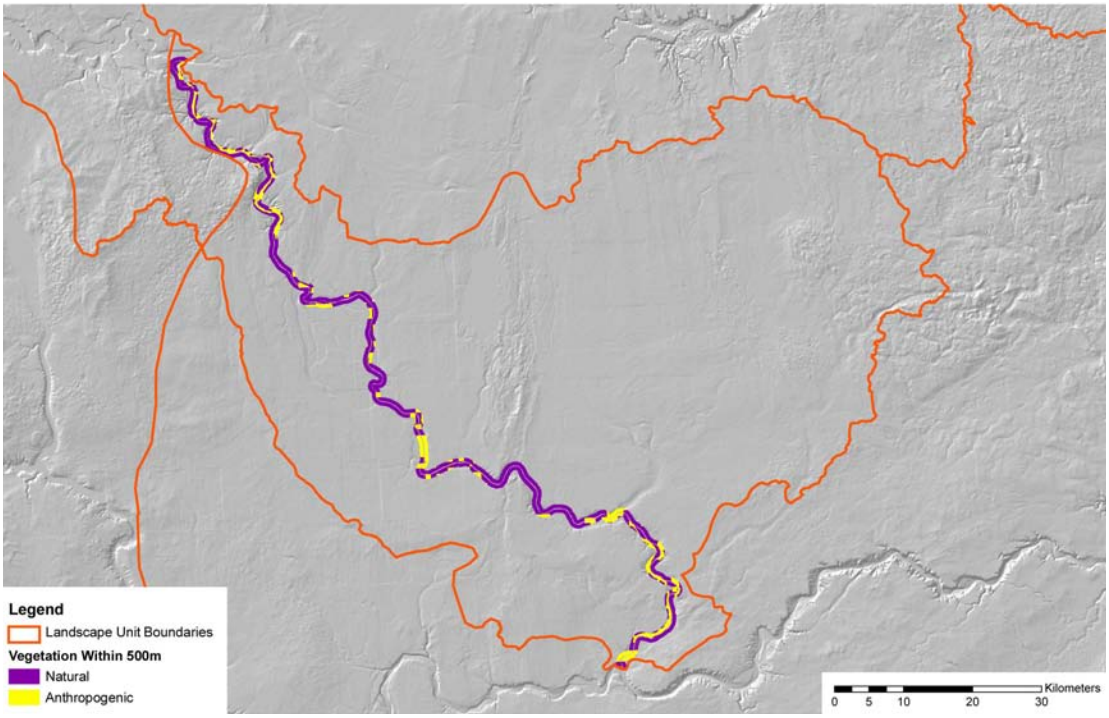


Figure 8-7 The Bow River Regional Corridor: Land Cover Condition within 500 m of the Bow River

Natural riparian buffer widths are an additional key landscape indicator that must be considered, as these buffers perform many key ecosystem services related to water quality, erosion control, habitat, and recreation. A 60 m buffer width is particularly important for maintaining water quality ecosystem services and drinking water supplies (See Section 5.2.4); therefore, natural habitat within this zone tends to be more important for ecosystem services. Figure 8-8 maps general land cover conditions within 60 m of streams in the Bow-Mixed Grassland LU. The total proportion of naturally vegetated land within a 60 m riparian zone in the Bow-Mixed Grassland LU was calculated at 73%. However, caveats are required since the SAL data set ignores all intermittent streams and appears to omit important sections of the existing hydrological network (Figure 8-8). A 150 m riparian width was also analyzed for land cover conditions. For this landscape, results for the total proportion of natural vegetation were only 1% lower than the results for the 60m buffer (72% vs 73%).

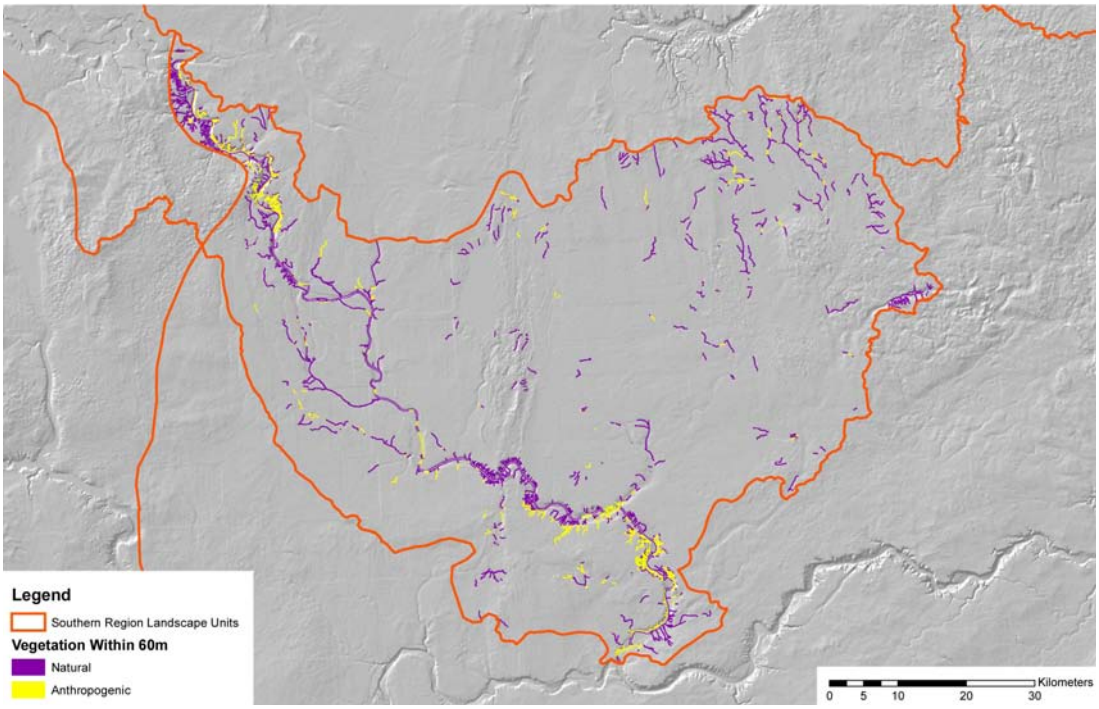


Figure 8-8 Riparian Buffers: Land Cover Condition within 60 m of Streams

Road density and habitat diversity are additional landscape scale indicators that should be examined in practice. However, these were not analyzed for the purposes of this case study due to data processing requirements and budget and staff constraints.

Step 3. Assess and Map Potential EGS Based on Land Cover

The next step of the framework for assessment consists of assessing and mapping ecosystem services utilizing the methods identified in the Phase II EGS Report [165]. This methodology consists of assigning "ecosystem service rating" values to specific land cover types [165]. For the purposes of this case study, the seven priority services considered in this report were mapped within the Bow-Mixed Grassland LU (Figures 8-9 to 8-14). In addition, the value for all seven of these ecosystem services were combined and averaged to create a map of areas most important for multiple services ("EGS hotspots" map-Figure 8-15).

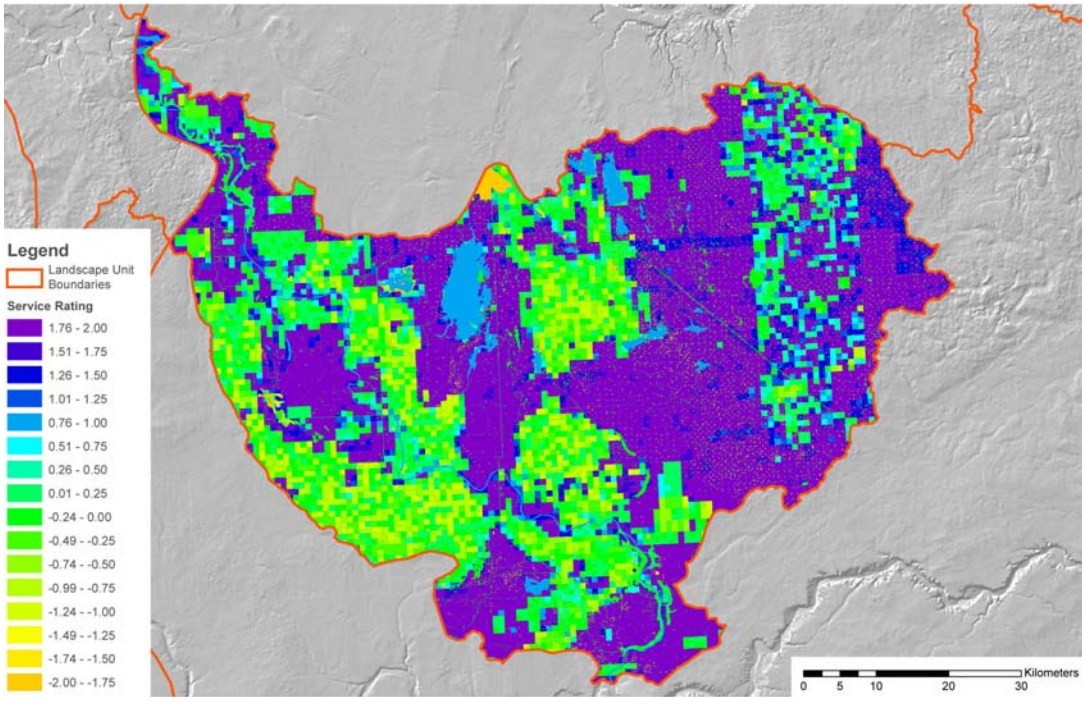


Figure 8-9 Climate Regulation Map: Bow-Mixed Grassland LU

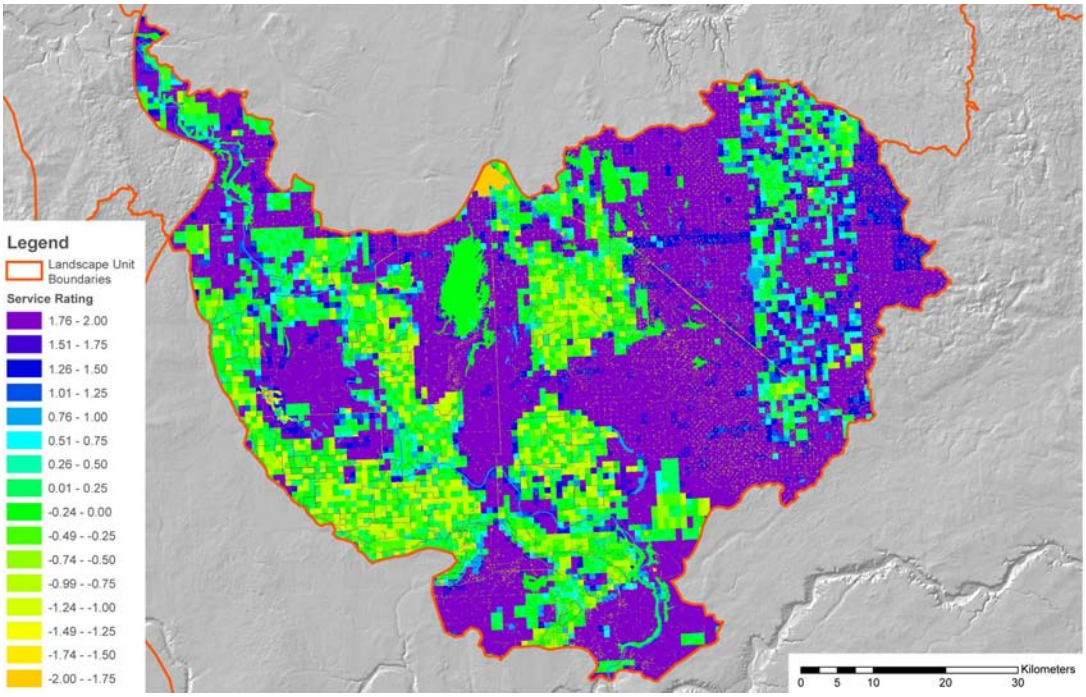


Figure 8-10 Disturbance Regulation Map: Bow-Mixed Grassland LU

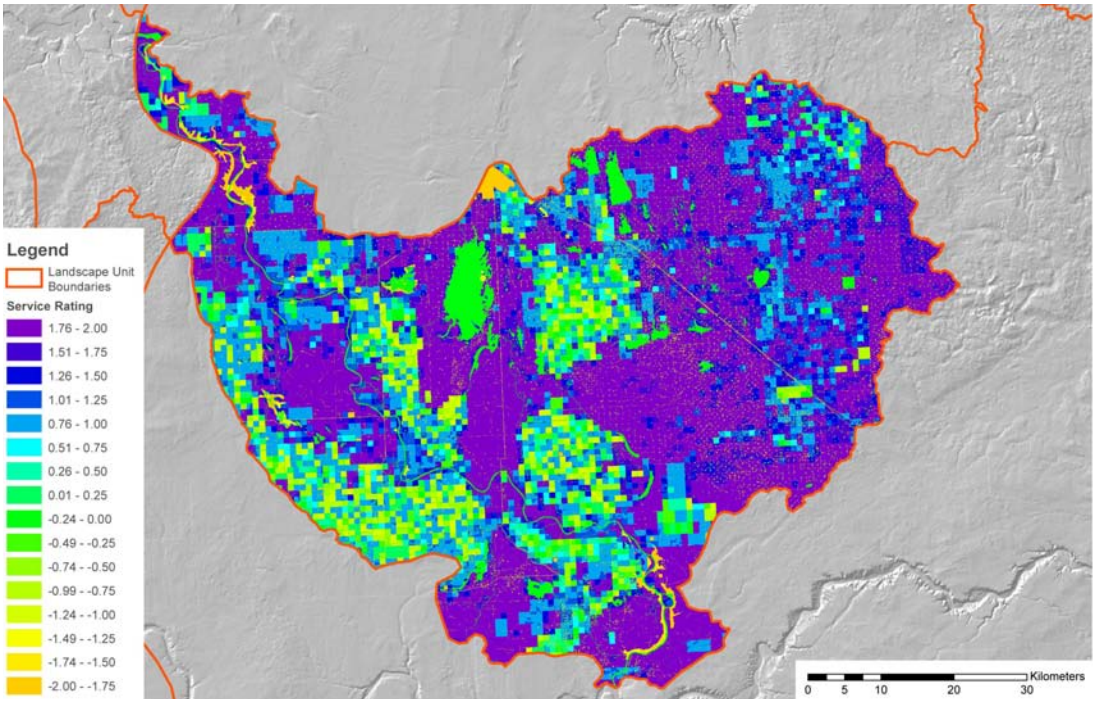


Figure 8-11 Erosion Control and Sediment Retention Map: Bow-Mixed Grassland LU

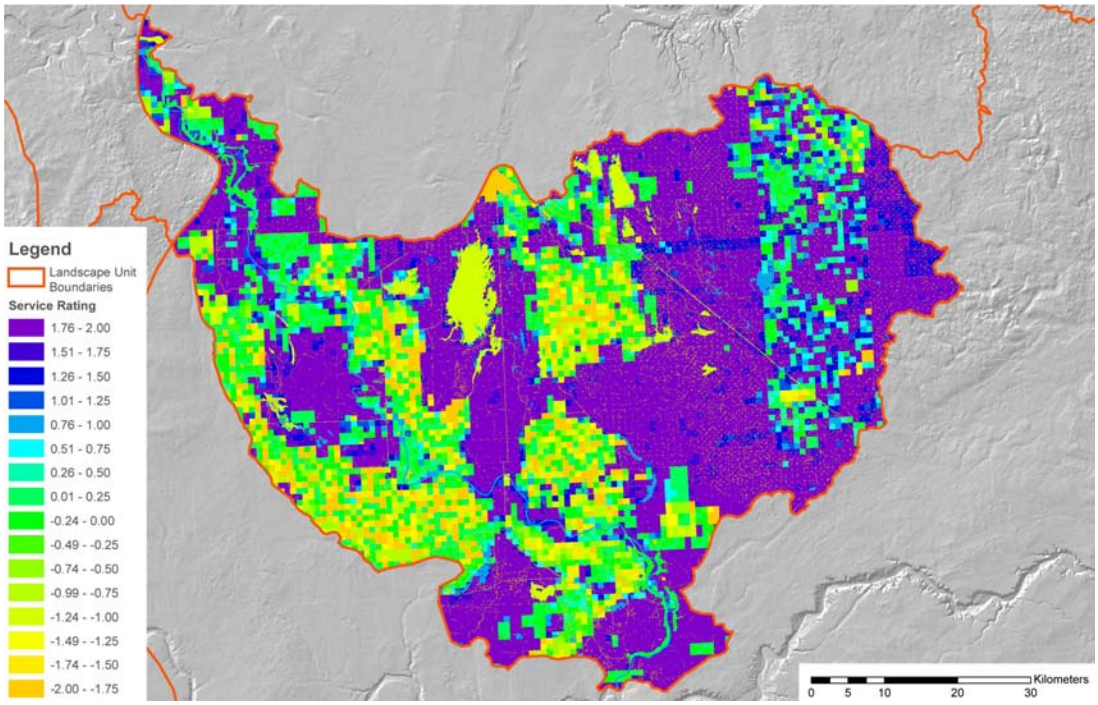


Figure 8-12 Biological Control Map: Bow-Mixed Grassland LU

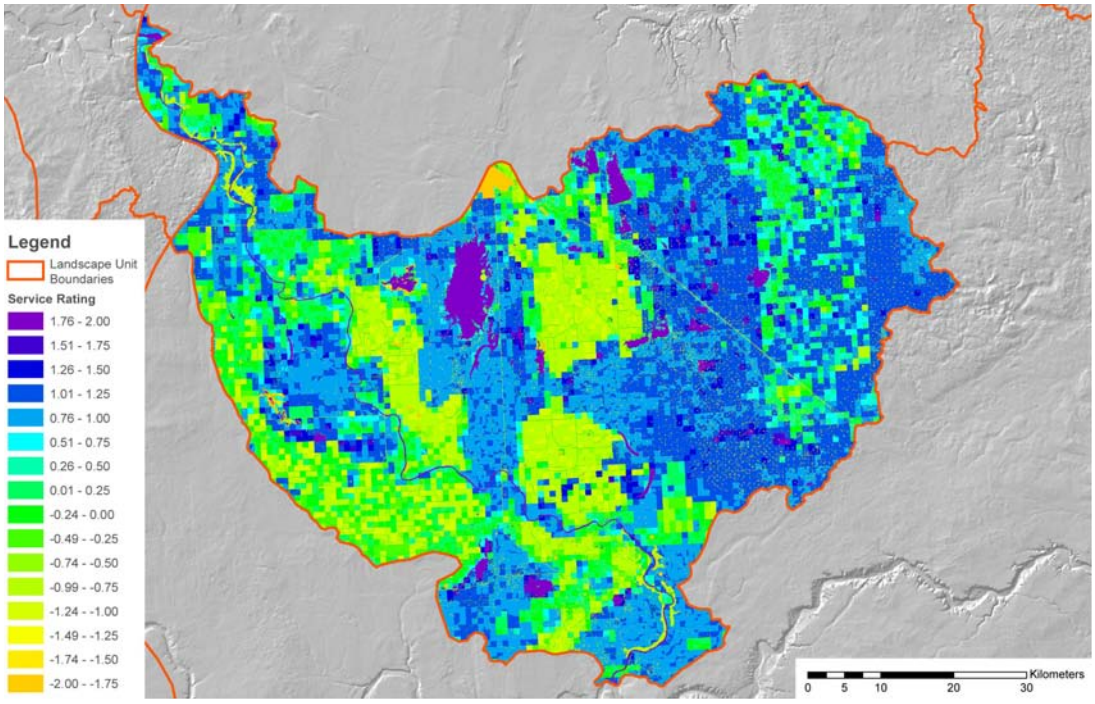


Figure 8-13 Water Supply Service Map: Bow-Mixed Grassland LU

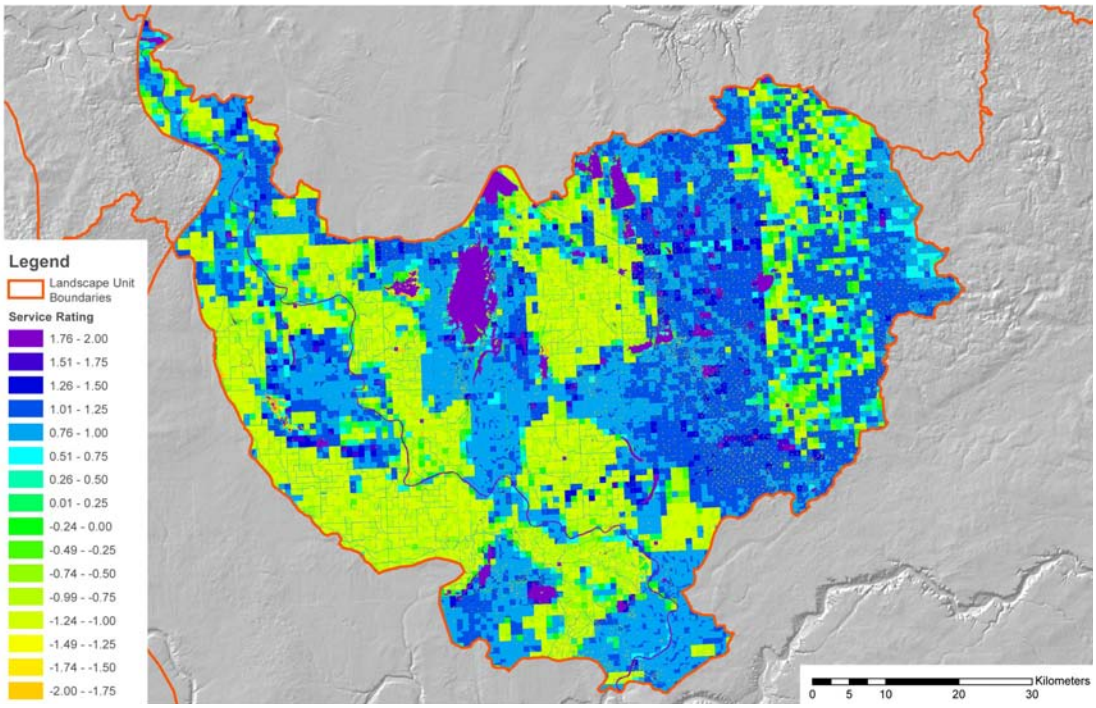


Figure 8-14 Recreation Service Map: Bow-Mixed Grassland LU

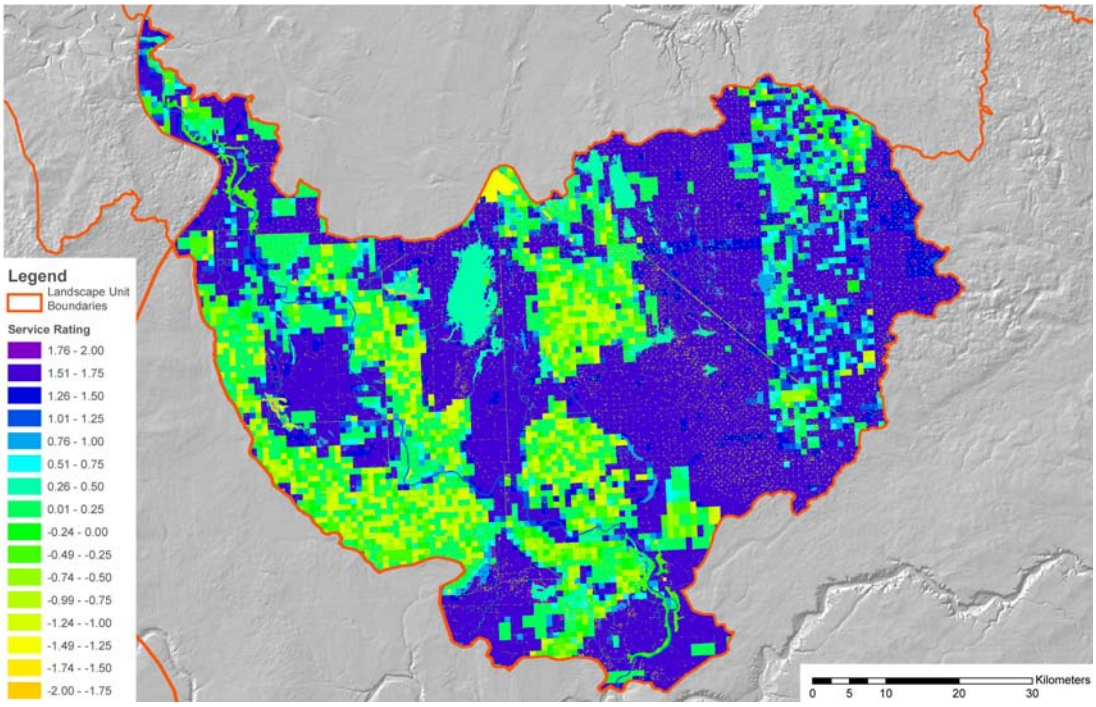


Figure 8-15 Ecosystem Service Hotspot Map: Bow-Mixed Grassland LU

In general, Figures 8-9 to 8-15 illustrate that patches of natural assets tend to provide more ecosystem services than anthropogenic cover types. Figures 8-13 and 8-14 illustrate that aquatic habitat types score highest on the water supply and recreation services. The ecosystem hotspots map (Figure 8-15) illustrates that the highest ecosystem service ratings for multiple services are attached to grassland habitats, with intermediate values assigned to water, and lower values assigned to cropland, and the lowest values assigned to well sites, roads, facilities, and the Town of Brooks. It should also be mentioned that during the process of land use planning, stakeholder consultations can be conducted to assign weights to individual services prior to creating summary maps or EGS hotspot maps.

Step 4. Mapping Synthesis: The Existing Green Network

This step synthesizes the previous analysis to identify a Green Network of natural assets providing important EGS.

The first component of the mapping synthesis was to integrate the selected broad-scale indicators of ecosystem services (Step 2). For the purposes of this example, this was accomplished by assigning weights to indicators, and creating an additive GIS map to identify areas scoring highly on multiple broad-scale EGS indicators.

Note that many permutations of weighting, classification, and mapping schemes are possible as required to meet stakeholder needs in the land use planning process. The approach taken below is only one possibility.

The weighting system was set as follows:

Large Patches:

- 100-1000 ha…….……..... 4 points
- >1000 ha……..... 5 points

Stepping Stone Complexes:

- Any stepping stone……..... 1 point
- Stepping stones in a complex between 2-100 ha…… 2 points
- Stepping stones in a complex between 100-1000 ha…… 3 points
- Stepping stones >1000 ha……..... 4 points

Bow River Corridor (>500 m) ……..…… 4 points

Riparian Natural Buffers:

- Natural vegetation from 0-60 m…… 4 points
- Natural vegetation from 60-150 m……..... 3 points

Results of the broad-scale indicator overlay synthesis are illustrated in Figure 8-16. This map identifies which patches of natural vegetation are located in a position that enables the provision of multiple key ecosystem services. It can be used in land use planning and management to set priorities. For example, the highest values in Figure 8-16 (red) are the highest priority for management due to their location:

- within one of the largest (>1000 ha) patches of natural vegetation (5 points);
- within the Bow River corridor (4 points);
- within a naturally vegetated 60 m riparian buffer (4 points).

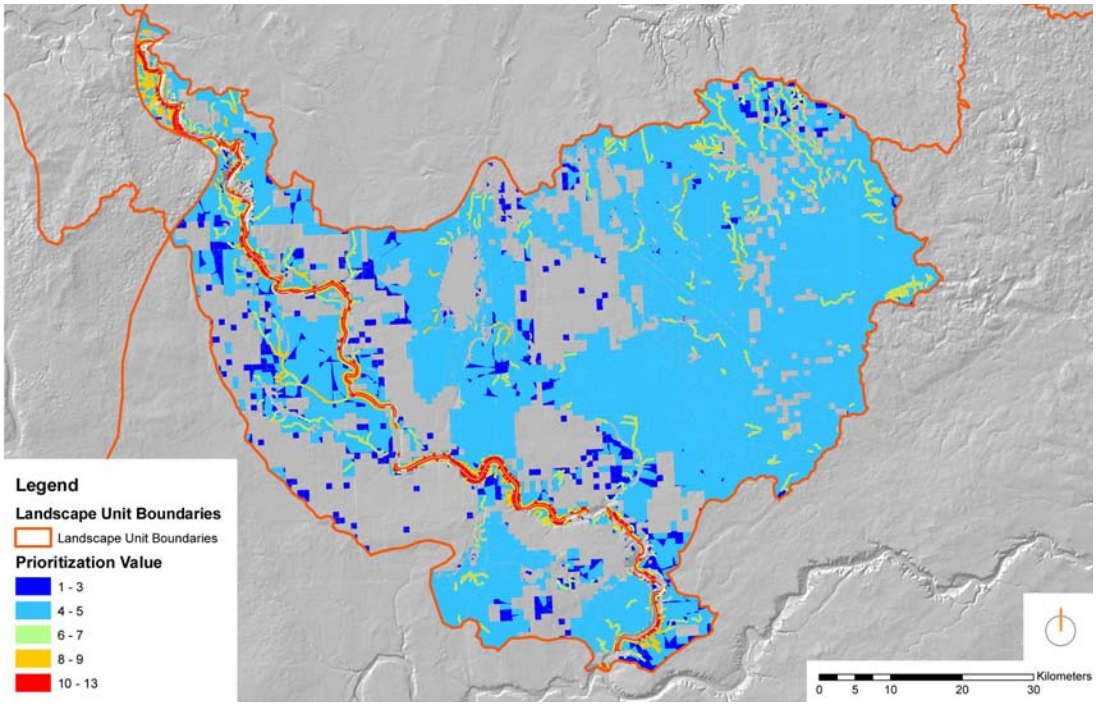


Figure 8-16 Synthesis of Broad-Scale Indicators

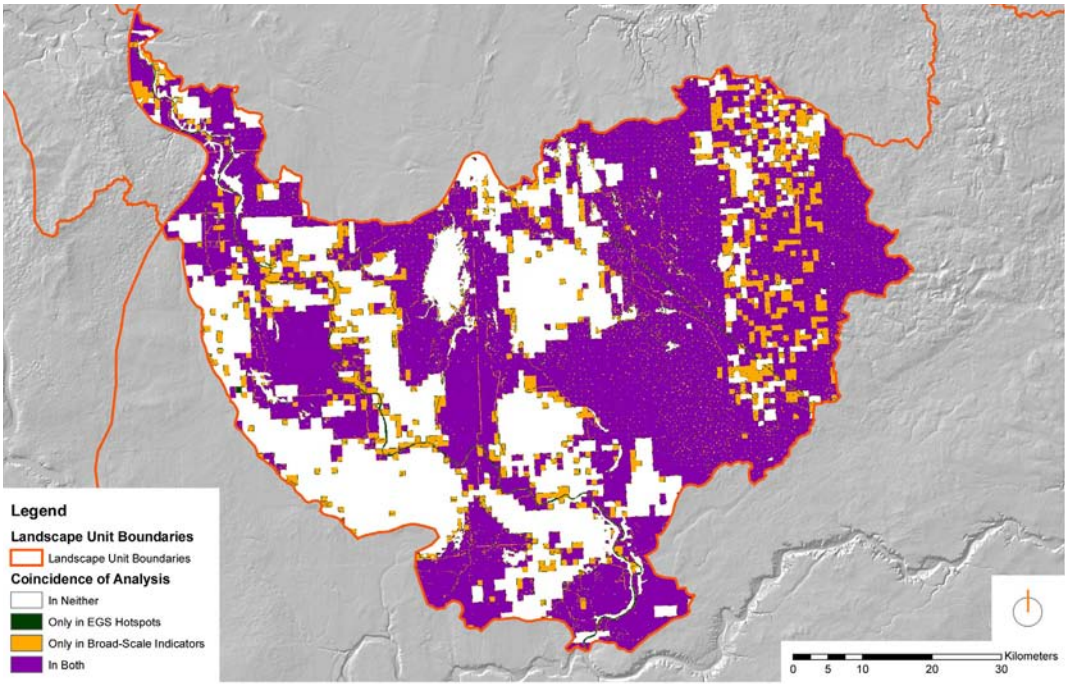
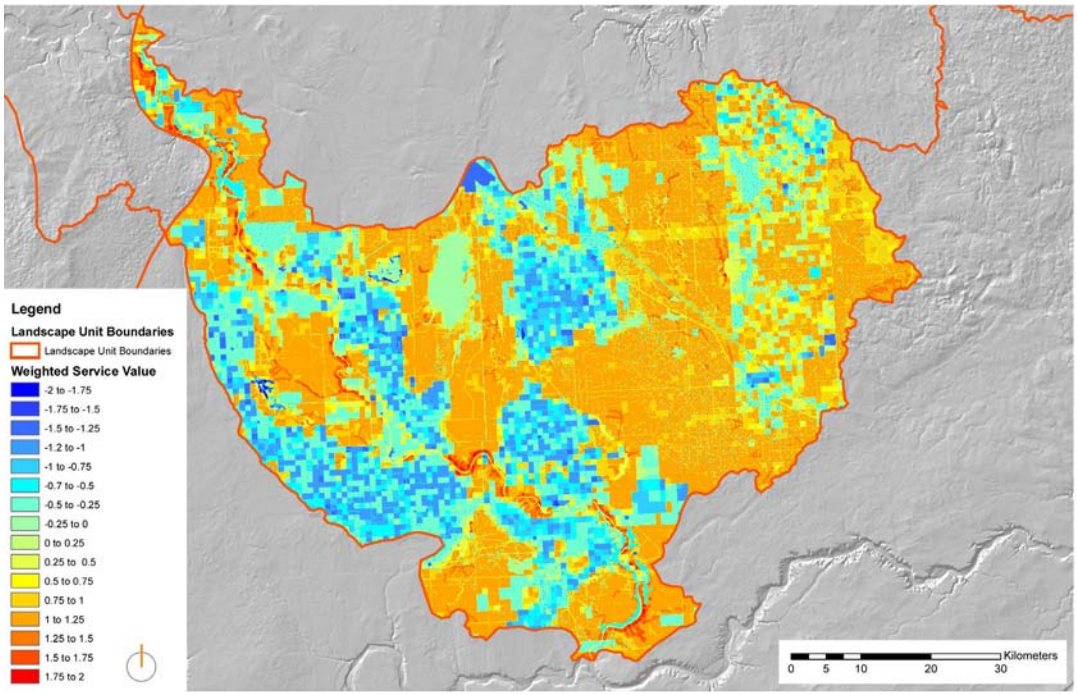


Figure 8-17 Coincidence of Analysis between Broad-Scale Indicators and EGS Hotspots

The next component of the synthesis was to analyze how well the broad-scale indicators captured EGS hotspots and vice-versa (Figure 8-17). The analysis shows that 99% of the EGS hotspots (value >1.00 on Figure 8-15) coincide with the broad-scale pattern indicators (Figure 8-16). Concordance between EGS hotspots and broad-scale pattern indicators is considered to be 85% for the Bow-Mixed Grassland LU.

Figure 8-18 Synthesis: The Existing Green Network: Bow-Mixed Grassland LU



The final step in the synthesis is to identify the existing Green Network of natural assets. A measure of importance for those areas within the Green Network should be captured and mapped. To conduct the analysis, numerical values for natural assets in the broad-scale indicators map (Figure 8-16) were first rescaled to range between 0 and 1. These rescaled values were then multiplied by the numerical values for the EGS hotspot map (Figure 8-15). Figure 8-18 displays the output map. This map provides the existing Green Network of natural assets that provide important EGS in the study area. The higher the value within the Green Network, the more important the area is for EGS provision.

Step 5. Set Targets for Broad-Scale Indicators

The maps discussed above provide examples of products that can help integrate EGS considerations into land use planning exercises. Further steps in the land use planning process would include integrating the above products with scientific information, land use planning tradeoff analyses, and desired land use outcomes. Throughout this process, desirable targets and thresholds for EGS indicators must be chosen.

Step 6. Gap Analysis

The maps discussed above provide information to assist in identifying key areas where improvements to the existing Green Network may be required in order to meet selected targets and thresholds for indicators. For example, there are obvious gaps where the regional corridor within the Bow River valley does not provide continuous permanent vegetated cover. Therefore, meeting identified targets for landscape connectivity may require targeted actions within those areas.

Step 7. Identify Threats

The next step in the framework is to identify and map potential future land use threats or stressors to the existing Green Network. In the context of the Bow-Mixed Grassland LU, threats might include:

- coalbed methane drilling in high-value areas of the Green Network (e.g., >0.8, Figure 8-18);
- any new proposed coal mining;
- new pipelines crossing high-value areas of the Green Network;
- expansion of irrigated cropland; and,
- urban or rural subdivision in the vicinity of the Town of Brooks.

Step 8. Prioritization

This step would consist of prioritizing areas within the Green Network that are highly valued and potentially threatened by existing or contemplated land uses. Within prioritized areas, finer-scale condition analysis should be conducted at a minimum in order to confirm asset condition and importance to EGS and to monitor changes over time. This will be particularly important where compensation is considered.

In the context of the Bow-Mixed Grassland, finer-scale condition analysis within prioritized areas might include measurements of:

- Range Health;
- Soil Organic Matter;
- Riparian Health;
- Trophic status of smaller reservoirs / lakes;
- Hydrological alteration indices;
- Fish-based IBI; and,
- Wetland water storage function capacity and wetland health scores.

Step 9. Management Actions

Within identified high priority lands, a range of guidelines, standards, zoning policies, and incentives can be designed. These must be appropriately designed to address the identified land use threat and the nature of the environmental impact on local, landscape-level, and regional ecological processes.

Summary

The approach described above allows for a staged analysis and mapping of EGS to support Regional Land Use Planning. In the short term, the broad scale analysis can be carried out using existing data sets while acknowledging that these data contain shortcomings. The analysis itself will help identify and prioritize areas of importance where data deficiencies exist and where finer scale work is required. Finer scale work will also be required to establish reference conditions for specific natural assets. This framework will allow for EGS work to inform the land use planning process while staging more demanding work.

8.2.1 Future Research + Adaptive Management

Applying the ecosystem services concept within land use planning can occur in the immediate future. Nonetheless, additional future research should address the following topics:

- Confirm the relationships between indicators and specific services;
- Explore methods for quantifying ecosystem service magnitudes;
- Describe asset conditions and ecosystem services in undeveloped/ pristine areas;
- Describe asset conditions and ecosystem services in heavily disturbed areas;
- Research and describe the effects of reclamation on ecosystem services; and,
- Research the relationship between broad and fine-scale indicators, including how fine-scale indicators can be used to inform and refine broad-scale landscape indicator targets and thresholds.

The best way to proceed with all of these research programs is to consider the relationships between an ecosystem service and a given landscape pattern or specific asset condition as a null hypothesis [35]. Applying this scientific approach to land use planning is an "adaptive management" approach, which is very useful in resource management circumstances where the knowledge base needs to be improved over time [359]. Adaptive management is a structured, iterative process of optimal decision making, with the aim of systematically testing assumptions, reducing uncertainty, and incorporating learning and adaptation over time. The approach is particularly useful for an ongoing process of evaluating management targets over time.

One major purpose of adaptive management should be to evaluate and test the validity of management targets for landscape indicators. One way to accomplish this is to probe the relationship between fine-scale and broad-scale indicators. Over time, data on fine-scale indicators can be compared against landscape indicator targets to determine whether these targets are appropriate. Adaptive management analyses should be done on an opportunistic basis using existing data sources and programs (see Appendix C), so that a wide range of fine-scale conditions at multiple scales are assessed and compared against landscape conditions. Any extra data collection efforts occurring within prioritized landscapes will serve to complement and strengthen these analyses.

In this way, over time, data collected on the fine-scale indicators can be used to validate targets set for broad-scale indicators and to improve scientific understanding of the linkages between fine-scale conditions and landscape conditions. This is important because thresholds and targets for many landscape indicators have been derived from regions with a different

climate and geography from Alberta [1, 13].

Many potential cross-scale adaptive management analyses could be undertaken. For example, the degree to which landscape composition metrics can indicate biological control services in agricultural landscapes could be assessed through statistical analyses of landscape connectivity and patch size metrics vs. ABMI data on groups of organisms important to ecosystem services (e.g., bird and bat species that feed on insect pests). Many possibilities also exist, as summarized in Table 8-7, which provides a matrix of landscape indicators and fine-scale indicators reviewed in this report. The matrix represents hypotheses of relationships between indicators. If a relationship between a landscape indicator and a site specific indicator has been established and documented in the literature, two checkmarks are placed in the corresponding cell (e.g., % impervious surface affects lotic river water quality). If a landscape indicator is likely to influence a site-specific indicator, one checkmark is placed in the corresponding cell. For all landscape variables considered to be independent from site-specific variables, an '×' is placed in the corresponding cell. The matrix provides a

list of hypotheses for future adaptive management.

Table 8-8 Matrix of cross-scale relationships between broad and fine-scale indicators

	BROAD-SCALE INDICATORS								
FINE-SCALE INDICATORS	Total Proportion of Natural Assets	Proportion of Wetlands	Proportion of Landscape-Specific Natural Assets	Proportion of Impervious Surfaces	Habitat Diversity	Patch Size	Road Density	Connectivity	Riparian Buffers
Grassland Range Health	✓	✗	✓	✗	✗	✓✓	✓	✓	✗
Grassland Soil Organic Matter	✗	✗	✓	✗	✗	✓	?	?	✗
Forest Canopy Structure	✗	✗	✗	✗	✓	✓	✓	?	✗
Forest Dead Wood Resources	✗	✗	✗	✗	✓	✓	✓	?	✗
Forest Age Class Distribution	✗	✗	✓	✗	✓	✓	✓	?	✗
Forest Tree Crown Condition	✗	✗	✗	✗	✓	✓	✓	?	✗
Riparian Health Index	✓	✓	✓	✓	✓	✓	✓	✓✓	✓
Lentic Water Levels	?	?	✓	✓	✗	✓	✗	?	✓
Lentic Trophic Status	✓	✓	✓	✓	✗	✓	✓	✓	✓
Lotic River Water Quality Indices	✓	✓	✓	✓✓	✗	✓	✓	✓	✓
Lotic Hydrological Alteration Indices	✗	✓	✓	✓✓	✗	✗	✗	✗	✗
Lotic Fish-Based Index of Biological Integrity	✓	✓	✓	✓✓	✗	✓	✓✓	✓	✓
Wetland Water Storage Index	✓	✗	✗	✓	✗	✗	✓	✗	✗
Wetland Health Score	✓	?	✓	✓	✓	✓	?	✓	✓
Future Groundwater Indicators	✓	✓	✓	✓	✗	✓	✓	✓	✓

✓✓=Relationship established or highly certain
✓=Direct relationship can be hypothesized
✗= Independent variables/ unlikely to be directly related
?=not enough information

8.3 Conclusions and Recommendations

To synthesize this report, the following summary points are derived from the study:

- Indicators of ecosystem services at the landscape scale (landscape composition, landscape configuration) and at the patch scale (ecological quality) were evaluated according to defined criteria.

- Landscape-scale indicators can be used to prioritize locations for measuring fine-scale indicators. In landscapes where identified targets are being approached, more intensive site sampling can be conducted to obtain a better picture of changing ecosystem conditions and ecosystem services.

- Each landscape is unique and requires different target values for indicators as based on the desired outcomes for the Land Use Framework. The selection of targets for indicators should be based on known ecological thresholds. If clear ecological thresholds cannot be identified, target selection can be informed by expert opinions and stakeholder input, paleoecological studies, or current baseline conditions.

- Fine-scale measures of ecosystem services can be used to test the validity of broad-scale indicators of landscape composition and patterns in an adaptive management approach. Many different relationships could be explored (e.g., patch size vs. insect-eating bird diversity, impervious area vs. fish-based index of biotic integrity, impervious area vs. lake trophic status, etc.)

- Support for the Land Use Framework Planning Process is feasible in the short term (1-2 years). Broad scale analysis can be conducted and the approach outlined in section 8.2 is suggested for the South Saskatchewan Study area.

In addition, recommendations for applying this framework can be broken down into discrete manageable chunks based on short term (immediate steps), medium term (1-5 years), and long term (>5 years) actions. Possible steps to be taken at each stage are shown in Table 8-9.

Table 8-9 Recommended short-, medium- and long-term actions for implementing the assessment framework

SHORT-TERM ACTIONS (IMMEDIATE)
1. Seamless GIS coverage of the region stitched together from existing information (e.g., GVI, AVI, Central Parkland Vegetation Inventory). For areas without existing information, supplement with classified SPOT imagery to provide a seamless high-resolution land cover map of the region. A method for cross-walking between datasets is needed.
2. Assess broad scale landscape indicators
3. Set targets for indicators within each landscape unit using a variety of information sources (e.g., baseline analyses from #2 above, known ecological thresholds, relevant targets from other jurisdictions, natural range of variability)
4. Compare simple landscape indicators against management targets

MEDIUM-TERM ACTIONS (1-5 YEARS)
1. Assess all landscape indicators and compare results to management targets
2. Focus fine-scale data collection efforts based on identified priorities
3. Ensure ecosystem services are fully considered in the Land Use Framework planning process
4. Research linkages between fine and broad scales in an adaptive management framework
5. Consider the application of economic valuation to assist in ecosystem service assessment

LONG-TERM ACTIONS (5+ YEARS)
1. Use research program outcomes for adaptive management and refocusing management targets
2. Assess landscapes (mapping and analysis) at least once every five years
3. Make the ecosystem services framework more explicit, including consideration of primary demand areas for human beneficiaries, scarcity of particular assets in the landscape, availability of complementary or substitutable inputs, risks and changed conditions (future benefits), equity and distributional concerns [43]

The list of recommended indicators can also be placed along a timeline, from those that can be assessed immediately with minimal data processing, and those that require further data collection, processing, and research. Short-term, medium-term and long-term priority indicators are summarized in Table 8-10. It is recommended that all indicators are reassessed at a minimum of at least once every five years. However, in cases where this is not feasible, longer periods between assessments may be possible. In other cases, simpler indicators should be tracked more frequently (e.g., once every two years).

Table 8-10 Prioritization of indicators based on data availability

Indicator		Data Available	Processing Required	Notes
Short-term				
Landscape composition	Proportion of total natural assets	GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover Mapping, Provincial Wetland Inventory	developing seamless coverage for region	
	Proportion of wetlands	GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover Mapping, Provincial Wetland Inventory	developing seamless coverage for region	
	Proportion of specific natural assets	GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover Mapping, Provincial Wetland Inventory	developing seamless coverage for region	
	Proportion of impervious surfaces	GVI, AVI	estimations of IS from existing data	
Landscape pattern	Patch size	GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover Mapping, Provincial Wetland Inventory	developing seamless coverage for region	use rough targets based on biodiversity
	Riparian Buffers	AENV 2008 Assessment of Riparian Zones in Southern Alberta using aerial video ASRD mapping of riparian areas in forested regions (2008-09) GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover Mapping	calculating width statistics for riparian corridors developing seamless coverage for region	

Indicator		Data Available	Processing Required	Notes
Medium-term				
Landscape composition	Proportion of impervious surfaces		refine estimates from remote sensing coverages	refine targets for IS in different landscapes
	Habitat diversity	ABMI	set metrics to be used and work into ABMI data	define targets for different landscapes
Landscape pattern	Patch size			refine targets using ecosystem functions/ services, i.e., minimum area point, minimum dynamic area
	Road density	GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover Mapping, new SPOT data set	developing seamless coverage for region calculations from datasets	
	Connectivity	GVI, AVI, Central Parkland Native Vegetation Inventory, Montane Bioregion Landcover existing spatial analysis software (e.g., FRAGSTATS)	developing seamless coverage for region obtaining spatial statistics software and running applications	
Ecological Quality	Range Health Assessment Score (grasslands, prairie shrub, badlands, forest shrub)	GVI shows extent of native prairie and assigns reference Ecological/ Range Sites	field sampling	
	Soil organic matter (grasslands, prairie shrub)	ABMI will be collecting data on soil carbon	translate soil carbon into measures of soil organic matter field sampling where necessary	
	Canopy structure (deciduous and mixedwood forest)	AVI and Montane Bioregion Landcover Mapping contain information on species composition, height and age classes	field sampling where required	
	Age class distribution (coniferous forest)	AVI and Montane Bioregion Landcover Mapping contain information on species age classes	field sampling where required	
	Riparian Health Index (riparian)	Cows and Fish have conducted riparian health inventories on sites across Alberta	field sampling where required	
	Water level of lentic water bodies	Water levels are regularly measured on many Alberta lakes		
	Chlorophyll-a (lentic)	AENV (many water bodies) ABMI lake program (administered by ACA) Community watershed groups	compiling data from various sources field sampling as required	
Cross-scale Indices	Alberta River Water Quality Sub-indices (lotic)	Alberta Long Term River Network Monitoring Sites	extracting sub-indices field sampling as required	
	Hydrological Alteration Sub-indices (lotic)	monitoring stations across Southern Alberta	extracting sub-indices field sampling as required	
	Carbon Management Index	ABMI will be collecting data on soil carbon	translate soil carbon into measures of soil organic matter field sampling where necessary developing seamless coverage of region	
	Primary productivity estimated by remote sensing	Canadian Centre for Remote Sensing NDVI data	analysis of spatial resolution and seamless coverage processing to derive primary productivity	

Indicator		Data Available	Processing Required	Notes
Long-term				
Ecological Quality	Presence and abundance of dead wood resources (deciduous and mixedwood forest)		field sampling program developed and implemented	
	Tree crown condition (coniferous forest)		field sampling program developed and implemented	
Ecological Quality continued	Fish-based Index of Biotic Integrity (lotic)	use methods from existing IBI programs	field sampling program developed and implemented	
	Water Storage Functional Capacity Index (wetlands)	use methods from U.S. Army Corps of Engineers	field sampling program developed and implemented	
	Ice Quality (geological)		field sampling program developed and implemented	may use if desired, but not a priority
	Groundwater			indicators and targets to be developed and assessed in the future

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LIST OF ABBREVIATIONS

ACA	Alberta Conservation Association
AENV	Alberta Environment
AESA	Alberta Environmentally Sustainable Agriculture
ABMI	Alberta Biodiversity Monitoring Institute
AGRASID	Agricultural Region of Alberta Soil Inventory Database
ARWQI	Alberta River Water Quality Index
ASRD	Alberta Sustainable Resource Development
AVHRR	Advanced Very High Resolution Radiometer
AVI	Alberta Vegetation Inventory
CAF	Cows and Fish
CCRS	Canadian Centre for Remote Sensing
CMI	Carbon Management Index
CPI	Carbon Pool Index
DBH	Diameter at Breast Height
EC	Environment Canada
EGS	Ecosystem Goods and Services
ENN	Euclidean Nearest Neighbour
ERCB	Energy Resources Conservation Board
ESTR	Ecosystem Status and Trends Reporting
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FCI	Functional Capacity Indices (wetlands)
FMA	Forest Management Area
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GPP	Gross Primary Production
GVI	Grassland Vegetation Inventory (Alberta)
HANPP	Human Appropriation of Net Primary Production
HCL	Hydrogeological Consultants Ltd.
IEL	Integrated Environments (2006) Ltd.
IFN	Instream Flow Needs
IGBP	International Geosphere-Biosphere Programme
IHA	Indicators of Hydrological Alteration
IRS	Indian Remote Sensing
IS	Impervious Surface
LAI	Leaf Area Index
LI	Lability Index (Carbon)
LIDAR	Light Detection and Ranging
LU	Landscape Unit
LUF	Land-Use Framework
MODIS	Moderate Resolution Imaging Spectrometer
NDVI	Normalized Difference Vegetation Index
NPVI	Native Prairie Vegetation Inventory
NRC	Natural Regions Committee (Alberta)
NRV	Natural Range of Variability
NRVI	Normalized Ratio Vegetation Index
NS	Natural Subregion
O2	O2 Planning + Design Inc.
OECD	Organisation for Economic Co-operation and Development
PCAP	Prairie Conservation Action Plan

PPR	Prairie Pothole Region
RHI	Riparian Health Index
SAL	Southern Alberta Landscapes
SARP	Southern Alberta Regional Plan
SPOT	Satellite Pour L'Observation de la Terre
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
TM	Thematic Mapper (Landsat)
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WCO	Water Conservation Objectives
WHI	Wetland Health Index

GLOSSARY OF TERMS

Adaptive management A structured, iterative process of optimal decision making, with the aim of systematically testing assumptions, reducing uncertainty, and incorporating learning and adaptation over time.

Anthropogenic asset A man-made asset which occupies areas of former natural assets.

Asset Refers to something valuable or useful. In this study, 'asset' refers to land cover types.

Chlorophyll-a Photosynthetic pigment present in algae and plants.

Configuration Specific arrangement of spatial elements; often used synonymously with spatial structure or patch structure [352].

Connectivity The degree to which the landscape facilitates or impedes the flow of energy, materials, nutrients, species and people across the landscape [199].

Contagion A landscape pattern metric that quantifies the degree to which land cover types occur in clumped distributions as opposed to being dispersed in many smaller fragments [199].

Corridor A corridor can be defined structurally as a narrow strip of land which differs from the matrix on either side or, functionally, as a wildlife movement corridor, barrier, or filter corridor.

Cover type Category within a classification scheme defined by the user that distinguishes among the different habitats, ecosystems, or vegetation types on a landscape [352].

Ecological quality Specific biological, chemical, or physical attributes of a natural asset or ecosystem.

Ecosite phase Finely detailed ecological land classification based on dominant tree species or variations of specific environmental influences. Ecosite phases have a distinct range in tree canopy composition and understory floristic. Differences in the phases of the same ecosite may be expressed as differences in plant species abundances or pedogenic processes.

Ecosystem function The ability of earth's processes to sustain life over a long period of time [13].

Ecosystem goods The products or outputs obtained and consumed from the environment.

Ecosystem services The conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life [95].

Edge Portion of an ecosystem or cover type near its perimeter and within which environmental conditions may differ from interior locations in the ecosystem; also used as a measure of the length of adjacency between cover types on a landscape [352].

Edge contrast A basic measure of the amount of contrast between adjacent land cover patches, where contrast must be defined for each application based on one or more attributes of interest (e.g., floristics, vegetation structure, hydrography).

Edge species Species occurring primarily or only near the border of a spatial element.

Eutrophic "Well-nourished" or high productivity water bodies.

Eutrophication A process whereby water bodies receive excess nutrients that stimulate excessive plant growth (algae, periphyton attached algae, and nuisance weeds). This enhanced plant growth, often called an algal bloom, reduces dissolved oxygen in the water when dead plant material decomposes and can cause other organisms to die.

Evapotranspiration The sum of evaporation and plant transpiration of water into the atmosphere.

Floodplain The area adjoining a river channel which overflows at times of high discharge. This is often considered as the area subjected to a 1 in 100 year flood based on past climate and hydrological statistics.

Fragmentation Breaking up of a habitat or cover type into smaller, disconnected parcels [352].

Groundwater Recoverable water that occupies voids in the subsurface.

Hydrogeomorphic Approach US Army Corps of Engineers method for developing wetland functional indices and the protocols used to apply these indices to assess wetland functions at a site-specific scale.

Indicator Measurable surrogates for environmental end points of value to the public [255].

Interior Species Species occurring primarily or only distant from the border of a spatial element.

Landscape A heterogeneous land area composed of a cluster of interacting ecosystems or patches that is repeated in similar form throughout.

Landscape composition The types and amount of natural and anthropogenic assets or land cover types within a landscape mosaic.

Landscape design Intentional change of landscape pattern, for the purpose of sustainably providing ecosystem services while recognizably meeting societal needs and respecting societal values [249].

Landscape metrics Algorithms that quantify specific landscape characteristics [199].

Landscape pattern The sizes, shapes, distribution, and spatial relationships between land cover types in a landscape mosaic.

Land cover Biophysical aspects of the land's surface including vegetation, water, bare rock, soil, and anthropogenic assets.

Land use Any human use of land that alters the land from its natural state.

Lentic Aquatic systems consisting of standing water (lakes, ponds, reservoirs)

Lotic Aquatic systems consisting of flowing water (streams, rivers)

Matrix The background ecosystem or land-use type in a mosaic, characterized by extensive cover, high connectivity, and/or major control over dynamics [128].

Mesotrophic Moderately productive water bodies.

Minimum area point Area where an abrupt change in slope takes place on a species-area curve [128] .

Minimum dynamic area Patch size required so that natural disturbance regimes will not eliminate a species within the patch [128].

Natural asset The stock of valuable natural resources from which many goods and services are derived. In this report, they have been categorized into native prairie, forest, aquatic, and geological assets.

Oligotrophic "Poorly-nourished" or low productivity water bodies.

Patch A relatively homogeneous nonlinear area that differs from its surroundings [128].

Reference Wetlands A group of wetlands that encompass the known range of variability in the regional wetland subclass resulting from natural processes and human alteration [138].

Region A broad geographical area with a common macroclimate and sphere of human activity and interest [128].

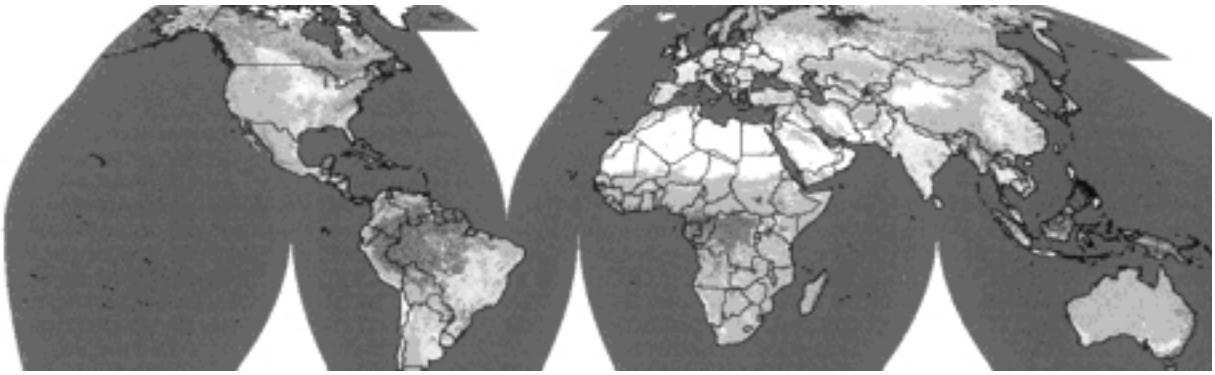
Scale Spatial or temporal dimension of an object or process, characterized by both grain and extent [352].

Stream order The number assigned to a particular stretch in a dendritic river system and determined by the numbers assigned to upstream tributaries (e.g., two 3rd-order streams coalesce to form a 4th-order stream).

Threshold A critical value of an ecosystem property or landscape attribute at which sudden, non-linear and often irreversible change occurs.

Watershed A topographically delineated area drained by a stream or river system [50].

APPENDIX A: LITERATURE REVIEW METHODOLOGY



A.1 Methods

The ISI Web of Knowledge (ISI) online database was utilized as the main search engine to perform an up-to-date literature review on ecosystem services. The ISI database is well suited for interdisciplinary research, as it simultaneously conducts searches in the Science Citation Index, the Social Science Citation Index, and the Arts & Humanities Citation Index. Additional sources of information included books, journal articles, and reference materials in the personal library of the project team.

Key word selections in the ISI database search were designed to highlight: (a) services identified as priorities in the *Phase 2 Report* [165] (b) indicators of ecosystem condition and services, (c) research on threshold conditions for ecosystem service provisioning, and (d) natural asset types occurring in southern Alberta. The results were also intended to provide a reasonable sample of the range of published articles applying the ecosystem services concept. With these objectives in mind, the following key word searches were conducted using ISI:

Ecosystem service* AND indicator*
Ecosystem service* AND climate regulation
Ecosystem service* AND erosion control
Ecosystem service* AND sediment retention
Ecosystem service* AND biological control
Ecosystem service* AND nutrient cycling
Ecosystem service* AND primary productivity
Ecosystem service* AND water supply
Ecosystem service* AND recreation
Ecosystem service* AND Alberta
Ecosystem service* AND Canada
Ecosystem service* AND Canada* prairie*
Ecosystem service* AND prairie
Ecosystem service* AND Rocky Mountain Foothills
Ecosystem service* AND fescue
Ecosystem service* AND riparian
Ecosystem service* AND badland
Ecosystem service* AND hardwood forest
Ecosystem service* AND mixedwood forest
Ecosystem service* AND parkland

Ecosystem service* AND spruce fir forest
Ecosystem service* AND pine forest
Ecosystem service* AND lentic
Ecosystem service* AND lotic
Ecosystem service* AND wetlands
Ecosystem service* AND ice
Ecosystem service* AND glacier
Ecosystem service* AND traditional knowledge
Ecosystem service* AND indigenous Alberta
Ecosystem service* AND indigenous Canada
Ecosystem service* AND aboriginal Canada
Ecosystem service* AND aboriginal Alberta

Results were screened to focus on key articles with high potential utility for assessing natural asset condition in an ecosystem services theoretical framework. Articles lacking a specific analysis of ecosystem services were screened out (e.g., general biodiversity research). Articles that did not focus on one of the identified priority services were also screened out. For several publications of interest, the ISI citation mapping tool was utilized to browse for additional articles that either cited the publication (forward citation map), or was cited by the publication (backward citation map).

Search results judged as relevant and useful were input as data entries in a Microsoft Access database, in order to enable future queries, sorting, and generation of summary statistics. Database fields included:

- Research_Database: method used to locate the article
- Search_Criteria: article search criteria used
- Reference: citation
- Journal: journal of publication
- Journal_Impact: journal's impact factor in Journal Citation Reports[1]
- Location: location of the study (e.g., country, state, county, etc.)
- Scale: scale of study (categorical)[2]:
    - site (plots or detailed site surveys)
    - landscape (<2000 km^2)
    - regional (> 2000 km^2)
- Scale_Comments: additional written details on scale
- Asset_1, Asset_2, Asset_3: natural asset types (categorical):
    - Multiple/Complex Landscape
    - Badlands and Thin Breaks
    - Forest-Deciduous/Mixed Wood
    - Forest-Coniferous
    - Forest-Other/Unspecified
    - Forest Shrub
    - Grassland-Fescue
    - Grassland-Mixed

1 The journal impact factor is a measure of the frequency with which the "average article" in a journal has been cited in a particular year. The impact factor helps to evaluate a journal's relative importance, especially when comparing it to others in the same field.
2 The 'landscape' category encompasses a relatively wide range of scales, including both subregional landscapes (~50 to 2000 km2) and local landscapes (~1 km2 to 50 km2).

    - Grassland-Other/Unspecified
    - Geological
    - Lentic
    - Lotic
    - Prairie Shrub
    - Riparian
    - Wetlands-Prairie
    - Wetlands-Forest
    - Wetlands-Other/Unspecified
- Other_Assets: Additional assets assessed in the paper
- Service_1, Service_2, Service_3: ecosystem service types (categorical, based on identified priorities in *Phase 2 Report*):
    - Climate regulation
    - Disturbance regulation
    - Erosion control/sediment retention
    - Biological control
    - Nutrient cycling
    - Primary production
    - Water Supply
    - Recreation
    - *Other (non-priority)
- Other_Services: Description of additional services assessed by the paper
- Goals_Objectives: Stated goals/objectives of the study, or what is being measured by identified indicators
- Performance_Indicators: Quantitative indicators of asset condition or ecosystem services
- Desirable_Conditions: Any reference to 'optimum' or desirable endpoint conditions
- Thresholds: Any reference to threshold values beyond which major unacceptable changes occur (non-linear ecosystem 'flips', major changes to asset condition, degradation of ecosystem services, etc.)
- Comments: Any additional notes drawing attention to important or interesting aspects of the article

Database fields were filled out primarily based on the abstract for each article. If the abstract did not provide a sufficient level of detail, the entire article was scanned to complete the fields. In addition, articles containing specific information on indicators or thresholds were reviewed to a greater level of detail.

Review articles or theoretical articles that did not analyze any particular geographic area were saved as PDF files for future reference, and did not appear in the database due to a lack of appropriate fit with the searchable data fields.

A.2 Results

The original Microsoft Access database contained 257 records of recently published articles addressing ecosystem services. This has since been expanded to include additional literature referenced in the report since the September submission of the literature review report. The final database contains over 500 records. The database has functionality for a range of applications not only for this project, but also for diverse research projects in the future. Articles can be sorted and the database can be queried using criteria such as location, scale, natural asset types, and ecosystem service types. The database can also assist users to summarize which indicators have been applied (directly or indirectly) to measure specific ecosystem services and/or the condition of specific asset types. It can also be used as a scoping tool to determine how to address complicated issues such as defining 'optimal' or 'desirable' conditions for natural assets, or thresholds and targets related to ecosystem dynamics or ecosystem service degradation. The database can also undergo organic growth or improvement, by, for example, adding new publications periodically, or elaborating on existing database entries after conducting more in-depth reviews. Figures A-1 through A-7 summarize general information on trends identified by the initial literature review.

Figure A-1 illustrates the rapid recent growth in research publications applying the ecosystem services framework. Prior to 1991, no relevant articles explicitly assessed ecosystem services. Our sample of the literature indicates a rapid growth in publication rates beginning in 2004.

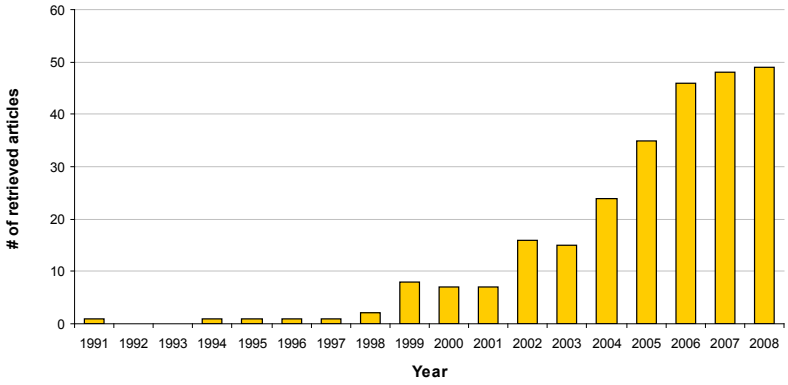


Figure A-1 Time series of retrieved articles on ecosystem services

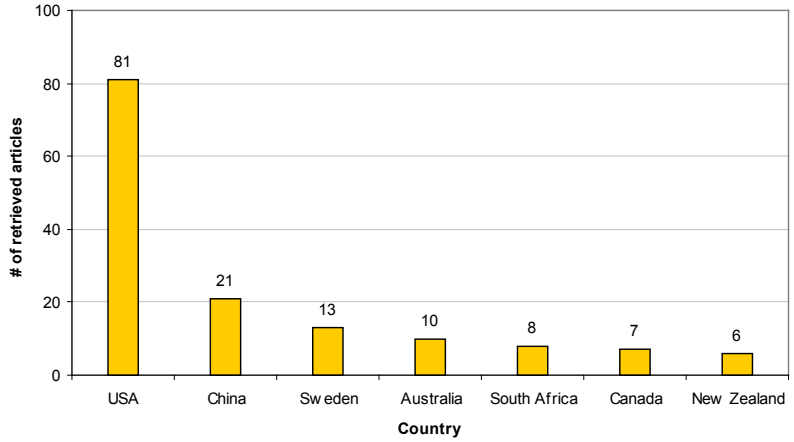


Figure A-2 Leading countries conducting ecosystem services research[1]

[1] Note that local institutional sources in Alberta (e.g., Cows and Fish, ASRD) are not included in this graphical summary.

Figure A-2 illustrates which countries are most heavily involved in publishing research on ecosystem services and asset condition. The majority of publications have been focused in the United States. This trend originated in the mid-1990s [85, 97] when two Americans published articles on the topic. More recently, China has emerged as a leading centre of research on this topic. Sweden, Australia, South Africa, Canada, and New Zealand are also leaders of research on this topic (Figure A-2). On a per capita basis, Sweden and Australia appear as leaders in publication output on ecosystem services. Notably, the ISI search for "Ecosystem service* AND Alberta" did not reveal results on the identified priority services. However, it did locate two notable articles on pollination services, including analyses of interactions between habitat, bee abundance, and canola yields [240, 241].

Figure A-3 summarizes which journals most frequently publish research on ecosystem services assessments. There are generally no journals dominating this field of publication. This is a reflection of the highly interdisciplinary nature of research on ecosystem services. The majority of retrieved articles were published in journals that encourage an interdisciplinary, policy-oriented focus, including *Ecological Economics* (7%), *Environmental Management* (4%), and *Ecological Applications* (3%). However, articles were retrieved from over 128 different journals across a wide spectrum of disciplines, including agricultural research (e.g., *Agriculture, Ecosystems and Environment*), biological research (e.g., *Ecology Letters, Aquatic Botany)*, conservation biology (e.g., *Biological Conservation*), forestry (e.g., *Forestry Chronicle*), the physical sciences (e.g., *Geomorphology, Atmospheric Environment),* water resource management (e.g., *Water Resources Research)*, and urban planning (e.g., *Landscape and Urban Planning*).

Figure A-4 indicates that the majority (43%) of articles on ecosystem services and asset condition address the landscape scale. Fewer articles address the regional scale or the site scale. Several articles (2%) assess ecosystem services at the global scale.

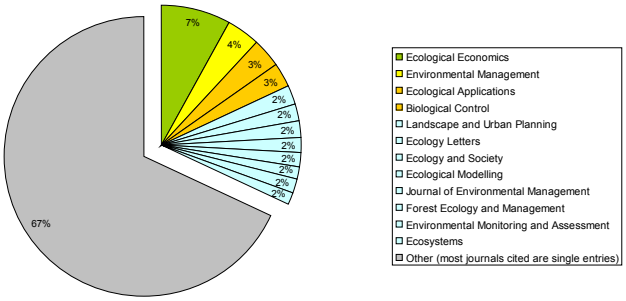


Figure A-3 Top journals publishing ecosystem services research

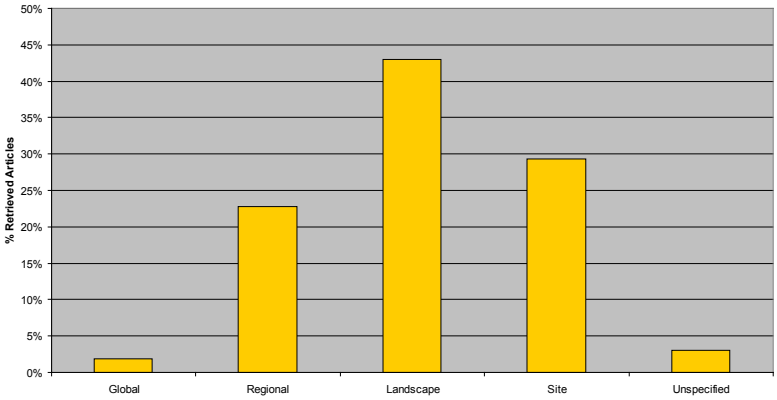


Figure A-4 Scale of analysis in literature review

Figure A-5 illustrates that researchers typically analyzed either more than three natural assets (landscape studies), or focused on one specific natural asset. Fewer papers examined two or three specific assets.

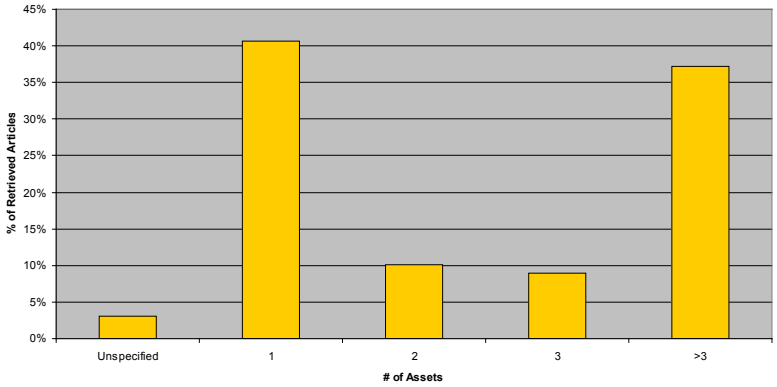


Figure A-5 Number of natural assets assessed in literature review

Figure A-6 illustrates that aquatic systems (lotic, lentic, or wetland systems) were the most analyzed asset type, followed by forests, grasslands, riparian areas, and geological assets (primarily soils).

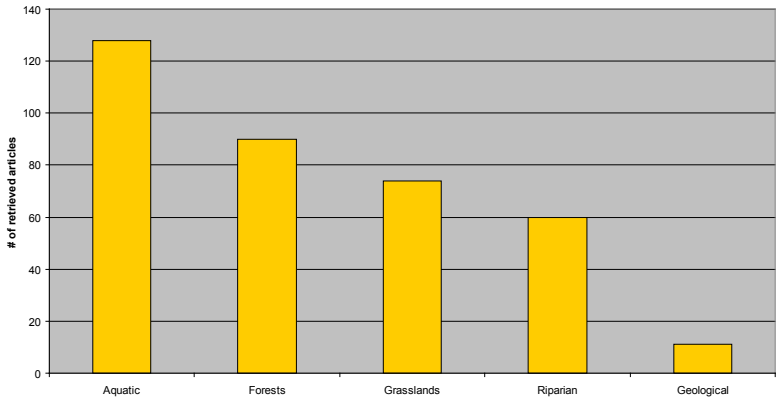


Figure A-6 Types of natural assets assessed in literature review

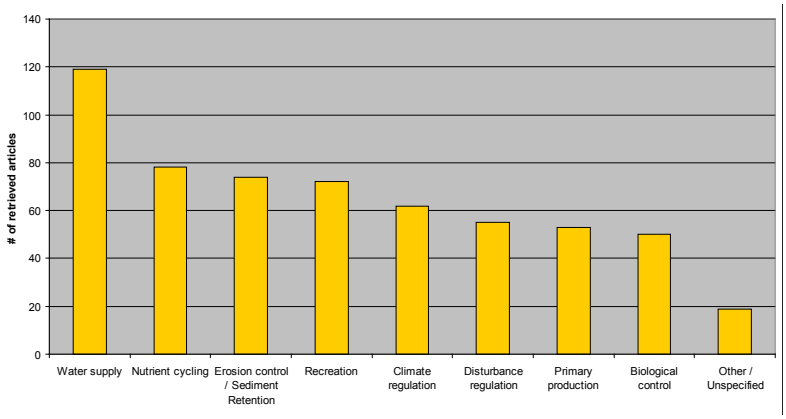


Figure A-7 Ecosystem services assessed in literature review

Figure A-7 summarizes which ecosystem services were analyzed in the sample of the literature. Although water supply was most commonly analyzed, no category dominated the results. In addition, the majority of papers (74%) addressed more than one type of ecosystem service, reflecting the multi-disciplinary, integrative nature of ecosystem services research.

Only four articles in the database referred to quantitative values for ‘optimal’ conditions. On the other hand, many articles did refer in one way or another to “desirable” conditions. Along a similar vein of thought, 16% of papers in the database referred to some type of ‘threshold’ beyond which ecosystem dynamics and/or ecosystem services degraded considerably.

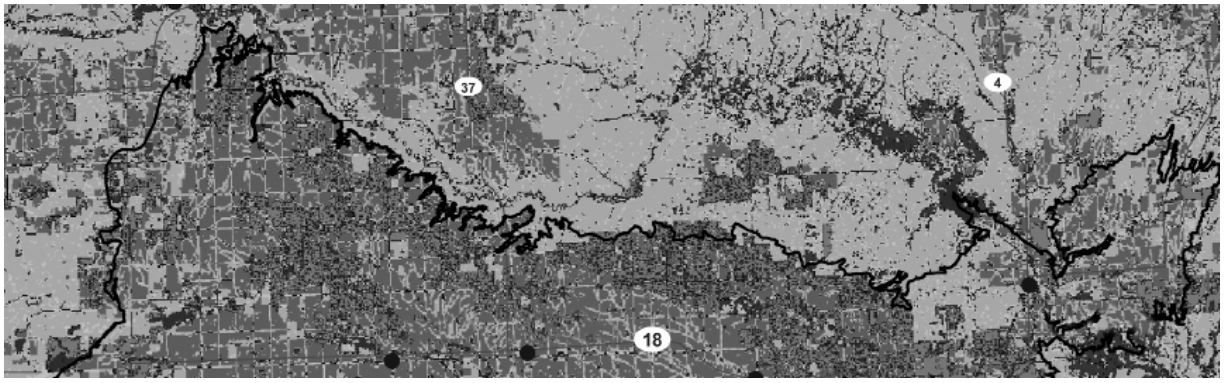
In addition to the MS Access database, several important general review articles addressing ecosystem services were also located during the literature review. These included review articles regarding:

- water-related ecosystem services [46, 291];
- wetland ecosystem services [383];
- water quality services performed by riparian buffers [26];
- soil-related ecosystem services [28, 50, 186, 267];
- the role of soil invertebrates in providing ecosystem services [199];
- nitrogen cycling and plant root systems [169];
- ecosystem services and agricultural lands [332];
- responses of woody plants to environmental stresses [192];
- regime shifts and non-linear ecosystem dynamics [129];
- restoration of ecosystems and related services [221];
- applying landscape ecological metrics in landscape planning [201]; and,
- the role of ecosystem services in global production systems [32].

APPENDIX B: ADDITIONAL POTENTIAL FUTURE INDICATORS OF ASSET CONDITION

Table B-1 Potential future indicators of ecosystem services

Asset Type	Potential Future Indicator	Reference / Justification
Landscape-scale	Human appropriation of net primary production (HANPP)	Wrbka et al. 2004
Grasslands	Phospholipid fatty acid (PLFA) profiles in soil biota	Kaur et al. 2005
	Water yields (transpiration losses)	Mark and Dickinson 2008
Deciduous forest	Litter depth (typically deeper in deciduous than coniferous forest)	
	Biomass	Bork and Su (2007) integrated LIDAR (Light Detection and Ranging) data with multispectral imagery for enhanced classification of rangeland vegetation in the Aspen Parkland ecosystem of Alberta, including quantification of condition aspects such as vegetation height, cover and biomass. Their method had high classification accuracy for bare ground, shrubland, grassland, and riparian meadows
	Carbon sequestration	Farley 2007
	Green plot ratio (the average leaf area index on urban sites)	Ong 2003
Coniferous forest	Distribution of forest fire patch size	
	Area and severity of fire and pest/pathogen outbreaks	
	Amount and extent of soils with erosion, compaction and puddling risk and mass wasting potential	
	Species composition by canopy layer (e.g., distinguishes between pioneer species such as pine or climax species such as white spruce)	
	Diameter of trees (relates to habitat provision functions)	
Riparian	Mediation of flood control	Sedgwick and Knopf 1991
Lentic	Algal indicators	
	Water temperature (affects seasonal mixing regimes and fish habitat)	Meyer et al. 1999
Lotic	Dissolved oxygen changes (as a measure of ecosystem metabolism)	Bott et al. 2006
Wetlands	Frost events in adjacent land	Marshall 2003
	Methane emissions	Duan et al. 2005



C.1 Alberta Biodiversity Monitoring Institute

The Alberta Biodiversity Monitoring Institute (ABMI) monitors species, habitats, and ecosystems in Alberta [8]. More than 5,000 species and habitats are tracked using both remote sensing and field sampling protocols at 1,656 terrestrial sites distributed evenly across the province by using a 20 km grid spacing. Terrestrial sites are 1 ha each in size. Field crews collect data on both species and habitats. The goal is to complete winter, spring, and summer surveys at each of 340 sites annually, and to return to each site at least once every five years [8].

Separate data collection protocols have been developed for terrestrial ecosystems, wetlands, lakes, rivers, and streams. Wetlands are sampled by defining the 10 closest permanent wetlands to the grid, and then randomly selecting one of these wetlands. In lotic and lentic habitats, the Alberta Conservation Association (ACA) conducts sampling of fish species as well as some select physicochemical parameters. The goal is to sample 105 lakes and 105 rivers based on an 80 km provincial sampling grid (Jim Herbers, personal communication).

After undergoing quality control, ABMI data are publicly available in a raw data format. The ABMI raw data currently includes access to terrestrial prototype data (2003-2006), as well as terrestrial, wetland, lake, and river data from 2007. The on-line Biodiversity Browser includes access to all ABMI sites sampled. Sites at which each species has been detected are highlighted. The Biodiversity Browser also provides species descriptions, life history information, and Alberta and North American distribution range maps. The GIS mapping application allows users to select particular regions of Alberta so that data can be filtered depending on the area of interest.

To date, ABMI data collection efforts have been focused in northern Alberta. During the four year prototype rotation period (2003-2006), all 125 of the ABMI terrestrial sites surveyed were located north of Edmonton in the boreal forest. During the 2007 sampling season, the majority of terrestrial sites were also located in the boreal forest. Exceptions included five sites northeast of Medicine Hat and four sites west of Lethbridge in the Grassland Natural Region, as well as three sites south of Hardisty in the Parkland Natural Region, and one winter snow tracking site west of Rocky Mountain House in the foothills [8].

For habitat monitoring through remote sensing, ABMI tracks trends in two distinct components of landscape status: 1) changes in habitat area (in hectares) for 130 natural landscape elements, and 2) changes in landscape configuration (pattern metrics) for major vegetation types. The presence, location, and extent of habitat area for each element is determined by manually interpreting air photos (1:20,000 scale) based on a 4 km x 8 km rectangle centred on the ABMI site. Following interpretation, landscape configuration metrics are derived from digitized imagery using FRAGSTATS. Indices for area and configuration are derived separately and then combined within quantification protocols for a Landscape Habitat Index (*LHI)* [9]. ABMI classifies 181 elements on the landscape; including those that occur naturally (n=130), and those created by humans (n=61) [9]. A review of the types of natural elements tracked by ABMI reveals that this index is only suitable for forested areas (boreal forest, foothills).

In addition to raw data, ABMI also reports on status, trends, and associations. Status reports describe biota and habitats for each region measured by degree of "intactness", or deviation from reference conditions. Trends describe the percentage change in biota and habitats over time, including reference state and indices graphed over time. Associations provide correlations between biodiversity and human activity (e.g., road density dose-response relationships).

ABMI also organizes data into information pyramids to enable aggregation and simplification of biodiversity data. Lowest levels in the pyramid consist of species-specific information and data, whereas higher levels in the pyramid consist of groups of data based on habitat guilds or taxonomy.

C.2 ASRD Rangeland Health Assessments

Rangeland in Alberta within native forest, native grassland, and tame pasture is assessed visually using field surveys on public lands (e.g., grazing leases) as well as private rangelands. The approach uses a visual assessment of plant community types in relation to reference native plant communities. The reference plant community is the potential natural community for the site under light grazing disturbance. Data is collected in the field for a number of parameters, which are subsequently integrated into a Range Health score which is used as an indicator of overall rangeland health. The parameters as well as the overall Range Health score are meant to capture the functions of healthy rangeland, including productivity, site stability, capture and beneficial release of water, nutrient cycling, and plant species diversity [3].

The Range Health score is used to partition sites into one of three categories: Healthy, Healthy with Problems, or Unhealthy, as follows [3]:

- Healthy = 75-100 %. All of the key functions of healthy rangeland are being performed.

- Healthy with Problems = 50-74%. Most but not all key functions of healthy range are being performed. Minor to major change in grazing practices are required.
- Unhealthy = < 50%. Few of the functions of healthy range are being performed. Major change in grazing practices required.

C.3 ASRD Forest Health (Pests and Invasive Plants)

Alberta Sustainable Resource Development (ASRD) monitors and reports on forest insect pests, diseases, and invasive alien plants on forested Crown land, as well as pest management programs. Monitoring for spruce budworm infestation is concentrated in northern Alberta where both spruce-dominated forests and the forestry industry are more prominent. In southwestern Alberta and particularly across the eastern slopes of the Rockies and the foothills, ground plots and pheromone-baited traps have been used extensively to detect mountain pine beetles in uninfested, high-risk lodgepole pine stands [21]. Aerial overview surveys of red fader trees indicative of late-stage mountain pine beetle damage have also been carried out using fixed-wing aircraft over areas with mature, beetle-prone pine stands on the eastern slopes [21]. Similarly, aerial surveys over provincial Crown land have been conducted to assess major aspen defoliators (the large aspen tortrix is the primary aspen defoliator in southern Alberta). The forest health reporting also summarizes information on invasive plants throughout Alberta, including major areas of infestation on Crown land and weed control programs. For example, Beaver Creek in the southern Porcupine Hills has had major problems with hound's tongue, and although the population is slowly decreasing, many new hound's tongue sites have appeared farther north and the plant is creeping across the north side of the pass via infested grazing leases [21].

C.4 Alberta GVI (Grassland Vegetation Inventory)

The Grassland Vegetation Inventory (GVI) represents Alberta's new vegetation inventory for the Grassland Natural Region [250] of the province, set up to assess changes in native vegetation characteristics of Alberta's prairie landscape [124]. Compilation of the inventory with colour infrared photography was initiated by ASRD in 2006-2007 with about 100 townships, and will include over 1,300 townships after completion in approximately 2010. The GVI replaces the original Native Prairie Vegetation Inventory (NPVI) completed in 1993 with a more comprehensive and detailed GIS product. The GVI is a polygonal, line and point relational spatial database that provides information on a number of different landscape features. These features include:

- 14 upland range site descriptions (loamy, limy, sandy etc.);
- 10 wetland/riparian feature classes;
- Four anthropogenic agricultural classes;
- Two industrial classes; and,
- Two anthropogenic urban/rural classes.

Some of the classes may contain a multitude of modifiers such as salinity extent in agricultural lands, gravel pits, quarries, processing plants, confined feeding operations or even green spaces in urban/rural habitat areas. Vegetation characteristics are described in general by tree, shrub, herbaceous percent cover, height, density, and distribution pattern. The database also allows for more specific entries regarding species type and their percent component cover. Line and point topological layers have been introduced to the database to delineate features such as shelterbelts. A key application of the GVI is rangeland health assessments, whereby the GVI range site and its associated ecological district determine a reference plant community [124].

C.5 Alberta Vegetation Inventory

The Alberta Vegetation Inventory (AVI) has been maintained for the forested portion of the province by ASRD since 1987 with regularly scheduled updates. The AVI is a photo-based digital inventory developed to identify the type, extent, location, and ecological conditions of vegetation, including any changes occurring. AVI data covers all forested land managed by the Crown, including land managed under a Forest Management Agreement (FMA), as well as Métis Settlements, First Nations Reserves and Federal Parks. Within southern Alberta, AVI data for the majority of the forested areas has been completed, including coverage for the eastern slopes as well as the Cypress Hills upland area [22]. AVI data standards were developed to ensure data consistency [252], and are available for viewing online. AVI polygons in the database include information on the following attributes [22]:

- Moisture Regime
- Crown Closure
- Stand Height
- Species Composition and Percentage
- Stand Structure and Value
- Stand Origin
- Timber Productivity Rating
- Interpreters Initials
- Naturally Non-Forested Vegetated Land (i.e. shrubs, forbs)
- Naturally Non-Vegetated Land (i.e. rivers, rock barren)
- Anthropogenic Vegetated Land (i.e. agriculture, industrial)
- Anthropogenic Non-Vegetated Land (i.e. created by man)
- Stand Modifier, Extent and Year (i.e. burn, clearcut)
- Data Source

C.6 Central Parkland Native Vegetation Inventory

A vegetation/land use database for the Central Aspen Parkland Natural Region has been developed with the following objectives [20]:

- Classify native vegetation cover classes within the Parkland Natural Region from aerial photography (1:30,000);
- Update hydrography and small open water hydrography within the Parkland Natural region from a combination of aerial photography (area

> 0.5 ha) and Indian Remote Sensing (IRS) imagery obtained in 1999 at 5 m resolution (area > 0.04 ha);
- Classify deciduous and coniferous treed areas from Landsat TM 7 imagery at 25 m resolution;
- Obtain municipality and ownership information; and,
- Create a complete GIS database from the above objectives.

Additional details on data quality control and methodology can be viewed online [20].

C.7 Parks Canada Montane Bioregion Landcover Mapping Project

Parks Canada's Montane Bioregion Landcover Mapping Project covers the mountain parks of Alberta. Run by the University of Calgary's Department of Geography, it consists of ground-truthing a series of remote sensing protocols developed for mapping and annually updating large landscape-level processes throughout the mountain parks. The project had three complimentary objectives [225]:

1. Based on the assessment currently being done, identify and sample areas in Banff, Yoho, Kootenay, Jasper, and Waterton Lakes where vegetation plots can aid in ground-truthing the remotely sensed map
2. Review all plots for internal quality and consistency
3. Produce land cover mapping for the Rocky Mountain National Parks incorporating new vegetation plot data

C.8 Agricultural Region of Alberta Soil Inventory Database (AGRASID)

AGRASID (Version 3.0) provides extensive soil information for the 26 million hectares of arable land known as the White Area of Alberta. It is a compilation and update of soil survey reports, including maps gathered over the past 75 years. Free downloads of AGRASID 3.0 data are available containing a standardized digital spatial database comprised of the following components (AAFRD 2008):

- Soil Landscape polygons, describing an area containing common communities of soils, intended to be displayed at a scale of 1:100,000;
- Detailed information on soil communities contained within each soil landscape, including names and descriptions of soils at the series level as well as landscape features (i.e., hummocky), and chemical and physical properties for each soil name;
- Land Systems polygons, a generalized form of Soil Landscapes, intended to be displayed at a scale of 1: 250,000; and,
- Descriptions of representative soils, landscapes, and the amount of wet and/or saline areas within Land Systems polygons, including up to three major and two minor soil types, two landscapes, and assignation of land systems to the Ecozones, Ecoregions, and Ecodistricts of the National Ecological Framework for Canada [220].

C.9 Monitoring Programs for Surface Water Quantity

A network of surface water flow and water level (stage) monitoring stations on streams, rivers, and lakes of Alberta is maintained by the Water Survey of Canada's hydrometric program under a formal agreement between Environment Canada and the province of Alberta. Real-time hydrometric data (e.g., discharge in m^3/s), as well as archived water level and flow statistics (e.g., hydrographs) are available. Sampling coverage is relatively good on major rivers in southern Alberta (e.g., 7 stations on the Bow River). Many monitoring stations exist on smaller streams and rivers as well [117].

Additional programs assessing surface water quantity in Alberta include, but are not limited to:

- Alberta Environment's snowpack monitoring and water supply outlook reports;
- Monitoring and reporting on water diversions, water quantities in canal and reservoir systems, and return flows by the irrigation districts of Alberta[3]; and,
- Major water users such as municipalities, which must collect data on licensed water diversions and associated return flows.

C.10 Surface Water Quality Monitoring Programs

Environmental water quality monitoring within southern Alberta is primarily the responsibility of Alberta Environment. Alberta Environment is currently monitoring key water quality parameters at its river network sites, the majority of which have been monitored over the past 30 to 50 years as part of the Long Term River Network (Fig. 3-3). The parameters are integrated into an Alberta River Water Quality Index based on the average annual value of four different sub-indices, including:

- Metals (up to 22 variables measured quarterly);
- Nutrients & related variables (six variables measured monthly);
- Bacteria (two variables measured monthly); and,
- Pesticides (17 variables measured four times during open-water season).

To provide a measure of quality related to targets, water quality variables in the first three groups are compared to Alberta and federal water quality guidelines. The fourth group (pesticides) is evaluated based on whether they are detectable in water samples. This conservative approach is used because some pesticides do not yet have official guidelines and, unlike metals, nutrients and bacteria, pesticides do not occur naturally in the environment.

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3 One pilot project on the Milk River, organized by Alberta Environment and Alberta Agriculture and Food, is currently reporting near real-time water use of private irrigators along the mainstem (AENV 2008).

The data are compiled into the Water Quality Index formula, which compares monitoring results to water quality objectives. The index formula incorporates aspects such as how many variables do not meet the objectives, how frequently measurements do not meet objectives, and the amplitude of how far measurements exceed objectives [4].

The Alberta Environmentally Sustainable Agriculture (AESA) program has also monitored water quality in 23 small agricultural watersheds, 12 of which are located in southern Alberta. Watersheds were selected on the basis of agricultural intensity variables addressing livestock and cropping as well as factors such as soil types and erosion rates [5, 16]. Water quality parameters examined by AESA included chemical parameters related to nitrogen and phosphorus, as well as data on over 71 pesticides, and faecal bacteria [7]. However, the AESA program has been discontinued.

All wastewater facilities licensed under the *Alberta Environmental Protection and Enhancement Act* also have monitoring requirements related to discharges of treated wastewater to the environment.

Additional water quality monitoring programs and requirements in Alberta include community-based programs, and project-specific monitoring carried out by consulting companies (e.g., turbidity monitoring during construction at watercourse crossings, contaminant monitoring). Data from these sources are difficult to include in indicator assessments, since collection efforts are somewhat ad hoc, data may be confidential, and quality control and scientific validity may not be adequately established.

C.11 Groundwater Monitoring Programs

Assessments of groundwater in Alberta include:

- The 1: 250,000 scale Hydrogeological Map Series of Alberta provide data on likely long-term yields of water wells by location and depth, as well as the expected chemical quality of shallow aquifers. These were published by the Alberta Research Council, mostly during the 1970s, and have never been updated, so their use is discretionary [343]. However, they can be useful for estimating some general baseline conditions over very broad scales.
- Hydrogeological Consultants Ltd. (HCL) has been preparing county-specific reports assessing regional groundwater resources and characteristics.
- A groundwater quality database has been compiled for coalbed methane production areas.
- The Energy Resources Conservation Board (ERCB) and Alberta Environment both monitor groundwater through water well observation networks.
- Many other project-specific groundwater modelling reports have been prepared throughout southern Alberta by environmental consultants working for the oil and gas industry. Although many of these focus on contaminant plumes, groundwater quantity data can also be extracted from them. However, this “gray literature” can be difficult to locate and many reports are confidential. In addition, the application of differing

methodologies means that standardization and crosswalking between methodologies and collation can be difficult to achieve for future monitoring purposes.

C.12 Cows and Fish Riparian Health Assessments

The Alberta Riparian Habitat Management Society, more commonly known as 'Cows and Fish', strives to foster a better understanding of how improvements in grazing and other management of riparian areas can enhance landscape health and productivity for the benefit of landowners, agricultural producers, communities and others who use and value riparian areas [55]. The majority of their activities are concentrated in southern Alberta.

Cows and Fish have conducted riparian health surveys using an indicator system that targets specific ecosystem functions, including:

- trapping sediment
- building and maintaining banks
- storing water and energy
- recharging aquifers
- filtering and buffering water
- reducing and dissipating energy
- maintaining biodiversity, and
- creating primary productivity.

Field surveys collect basic data to evaluate the following twelve riparian health parameters:

- vegetative cover of the floodplain
- invasive plant canopy cover
- invasive plant density distribution
- disturbance-caused plants
- preferred tree/shrub vegetation
- utilization of preferred trees/shrubs
- dead woody material
- root mass protection
- human-caused bare ground
- alteration of streambanks
- human alteration to the site
- channel incisement

Health Category		*Score Ranges*	*Description*
Healthy		*80-100%*	little to no impairment to any riparian functions
Healthy, but with problems		*60-79%*	some impairment to riparian functions due to management or natural causes
Unhealthy		*<60%*	severe impairment to riparian functions due to management or natural causes

Table C-1 Cows and Fish Riparian Health Categories. Source: [92]

The approach and rationale for collecting data on these parameters is very similar to the Range Health Assessment described above (Section C-2). Results can be separated into a Vegetative Health Index and a Soil and Hydrology Health Index. In turn, these two indices are combined into an Overall Riparian Health Index. The total score of the Riparian Health Index is lumped or subdivided into three categories as shown below (Table C-1).

C.13 Cows and Fish Wetland Health Assessments

Cows and Fish have also developed a wetland health index [54], using almost identical principles and parameters as their riparian health index described in Section C-11. Slightly different field protocols and parameters are used for wetlands associated with large river systems [90], smaller rivers or streams [91], or lakes [53]. The total score of the Wetland Health Index is lumped or subdivided into three categories identical to those shown in Table C-1 above.

C.14 Provincial Wetland Inventory

Alberta's provincial wetland inventory is an initiative spearheaded by AENV, with technical support from Ducks Unlimited Canada. The inventory has developed a protocol and process for the implementation of the provincial wetland inventory under Alberta's *Water for Life* strategy. The method uses new and historical aerial photographs to assess wetland cover changes over time. Each photograph is digitized by a GIS specialist and individual wetlands are traced and classified into various categories. The results are comprehensive, and provide number, area, type, and status of wetlands within the watershed. This comprehensive wetland inventory is intended to provide watershed managers in Alberta with a detailed inventory of their current wetland base that will indicate which wetlands have been lost or altered, and can serve as a benchmark for future success of protection and conservation efforts[114].

C.15 Watershed Indicators

Alberta Environment has identified generic condition and pressure indicators for land condition, water quantity, water quality, and aquatic and riparian ecosystems within watersheds of Southern Alberta [5]. Table C-2 below summarizes the indicators suggested within this report.

Table C-2 Alberta Environment Watershed Condition Indicators [5]

Land Condition Indicators
Amount and delineation of native/natural cover types from the Grassland Vegetation Inventory, including: (i) riparian areas, (ii) grasslands, and (iii) wetlands
Amount and delineation of native/natural cover types from the Alberta Vegetation Inventory, including (i) burnt, (ii) regenerating and mature forests with age and size class, and (iii) natural non-forested vegetated land
Model-predicted soil erosion rates
Site-specific land quality measures on rangeland (from Adams et al., 2005) including: (i) plant species composition (diversity and richness), (ii) presence of plant community structural layers, (iii) amount of plant litter, (iv) amount of human-caused bare ground
Site-specific land quality measurements of riparian areas on public and private land (from Cows and Fish), including: (i) regeneration of palatable woody riparian species (where applicable), (ii) livestock browse intensity on palatable woody riparian species, (iii) amount of riparian area covered in deep binding roots, (iv) amount of human-caused bare ground
Water Quantity Condition Indicators
Deviation of recorded flows from naturalized flows
Deviation of recorded flows from Water Conservation Objectives (WCOs)
Deviation of recorded flows from Instream Flow Need (IFN) values determined for water quality, fish, and riparian health
Deviation of recorded flows from Instream Objectives
Water Quality Condition Indicators
Water temperature and dissolved oxygen
Nutrients, including (i) nitrogen and (ii) phosphorus
Total Suspended Solids (TSS)
Pathogens, including (i) faecal coliforms, (ii) *E. coli*
Biological Condition Indicators
Presence, absence, and condition of umbrella species
Presence, absence, and condition of species with limited dispersal
Presence, absence, and condition of species that depend on environmental processes to reproduce (e.g., cottonwoods and floods)
Single-metric measures of community diversity (e.g., number of species or families)
Multi-metric indices (e.g., Index of Biotic Integrity)

C.16 Ecosystem Status and Trends Reporting Program

The Ecosystem Status and Trends Reporting (ESTR) program is a multi-jurisdictional and inter-departmental initiative that provides an integrated ecological framework for reporting and synthesising existing knowledge on biodiversity, ecosystem health, and ecological goods and services. The program is intended to meet a variety of national and international reporting objectives related to biodiversity. The scope of the project includes (Ted Nason, personal communication):

- A synthesis of science based information on status and trends and stressors of the terrestrial, freshwater, and marine ecosystem component of natural capital.
- A synthesis of species information where it relates directly to, or is an indicator of, ecosystem health or an ecosystem good or service.
- Aboriginal Traditional Knowledge (ATK) in the public domain.
- Multi-jurisdictional and inter-departmental integration of ecosystem information that provides a baseline of ecosystem information for future reporting.
- Ecological Goods and Services provided by ecosystems.
- Measuring status and trends information against historic conditions, ecological thresholds, or accepted reference values; setting the stage for science-based targets
- Identification of ecosystems needing priority attention.
- Lessons learned from ecosystems that are managed well to sustain their structure and function.
- Recommendations on technical aspects of ecosystem assessments (i.e. on-going ecosystem monitoring and status and trends reporting).
- As a minimum, the foundation information needed to classify ecosystems into qualitative categories (e.g. healthy, impaired, critical).
- Understanding of ecosystem issues that are national in nature and those that are more regional in nature.

Land reporting units in ESTR are based on the Ecozone[plus] classification system [286], which includes minor modifications based on the National Ecological Framework for Canada's land classification system [220]. Three terrestrial Ecozones are present within southern Alberta (Figure C-1). The Alberta provincial government is responsible for reporting on the Boreal Plains Ecozone, while Saskatchewan is the lead for the Prairies Ecozone, and British Columbia has been allocated the Montane Cordillera Ecozone. The Prairie Ecozone encompasses the Parkland Natural Region [250] of Alberta. All reports are scheduled to be released to the public in October 2009, and the project completion date is March 2010. Consequently, it remains to be seen what types of indicators will be used in these reports.

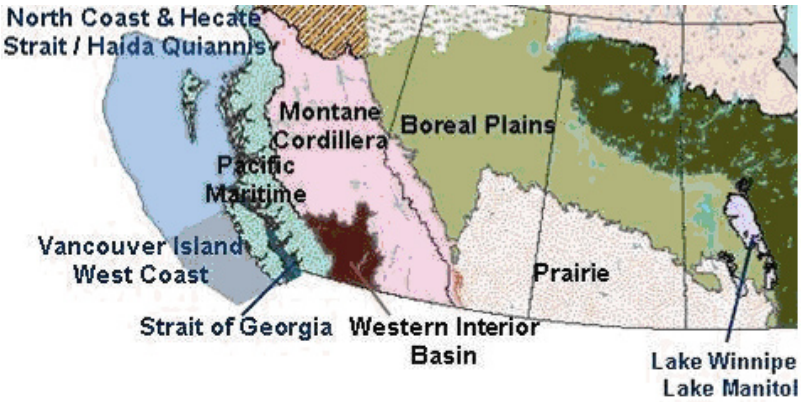

Figure C-2 ESTR's EcoZoneplus Classification System Across Western Canada