Delineating spatial units for coregonine conservation, restoration, and stewardship

Resolving Taxonomy Science Team

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1. A COREGONINE RESTORATION FRAMEWORK

Cumulative stressors have resulted in loss of biodiversity and its supporting habitats in the five Laurentian Great Lakes. The coregonine ciscoes were especially affected, with extinction of several species and subspecies (*Coregonus johannae*, *C. alpenae*, *C. kiyi orientalis*), and at least ten local extirpations (*C. nigripinnis*, *C. reighardi*, *C. zenithicus*, *C. hoyi*, *C. artedi*) across all five lakes. A basin-wide coregonine restoration framework (Figure 1) was developed to address nearly a century of losses in coregonine biodiversity (Bunnell et al. 2023).

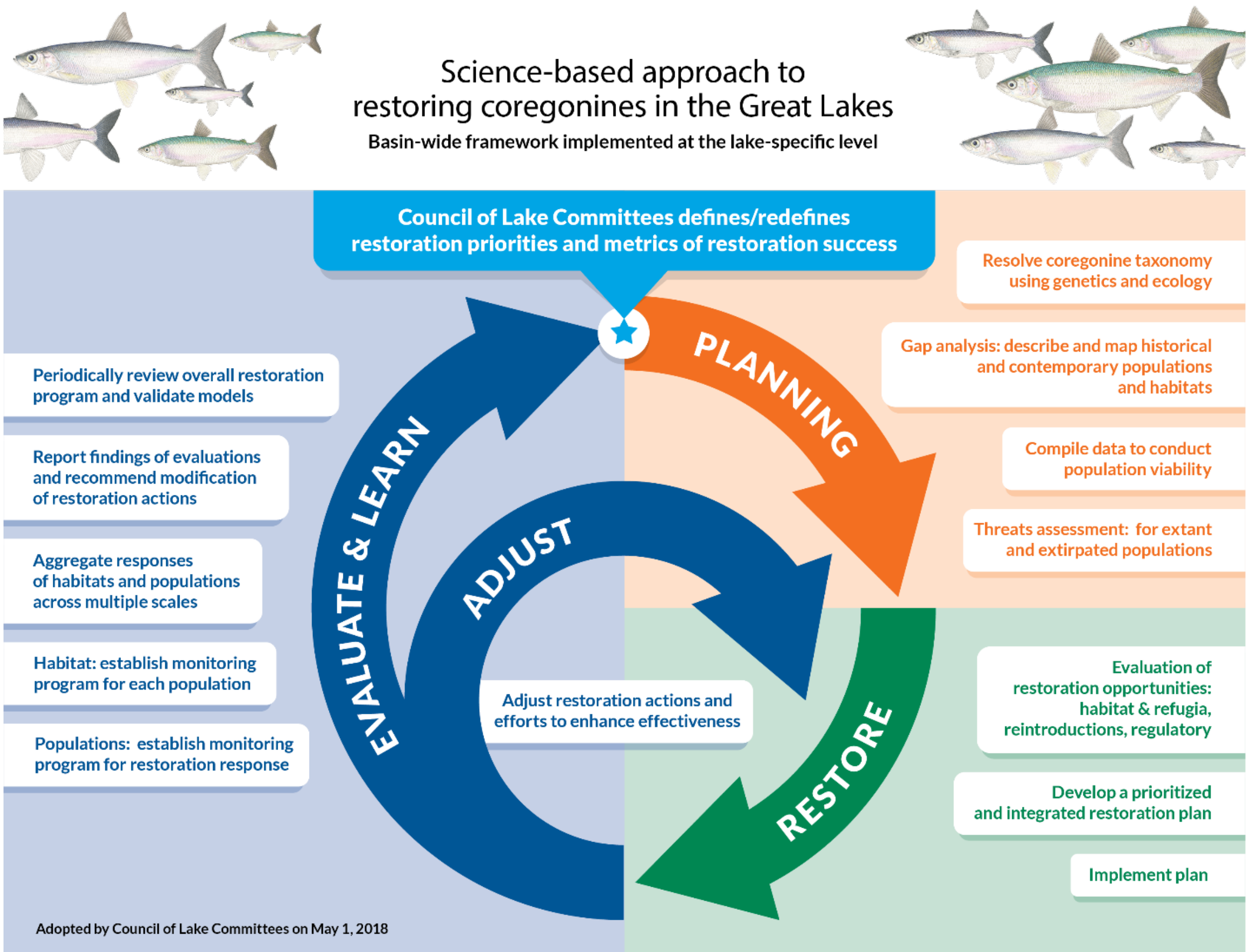

Figure 1. Coregonine restoration framework endorsed by Great Lakes fishery managers in May 2018. Managers define (or redefine) restoration priorities and metrics of success that are operationalized by planning (orange; upper right), restoring (green; lower right), and evaluating, learning, and adjusting (blue; left half; Bunnell et al. 2023).

The four planning tasks (orange boxes; upper right; Figure 1) identify a science-based approach to resolving coregonine taxonomy (Task 1), developing a gap analysis method for describing and mapping historical and contemporary populations and habitats (Task 2), assessing population viability (Task 3) and assessing threats for extant and extirpated populations (Task 4). In 2019, recognizing that activities were occurring in each area of the framework (i.e., planning, restoring, evaluating), fishery managers endorsed a plan to create teams to develop methods for operationalizing each of the four planning tasks (described by Bunnell et al. 2023). As an initial step, Task 1 (Resolve coregonine taxonomy) was subdivided into two objectives: (1) re-evaluate the taxonomy of Great Lakes ciscoes; and, (2) delineate spatial units for the conservation, restoration, or management of cisco diversity across the Great Lakes basin, independent of higher-order taxonomic decisions. The method for identifying spatial units is the subject of this paper and aimed to develop a transparent, semi-quantitative, repeatable process for identifying spatial units for resource management that merges principles of conservation and restoration ecology. To our knowledge, no existing spatial-unit concept integrates across conservation, restoration, and management objectives. The methods documented herein are tailored to fishes, specifically coregonines (Salmoniformes: Coregonidae); however, the criteria, evidence, and data can be appropriately modified and applied to any biota in any environment.

2. OVERVIEW OF SPATIAL UNITS

Three types of spatial units described herein encompass the following components:

1) the well-established concepts of conservation units for extant biota
2) restoration opportunities associated with historical occurrence of biota that are currently extirpated
3) management opportunities for provisioning ecosystem services (*sensu* Luck et al. 2003) where records of historical occurrence are poor or non-existent, environments are rapidly changing, and where novel introductions are under consideration

The three spatial-unit types described reflect management objectives of conserving extant biodiversity (occupied unit), restoring extirpated biodiversity (unoccupied unit), and generating provisioning (i.e., use), regulating (i.e., quality control), and cultural (e.g., spiritual, recreational, and aesthetic) services (service unit; resource management; Carpenter et al. 2009; Figure 2).

This spatial-unit approach holds no legal status, nor will it obligate any management action. Units represent a spatial survey of opportunities for conservation, restoration, and service; hence, they serve as a science-based planning tool for resource managers. Using the results of a spatial unit assessment, stewards can prioritize opportunities for actions. Once managers select a unit for potential action (e.g., habitat restoration), they can request population viability analyses (PVA; Task 3) and threat assessments (Task 4) for that unit. PVA and threat assessments may not be required by managers for all identified spatial units because: (1) existing data might be available and status is already known, such as commercially managed species; (2) some extirpated populations may never be viable for restoration due to other conflicting management objectives or known impediments; or, (3) some habitats may be unsuitable to support reintroductions or may currently support other ecosystem services, such as harvest of an alternative species, and, therefore, are not desirable for restoration. In summary, we envision the output from implementing the methods described herein to include a spatial delineation of significant extant populations, historically occupied habitats, and opportunities to provide provisioning, regulating, and cultural services that can be used to prioritize conservation, restoration, and management activities and upon which to focus subsequent PVA and threat assessments (Task 3 & 4; Figure 1). This spatial unit delineation method also leverages methods and output from the Gap Analysis Task Team (Task 2; Figure 1) as described below.

Conservation	Restoration	Management
Occupied	**Unoccupied**	**Service**
Space (i.e., habitat) occupied by extant biota	Space historically occupied (or with high probability of being historically occupied) by now locally extirpated biota	Space not historically (or low probability) occupied, and not currently occupied
1.1 Extant forms 1.1.1 Common 1.1.2 Rare, threatened, or endangered 1.2 Isolated populations 1.3 Evolutionarily distinct populations	2.1 Open habitat (i.e., previously occupied)	3.1 Provisioning (i.e., uses, such as food) 3.2 Regulating (i.e., quality control, such as water regulation) 3.3 Cultural (e.g., spiritual, recreational, or aesthetic)

Figure 2. Spatial-unit types(columns), definition (upper rows), and characteristics (lower rows).

2.1 Spatial unit types

The three types of spatial units defined in our methods (Figure 2) include:

1) ***Occupied Unit:*** space (i.e., habitat) occupied by extant biota;
2) ***Unoccupied Unit:*** space historically occupied or with high probability of being historically occupied by now locally extirpated biota; and,
3) ***Service Unit:*** space that was not historically or has a low probability of being historically occupied, and is not currently occupied by the biota under consideration, but could provide desired provisioning, regulating, and cultural services through biotic introductions or habitat enhancement.

By definition, the three unit types are mutually exclusive or non-overlapping for a given species or form. That is, a ***Service*** unit for *C. artedi*, cannot be established within a geographic area supporting extant *C. artedi* (i.e., an ***Occupied*** unit). For the practical purpose of delineating spatial units, we conveniently define space as reproductive habitat. Reproductive habitat is critical for all biota because it is where fundamental demographic processes, births and deaths, occur, and it serves as a propagule source for non-mobile species. Many migratory species, including coregonine fishes, annually visit reproductive habitats, whereas other habitats may be infrequently visited (Gap Analysis Task Team). Additionally, reproductive habitat is being used by the Gap Analysis Task Team to develop predictive models of historical coregonine occurrence. By contrast, PVA and threats assessments could be implemented at a whole-life-cycle scale because bottlenecks to conservation and restoration could present at any life-history stage. For instance, feeding grounds, migration corridors, and nursery habitats are important spatial components of habitat and each of these spatial scales has associated life-stage specific threats that influence viability and ultimately the feasibility of a conservation or restoration action. Focusing on reproductive habitats provides a convenient and biologically relevant means to bound spatial units with minimal management risk because habitats critical to other life stages are accounted for in management planning at the threats assessment and population viability stages of the planning process.

The methods outlined herein define ***criteria for unit designation***, specify ***types of evidence*** that can be gathered to support or refute applicability of a criterion, and indicate ***types of data*** that can be used as evidence supporting or refuting each criterion (Figure 3). Satisfying criteria establishes the validity of a spatial unit. To the extent possible, data should be quantitative; however, expert opinion and qualitative observation (whether or not they are peer-reviewed or published) are valid data sources and should be considered in conjunction with, or *in lieu* of, available quantitative data. We define "expert" broadly to include knowledge holders including, but not limited to, Indigenous Knowledge holders, harvesters, and technical experts. The spatial-unit delineation method explicitly recognizes that data may differ in the relevance, strength, and reliability of the support they provide for evidence used to evaluate criteria; therefore, data are weighted (as described below) using a modified Delphi method (Environment and Climate Change Canada 2021; Hemming et al. 2018; United States Environmental Protection Agency 2016). If sufficient evidence is not available to evaluate a criterion for a putative unit, that putative unit is deemed data deficient; it would not be recognized as a spatial unit, and the assessment process can provide a platform for identifying future research needs to reduce data gaps.

Unit criteria, excepting Indigenous Knowledge (IK, see subsection below), represent biotic and abiotic standards against which putative units will be evaluated. The intent of evaluating putative units against evidence-based criteria is to establish a repeatable method that reduces the number of units to those practical for conservation and restoration and to increase likelihood of successful stewardship, given limited financial and human resources. Failure to meet criteria for reasons other than data deficiency (e.g., data refuting criteria) means that a putative specific or subspecific (e.g., population) unit will not be recognized at the time of assessment. Evidence types represent broad categories of information (e.g., movement, genetics) related to a specific criterion that, in turn, can be supported by several types of data, including behavioral, genetic, and geographical data with sources ranging from theoretical modeling to direct observation to empirical studies (Figure 3). For each unit-specific criterion described below, only one type of evidence is required to satisfy a criterion. Because technologies and techniques rapidly evolve, the data types identified herein do not represent an exhaustive list. Unique data solutions may be required for specific situations under consideration.

The spatial units identified through implementation of these methods are not definitive. We recommend that previously defined units be subject to periodic re-evaluation based on new information, changing management needs, or changing ecology of the biota across the geographic landscape of interest. For instance, spatial-unit delineations based on Western science may require updating should Indigenous Knowledge become available.

3. INDIGENOUS KNOWLEDGES

Indigenous Knowledge (IK) can be defined as "a cumulative body of knowledge, practice, and belief evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (Berkes 2018). Principles of data ownership, control, access, and possession (OCAP®; https://fnigc.ca/what-we-do/ocap-and-information-governance/) will be adhered to as they apply to First Nations data in Canada. IK and Western knowledge are both equally important in the methods we describe for spatial-unit delineation. IK cannot be divorced from its holders—it is specific to People and place; nor can it be broken down into categorical components (i.e., data types per Western Knowledge systems with specific lines of evidence). While IK is considered throughout the entire process of spatial unit delineation, at the criterion level, IK alone could establish or refute delineation of a spatial unit under consideration.

A few First Nations and Tribes have representatives actively participating on the Task Teams associated with the restoration framework and through their participation, we hope to build better relationships (see McGregor et al. 2023) such that more First Nations and Tribes may choose to participate in implementing spatial unit assessments. Indigenous engagement will be sought for all assessments, but participation will be determined by the First Nations and Tribes on the assessed lake. Engagement of Indigenous Peoples extends beyond providing knowledge to the process, and entails participating as full partners. When approaching First Nations or Tribes, it would be appropriate to determine how each individual party would like to partner and, ultimately, the next steps for participation as decision makers in the future. Task Team members will serve as points-of-contact to seek inclusion of interested First Nations and Tribes in the Spatial Unit delineation process for a given lake. The timeline for bringing IK to the process may be asynchronous from the Task Team assessment of spatial units in a lake, due to the additional time required to engage Indigenous Peoples, acquire funding, undertake the research, and compile the knowledges. As spatial units are not fixed and carry no legal status, an assessment can easily be updated at any time; therefore, asynchronous timelines for bringing knowledge to the assessment do not impede implementation.

4. METHODS FOR DELINEATING SPATIAL UNITS

4.1 WEIGHTING DATA TYPES

Prior to undertaking a unit assessment, a weight-of-evidence approach is used to generate an overall weight for each data type considered in the decision-making process. Weight-of-evidence is a process for systematic and transparent integration of multiple datasets using ‘evidence groups’ (Environment and Climate Change Canada [ECCC] 2021). Herein, evidence groups represent the data used to support or refute types of evidence used to evaluate criteria for spatial-unit designation (Figure 3). Our weight-of-evidence process involves (1) identifying appropriate data types, (2) weighting data types with respect to the evidence they are supporting or refuting, and (3) integrating across properties following established processes for expert elicitation to assign a qualitative score (weight) to each data type (Hanea et al. 2017; Hemming et al. 2018; U.S. Environmental Protection Agency [USEPA] 2016). The weighting process is undertaken once prior to a unit assessment, but the assessment process may identify areas where re-weighting particular data types is necessary.

Data can provide variable levels of support for types of evidence used to determine whether criteria are met to establish a spatial unit. To address this variability, data will be weighted using a qualitative scoring approach developed by the USEPA (2016) that assumes a correlative, causal, or robust relationship between data and the evidence garnered from those data. Applying this method here, a qualitative weight will be assigned to each data type based on three properties: *relevance*, *strength,* and *reliability*. *Relevance* of a data type is the degree of correspondence between data and the type of evidence to which the data are applied. S*trength* of data is the degree of differentiation from control, reference, or randomness. *Reliability* consists of inherent properties that make data convincing, such as accepted and standardized methods with statistical power to draw conclusions, replication, and transparency of results.

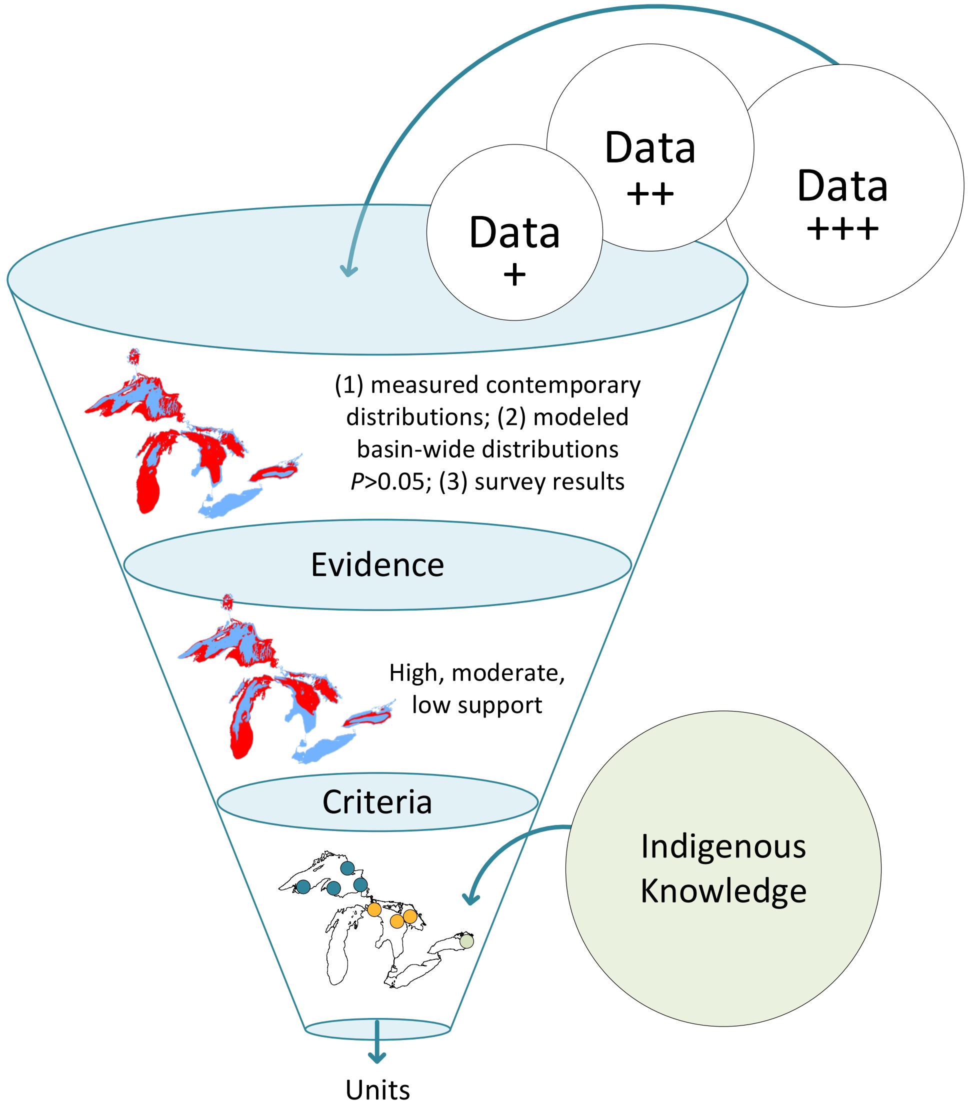

Figure 3. For occupied, unoccupied, and service unit types, weighted data (+, ++, +++, see Section 4.1) provide evidence supporting or refuting Western Science-based criteria for a unit designation. Criteria represent biotic and abiotic standards by which unit designations are evaluated and validated. Evidence types represent broad categories of information that can inform the acceptance or not, of a criterion. Indigenous Knowledge (IK) where available can directly inform a spatial unit assessment at the criterion level; IK is not broken down into individual data types providing supporting evidence, rather as a whole, IK can establish the validity (or not) of an occupied, unoccupied, or service unit. Lake illustrations are for illustrative purposes only and intended to reflect distributions of a fish species (upper two) and three unit types (bottom) identified via implementation of a spatial unit assessment.

Data types may differ in their *relevance*, *strength*, and *reliability* (ECCC 2021), and each data type can be evaluated with respect to these three properties to determine an overall weight that can be applied to each data type. Qualitative scoring systems generally use intuitive symbols (e.g., +, -) to indicate whether a data measure supports or refutes a hypothesis (USEPA 2016). The qualitative scoring system applied here follows the system implemented by ECCC (2021) to weight environmental data used in nearshore habitat assessments along the Canadian coastlines of the Great Lakes. This scoring system uses + symbols to indicate increasing levels of support (+, ++, +++) for data properties, which are then summarized with a single, overall weight applied to each data type (Table 1). The overall weight for each data type (+, ++,

+++) impacts how available data are aggregated (i.e., counted once [+], twice [++], or three times [+++]) to determine the level of support for evidence and criteria during a unit assessment.

Table 1. Qualitative scoring system used to assess information properties (relevance, strength, and reliability) and assign an overall weight to each information type. The scoring system was modified from USEPA 2016 and ECCC 2021.

LEVEL OF SUPPORT	DEFINITION
+	Support for data property
+ +	Strong support for data property
+ + +	Convincing support for data property

The process of weighting data types and assigning an overall weight to each data type will rely on expert judgement; therefore, a structured approach to elicitation known as the Delphi procedure was used (Hanea et al. 2017; Hemming et al. 2018). This protocol relies on the key concepts of 'Investigate,' 'Discuss,' 'Estimate,' and 'Aggregate' (IDEA) to mitigate potential biases and improve the quality of decisions. The process involves a four-step approach to refining an overall weight for each data type. Applied here, the IDEA approach includes the following four steps: (1) experts independently weight properties for each data type based on *relevance*, *strength*, and *reliability* using the +, ++, +++ system; (2) compiled results from independent weightings are discussed as a group, including points of consensus and conflict; (3) a second round of independent weighting is then undertaken; and, (4) rounded average weight from the second independent evaluation is assigned to each data type; when the process of averaging results in an intermediate weight (e.g., an equal number of + and ++), the lower weight is used. Following this systematic and conservative approach for evaluating the *relevance*, *strength,* and *reliability* of information sources, an overall weight conveys the risk associated with accepting evidence supporting a criterion. In other words, the higher the weight, the stronger the consensus assessment of the *relevance*, *strength*, and *reliability* of that data type, and, therefore, less risk associated with using those data to provide evidence for accepting or refuting a criterion (where risk = probability of occurring x magnitude of consequences).

4.2 SUPPORT FOR EVIDENCE & CRITERIA

Once overall weights have been established for each data type, available data for spatial-unit assessments will be compiled. Each data type identified as relevant to the evidence types will be evaluated during assessment. Data evaluation can lead to five levels of support for evidence types (Table 2): data deficient (DD); no support (NS); low support (Low); moderate support (Moderate); and, high support (High). Data deficient implies no data of a particular type are available at the time of assessment. Classifying data types as DD provides a mechanism for highlighting potential knowledge gaps. NS means that the available data refutes the specific type of evidence under assessment. For example, if "limited movement or migration" was a type of evidence under consideration and an available data type (e.g., telemetry) showed widespread movement or panmixia, this data type indicates no support for "limited movement or migration."

When data types show support for a specific type of evidence, the level of support can be assessed as low, moderate, or high via expert elicitation following the same systematic IDEA approach described above for data type weighting: (1) experts independently evaluate levels of support (DD, NS, Low, Moderate, High) each data type lends to a type of evidence; (2) compiled results from independent weightings are discussed as a group, including points of consensus and conflict; (3) a second round of independent evaluation is then undertaken; and, (4) the average level of support for the type of evidence under consideration will be assigned to the available data type. The predetermined weight for each data type will inform whether that level of support is counted once (+), twice (++), or three (+++) times in the assessment of support for a unit criterion.

Table 2. Data types can provide five levels of supporting evidence for a criterion.

Data Deficient (DD)	No support (NS = 0)	Low support (Low = 1)	Moderate support (Moderate = 2)	High support (High = 3)

One or more data types should be available for the evaluation of a criterion, otherwise, the putative unit under consideration would be considered data deficient (Figure 4). Where IK is available, it alone is sufficient to establish or refute establishment of a spatial unit. A criterion is met if at least one type of evidence is assigned a moderate or high level of support. Levels of support are assigned numerical scores (0 = NS; 1 = Low; 2 = Moderate; 3 = High) and, post-assessment, total scores for all evidence types are averaged and rounded to the nearest level providing a weighted average to determine the overall support of each line of evidence (e.g., Table 3). However, if an average falls exactly between two levels of support, the higher level of support is conservatively selected. This rule differs from the averaging process during data type weighting because the conservative approach for handling data types is not to upweight the significance of any particular data type without team consensus. Alternately, the conservative approach for unit designation is to err on the side averaging up. For example, if data types are equally split between low and moderate support for evidence of a criterion, then that line of evidence would achieve an overall moderate support designation. Note that we conservatively established the rule that only one data type was required to support or refute a line of evidence; however, the team undertaking an assessment may modify this rule if the available data or conclusions are highly uncertain.

Table 3. Example assessment using weighted information sources (data in this example) to determine support for evidence that establishes whether a criterion is met for a putative ***Occupied*** *unit. Some data sources have weights of ++, so there are two columns for "Support for Evidence" to capture the double weighting. Here, the unit criterion is met because one of the evidence types achieves moderate support. On the basis of this assessment the unit under consideration would be validated and established as a spatial unit.*

	Evidence	Data	Weight	Support For Evidence		Support For Criterion
Criterion	A	A1	+	High	-	Moderate
		A2	++	Moderate	Moderate	
		A3	+	Low	-	
	B	B1	+	NS	-	Low
		B2	+	Moderate	-	
	C	C1	++	DD	DD	DD
		C2	+	DD	-	

Below, we provide more detailed descriptions for each of the three potential spatial-unit delineations, including specific criteria that can be used to validate their delineation, and specific lines of evidence that can be used for each criterion.

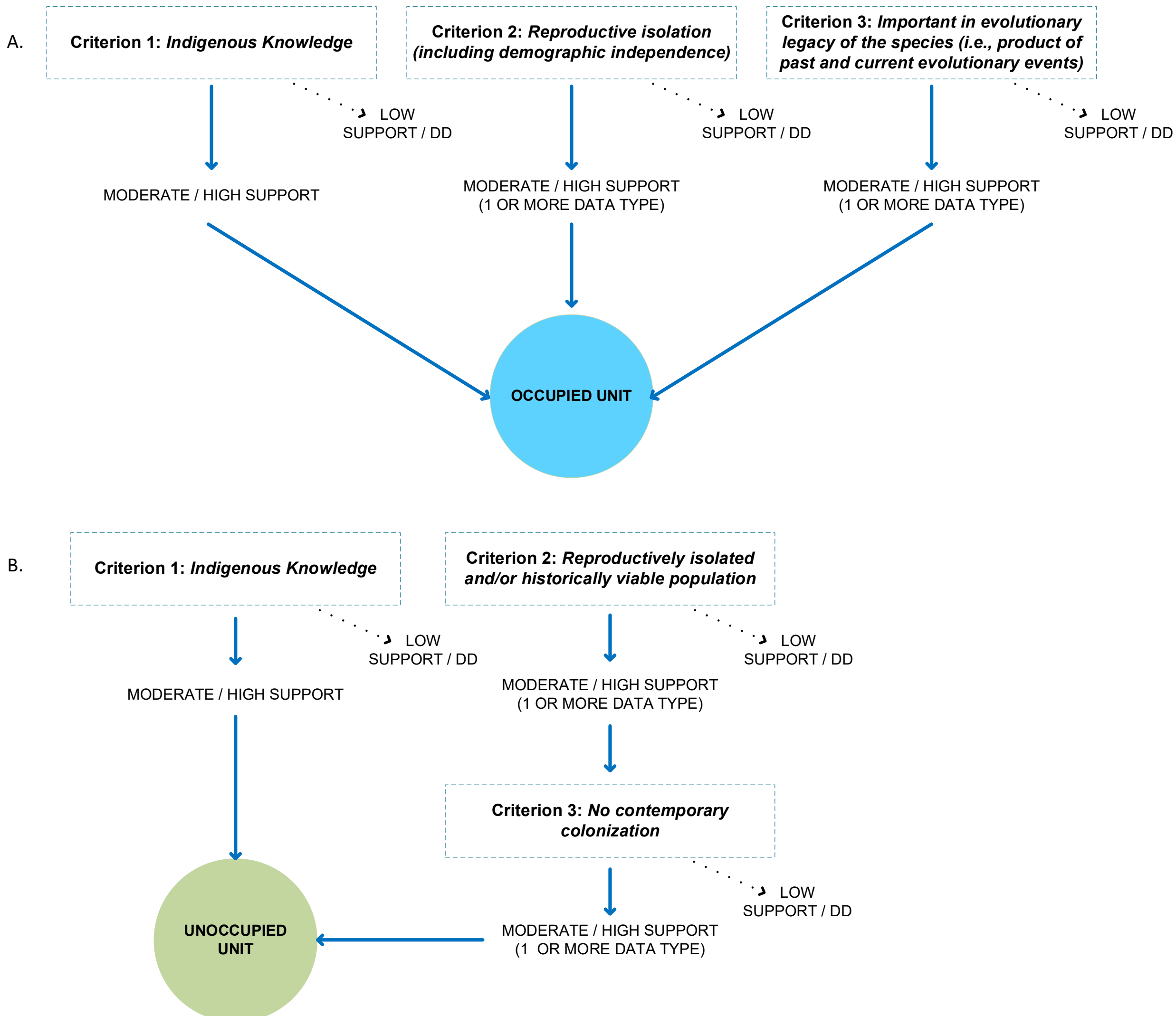

Figure 4. Process trees depicting the steps to criterion evaluation for delineating ***Occupied*** *(A) and* ***Unoccupied*** *(B) spatial units.*

4.3 Occupied Unit

Definition—space (habitat) occupied by an extant species, sub-species, form, population, or stock that is reproductively isolated or important in the evolutionary legacy of the species (i.e., product of past and current evolutionary events). Occupied units encompass both the focal biota and its reproductive habitat.

Occupied units are similar to established concepts of legislated conservation units (COSEWIC 2020; Crandall et al. 2000; Moritz 1994; Waples 1991; Waples 1995; Wood and Gross 2008) but without the corresponding regulations. Criteria for identifying occupied units were drawn from a survey of existing unit concepts from the conservation and restoration literature. Criteria and evidence supporting or refuting a unit designation were synthesized and adapted to meet needs across disciplines and reflect the current state of the science. The evolutionary significant unit (ESU; Waples 1991; Waples 1995; Fraser and Bernatchez 2001) concept associated with the U.S. Endangered Species Act captured well the criteria associated with all other unit concepts reviewed and, therefore, was used as the basis for the method herein to identify occupied spatial units (Table 4). Putative occupied units will be identified using species-level occurrence data compiled to develop species distribution models (Gap Analysis Task Team) and will also include sub-specific data where available or where taxonomy is unresolved. Data will be obtained from CORHIST (a geospatial database containing thousands of curated occurrence records for past spawning and nursery areas for Great Lakes coregonines, Brant et al. 2024), agency, and collaborator databases.

Criteria—Three criteria define an occupied spatial unit: (1) Indigenous Knowledge; (2) reproductive isolation, including demographic independence; and, (3) importance in the evolutionary legacy of the species.

Indigenous Knowledge (criterion 1) can establish or refute the establishment of a putative occupied unit through detailed understanding of seasonal movement and habitat-use patterns or based on phenotypic differences (e.g., Duncan 2020; Duncan et al. 2023). For example, the Denésqliné (Chipewyan) community of Lutsël K'é, Northwest Territories, Canada described changes in barren-ground caribou (*Rangifer tarandus groenlandicus*) movements and migrations in response to environmental change (Kendrick et al. 2005). Another prominent example is that of the Mi'kmaq peoples of Eastern Canada have lived with the American eel *Anguilla rostrata* for thousands of years during which time considerable knowledge has accrued regarding its distribution and role in the ecosystem (Giles et al. 2016; Reid et al. 2020).

Reproductive isolation (criterion 2) relates to the discreteness of a putative occupied spatial unit and differentiates it reproductively in space or time or both from other putative spatial units. Reproductive isolation does not have to be absolute, as some gene flow is expected, particularly among sympatric forms in recently de-glaciated regions (Skulason and Smith 1995), but it must be strong enough to permit heritable differences to evolve among units (COSEWIC 2020; Waples 1995). Demographic independence refers to units where population dynamics (e.g., population growth rate) depend primarily on local birth and death rates rather than immigration, similar to the stock concept in fisheries (Palsboll et al. 2007).

Importance in the evolutionary legacy of the species (criterion 3) refers to divergence in life-history traits or locally adapted phenotypic traits associated with past and current evolutionary events in the absence of demonstrated reproductive isolation. Importantly, contemporary divergence is recognized as potentially evolutionarily significant where it is not reconstitutable if lost (COSEWIC 2020). The evolutionary legacy criterion is similar to the Committee on the Status of Endangered Wildlife in Canada's (COSEWIC) concept of significance and recognizes local adaptation as critical to conserving and restoring biodiversity (COSEWIC 2020).

Evidence—Four lines of evidence can support *reproductive isolation* of a putative occupied unit (Table 4). First, detailed movement or migration patterns, such as localized movement or discrete distribution during the reproductive period, can demonstrate spatial or temporal reproductive segregation. For instance, gross directional differences in long-range migrations prior to breeding could indicate geographically disjunct breeding grounds (Heath-Acre et al. 2022). Second, differences in reproductive time, location, behavior, or even morphology of reproductive organs can lead to assortative or non-random mating. If observational evidence suggests that gene flow does not occur between populations, isolation can be inferred; however, adding genetic data strengthens this inference dramatically even at microgeographic scales (Finlay et al. 2020). Where populations temporally overlap on breeding grounds, isolation could still occur through pre-zygotic mechanisms such as behavioral or morphological character displacement (Johnson 1982; McPhail 1968; Pfennig and Ryan 2006). For example, in systems such as anuran frogs and insects, where males use pulsatile calls to attract female mates (Hobel and Gerhardt 2003), such advertisement calls can diverge among conspecific populations (Pfennig and Ryan 2006) leading to reproductive isolation. Third, genetic or -omic data can directly demonstrate reproductive isolation. Here 'omic' is used to encompass a broad subset of information sources (e.g., genomic, transcriptomic, proteomic, lipidomic, and metabolomic) that describe or derive from the underlying genomic architecture of a species. These data can reveal deep intraspecific phylogenetic divergence or reciprocal monophyly (i.e., fixed differences in mitochondrial, chloroplast, or nuclear DNA) indicating complete reproductive isolation that may or may not be reflected in observable phenotypic or behavioural differences. For example, genetic data have uncovered cryptic sympatric species in myriad taxa including insects (Ghisbain et al. 2020), fishes (Feulner et al. 2006; Takahashi et al. 2020), and frogs (Fouquet et al. 2007; Funk et al. 2012; Stuart et al. 2006). Significant allelic differentiation at neutral loci, non-neutral loci, or both can also be indicative of partial reproductive isolation of populations. Finally, barriers arising from geology or bathymetry (Babiychuk et al. 2019; Howell et al. 2004; Worsham et al. 2017), hydrology (Markevich et al. 2021), or dams (Barbarossa et al. 2020) can reduce or eliminate gene flow leading to reproductively isolated populations that may not have persisted long enough for detectable genetic/omic differences to accrue. Evidence for demographic independence could include differences in age-class structure (i.e., cohort strength), birth and death rates, effective or census sizes as estimated from genetic data, and historical divergence of effective sizes using genetic-based coalescence analyses. For example, if two 'populations' are panmictic, effective size estimates should be identical between them; in contrast, demographic independence could lead to different effective sizes for each population.

Two lines of evidence can demonstrate *important in the evolutionary legacy of a species*. First, divergent life-history traits can reflect incipient diversification and local adaptation, particularly within geologically young species (Skulason et al. 2019). These differences, while not yet isolating, could represent important elements of biodiversity and evolutionary potential and, therefore, should be reflected in the designation of spatial units. For instance, heterochrony is thought to influence head shape during ontogeny in Arctic charr *Salvelinus alpinus* that, in turn, drives differences in feeding habits (Skúlason et al. 1989). Size and age of maturity (e.g., dwarf vs normal; Vuorinen et al. 1993) can also result in size-based assortative mating (Foote 1988). Deviations in fecundity that can arise from differences in energy availability may lead to divergence in timing of reproduction (Goetz et al. 2011) or skipped spawning in lake charr *Salvelinus namaycush* (Sitar et al. 2014). Divergent trophic resource use is thought to represent a primary axis of resource polymorphism in vertebrates (Skulason and Smith 1995). Second, local adaptation or adaptive diversification of phenotypes through resource partitioning (i.e., occupation of differing eco-regions or use of different trophic resources) or via phenotypic traits under divergent selection (e.g., morphometrics, meristic, osteology) can represent critical elements of biodiversity in the evolutionary legacy of a species (Hakli et al. 2018; Kahilainen et al. 2007).

*Table 4. Data types that can provide evidence in support of criteria for the designation of **Occupied** spatial units. Either Indigenous Knowledge (IK) alone or where IK provides low support or is unavailable (i.e., data deficient), meeting at least one of the other two criteria with at least one data type is required for designation of an **Occupied** unit. Indigenous Knowledge cannot be broken down into categorical components (i.e., data types per Western Knowledge systems with specific lines of evidence); therefore, IK is considered at the criterion level where it alone could establish or refute delineation of a spatial unit under consideration. Weights (+, ++, +++) were pre-determined using the Delphi approach as described in Section 4.1 and Appendix I.*

Criterion	Indigenous Knowledge	Reproductive isolation (including demographic independence) [1,2,3,4,5,6]				Important in evolutionary legacy of the species (i.e., product of past and current evolutionary events) [1,2,6]	
Evidence	N/A	Limited movement or migration	Differences in reproductive time/location/behavior/morphology (e.g., leading to assortative or non-random mating; prezygotic isolating behaviour)	Genetic/ omic divergence	Efficacy of barriers	Life-history variation	Local adaptation / adaptive diversity
Data type							
Catch, harvest, effort			+				
Telemetry		++	++		++	++	
Conventional tagging, banding, marking		+				+	
Microchemistry		+				++	
Observation (e.g., radar, video, visual, ROV, gamete collection)		++	++			+	
Survey (e.g., harvest-independent, weir, passageway/flyway counts, etc)			++		++		
Demography (e.g., births, deaths, age structure at specific locations, times in the reproductive cycle)			+				
Reproductive status (e.g., fecundity; gonadosomatic indices; maturity schedule)	N/A		++			+	
Reproductive anatomy (e.g., organ size, shape)			+				
Ontogeny (e.g., divergent developmental rates)						++	
Hydrology, geology, topology					++		
Genetic/omic (e.g., epigenetics, genomics, proteomics, transcriptomics, lipidomics)				++	++		++
Phenotypic data (e.g., morphometric, meristic, osteology)							++
Resource partitioning (trophic ecology/ecological tracers, diet; stable isotopes; fatty acids, contaminants, habitat)					++		++

[1]Waples 1991; [2]Waples 1995; [3]Moritz 1994; [4]Fraser and Bernatchez 2001; [5]Wood and Gross 2008; [6]COSEWIC 2021

4.4 Unoccupied Unit

Definition—Space (habitat) that historically supported a viable population that is now locally extirpated. This unit type currently lacks the biota of interest; however, the habitat was documented to historically support viable populations through reproduction and recruitment.

Unoccupied units differ from occupied units in that the biota under consideration no longer occupy the reproductive habitat. Unoccupied units are analogous to the concept of critical habitat under the Canadian *Species at Risk Act* that may be identified for listed extirpated species if a recovery strategy has recommended the reintroduction of the species into the wild (Section 58(1); Government of Canada 2002) and the U.S. Endangered Species Act (Department of the Interior 1973). Likewise, unoccupied units are somewhat comparable to how the IUCN defines the indigenous range of biota when providing guidelines for reintroduction or translocation restoration efforts (IUCN/SSC 2013).

Criteria—Three criteria define unoccupied spatial units: (1) Indigenous Knowledge; (2) reproductive isolation or evidence of historically viable populations; and, (3) no contemporary colonization (i.e., occupancy of reproductive habitat; Table 5). Criteria two must be met with at least one type of evidence for a spatial unit to qualify as an unoccupied spatial unit. If criterion 3 cannot be satisfied, that is, the habitat may currently support reproducing biota, it should be evaluated against the criteria for an occupied spatial unit (see Section 4.3). Criterion 3 specifies habitat that supports reproduction because stray individuals can distribute broadly, and migratory biota can traverse non-reproductive habitat patches en route to reproductive habitat.

Indigenous Knowledge (criterion 1) can establish or refute the establishment of a putative unoccupied unit. Many examples highlight the value of Indigenous Knowledge in understanding species distributions (Duncan 2020; Service et al. 2014). Indigenous peoples have been studying the distribution and movement of plants and animals for thousands of years and possess considerable knowledge about their seasonal movements, corridors, life-stage specific habitats, and historical shifts in those distributions. For example, Indigenous Peoples used to migrate seasonally to Siskiwit Bay on Isle Royale to harvest what are now commonly referred to as the siscowet form of lake charr because its high body and organ lipid content was particularly valuable. Duncan (2020) used map biographies and semi-structured interviews in a community-based project to better understand Coregonus spp. biology, habitat, abundance, distribution, and natural history in the Saugeen Ojibway Nation Territories. Areas of Lake Huron that historically supported viable populations of bloater *Coregonus hoyi* were identified by Saugeen Ojibway Nation knowledge holders who participated in the project, and interestingly, a new form of shallow-water cisco was described as a result of this work (Eshenroder et al. 2021). Likewise, Indigenous Knowledge was critical in identifying grizzly bear *Ursus arctos horribilis* population units (Service et al. 2014). Contemporarily, many Great Lakes fisheries are largely prosecuted by Indigenous rightsholders who possess both knowledge and data about contemporary distributions.

Identifying *reproductive isolation or historically viable populations* (criterion 2) is straightforward where sufficient information exists but challenging where information is limited because the likelihood of type-II errors (i.e., false-negative) is inversely related to the amount of inference that must be made. For instance, few historical data are available for rare or under-sampled biota (e.g., deep-water coregonines); therefore, the probability is high of failing to identify historical populations that indeed existed. Data can also be patchy in spatial distribution or vary along a cline (e.g., gradients where data are sparse at the extremes of the distribution compared to the centroid or along a latitudinal gradient [e.g., south to north]). Incomplete information or sampling error (observation bias) could lead to the conclusion that a habitat did not historically support a viable population when indeed it did. Likewise, stochasticity in population demographics or interannual variability in habitat use due to large-scale migrations or climatic shifts (e.g., water levels in lakes or desiccation on land) could also lead to erroneous conclusions regarding historically viable populations where historical information is insufficient to detect such shifts in reproductive habitat use. A predictive modeling approach could minimize type-II error, potentially at the expense of introducing type I-error (i.e., false positive), that is identifying the presence of historical populations where they did not occur. As such, a predictive modeling approach followed by a set of data filters could be used to identify unoccupied spatial units (Hallfors et al. 2016).

The Coregonine Restoration Framework Gap Analysis Task Team will use species distribution models (e.g., Random Forests, Boosted Regression, Classification and Regression Trees, Maxent, Gam/GAMM; See Gap Analysis draft methods) to predict probability of occurrence (or habitat suitability) on historical reproductive habitat. The modeling framework employed will depend on data availability and spatial scale of interest to be determined by resource managers. Consistent with the methods herein, species distribution models will focus on reproductive habitat. Besides Indigenous Knowledge, historical information is primarily fishery dependent and may include effort, catch, or habitat data, but fishery-independent data will be used where available. Importantly, distribution modeling will occur at the species level; therefore, sub-specific biodiversity will not be explicitly captured using a modeling approach. This limitation is not inherent to the modeling; rather, it is a function of available historical data, which were largely captured according to Koelz's (1929) specific nomenclature, and only include a few recognized sub-species of *C. artedi*.

Species distribution model output could be in the form of occurrence probability (P) based on habitat suitability predictions which could be mapped along a spatial gradient (e.g., heat maps) at the whole-lake scale (Tingley and Beissinger 2009). Modeled occupied or suitable habitat will extend the utility of incomplete historical observation but, from a practical standpoint, resource managers will need to identify high-probability units for restoration. As such, transforming probabilities from whole-lake modeled distributions to unoccupied units that are practical for restoration actions will require a series of steps including the following: (1) determine a biologically meaningful threshold (e.g., $P>0.5$) above which historical occupation of a habitat by a species is highly probable; (2) spatially bound all modeled units that exceed the threshold as candidate unoccupied spatial units; (3) identify and bound additional candidate unoccupied units not captured during steps 1 and 2 above (i.e., subspecies or species lacking data sufficient for modeling); and, (4) determine the validity of candidate unoccupied units by assessing the two required criteria (Table 5); i.e., *reproductive isolation* or *historically viable populations* and *no contemporary colonization*, to determine designation of the candidate unoccupied spatial unit.

No contemporary colonization (criterion 3) is, by some measures, an easier criterion to demonstrate for a putative unoccupied spatial unit because multiple years of recent standardized monitoring and assessment data may be available and forensic methods are not typically required. Despite being informed by contemporary assessment, monitoring, or harvest data, the potential for failing to detect contemporary colonization remains a challenge given the vastness of the Great Lakes, the rate at which they are changing in response to environmental stressors, and the spatial and temporal coverage of existing fishery-dependent and fishery-independent data. As described above with respect to criterion 1, species distribution models could inform contemporary colonization. For instance, habitat with a probability of occupancy $P<0.5$ and where no contemporary biological data exist, could be targeted for sampling to demonstrate no contemporary colonization.

Evidence—Three lines of evidence support *reproductive isolation or historically viable populations* (criterion 2) for a putative unoccupied spatial unit. First, presence of historically viable populations can be shown using historical capture, harvest, or encounter records or by independent survey data. Data should not be ephemeral in that many (e.g., $n > 30$) individuals within a year or few (e.g., $n < 30$) individuals across multiple years using reproductive habitat during the breeding period would be required evidence to support the criterion of reproductive isolation or historically viable populations. For instance, 8-12 spawning-condition ciscoes have been captured each November since 2018 in the Escanaba River, MI (J.S. unpublished data), which would provide adequate evidence for *reproductive isolation or historically viable populations* (criterion 2). Second, evidence of reproduction within a spatial unit, whether mature adult records exist or not, could be indicative of habitat that historically supported populations. Many species that have external incubation, including birds (Keeton 1974) and fishes (Bett and Hinch 2016; Thorrold et al. 2001) display some level of homing to their natal origin to reproduce; therefore, fertilized gamete or embryo presence in a habitat across >1 y is indicative of sustained reproduction across multiple cohorts. Third, existing genetic or genomic data or new data collected from archived historical samples can demonstrate deep intraspecific phylogenetic divergence, reciprocal monophyly, or significant allelic differentiation. Genetic or genomic data from historical collections can demonstrate occupation by biota of a particular reproductive area (Nielsen and Hansen 2008; Shiozaki et al. 2021) where taxonomic uncertainty prevents assignment of a sample to a unit. Additionally, historical genetic data may yield supporting evidence for the presence of historically discrete populations and could provide information on how contemporary landscapes were a product of historical processes influencing gene flow (Epps and Keyghobadi 2015).

Lack of contemporary colonization (criterion 3) can be established via four lines of evidence. First, occurrence can be assessed using contemporary survey or harvest data, provided surveys are appropriately designed (e.g., Sandstrom and Lester 2009) to detect occupancy (Strayer 1999). Targeted systematic survey efforts outside of long-term monitoring programs could also identify unoccupied spatial units. Environmental DNA (eDNA) may also provide some insights into lack of contemporary colonization (Jerde 2021) but, as with other sampling techniques, confirming absence remains a challenge. Second, several contemporary technologies could provide data on reproductive habitat occupancy during reproductive periods. For example, location data are available for many freshwater fishes in the Great Lakes through the Great Lakes Acoustic Telemetry Observation System (GLATOS; https://glatos.glos.us/) and for many other animals via the Animal Telemetry Network (https://ioos.noaa.gov/project/atn/). Telemetry data could be analyzed to detect contemporary movements or migrations to historically occupied reproductive habitat during the reproductive period. Third, natural colonization of a historically occupied habitat may no longer be possible due to a natural or anthropogenic barrier to colonization. Finally, genetic or genomic data could provide insights on whether individuals sampled in a putative unoccupied unit are reproductively isolated from neighboring populations or migrants belonging to another population (i.e., are part of another larger spatial unit).

Table 5. Data types that can provide evidence in support of criteria for the designation of ***Unoccupied*** *units. Either Indigenous Knowledge (IK) alone or where IK provides low support or is unavailable (i.e., data deficient), meeting* ***both*** *of the other two criteria with at least one data type is required for designation of an* ***Unoccupied*** *unit. Indigenous Knowledge cannot be broken down into categorical components (i.e., data types per Western Knowledge systems with specific lines of evidence); therefore, IK is considered at the criterion level where it alone could establish or refute delineation of a spatial unit under consideration. Weights (+, ++, +++) were pre-determined using the Delphi approach as in Section 4.1 and Appendix I.*

Criterion	Indigenous Knowledge	Reproductively isolated and/or historically viable population			No contemporary colonization (i.e., occupancy)			
Evidence	N/A	Presence (non-ephemeral) of target biota	Reproduction	Genetic / omic	Absence of target biota	Lack of movement / migration through area	High efficacy of barriers	Genetic / omic
Data type								
Catch, harvest, effort		+			+			
Survey (e.g., harvest-independent, weir, passageway/flyway counts, etc)		++			++		+	
Modeled probability of occurrence		+			+			
Demography (e.g., births, deaths, age structure at specific locations, times in the reproductive cycle)			+					
Reproductive status (e.g., fecundity; gonadosomatic indices; maturity schedule)			++					
Observation (e.g., radar, video, visual, ROV, gamete collection)			+			++		
Genetic/omic (e.g., epigenetics, genomics, proteomics, transcriptomics, lipidomics)	N/A			++			++	++
Telemetry						++	++	
Conventional tagging, banding, marking						+		
Microchemistry						+		
Hydrology/geology/topology							+	
Resource partitioning (Trophic ecology/ecological tracers, diet, feeding; stable isotopes; fatty acids, contaminants)							+	

4.5 SERVICE UNIT

Definition—space (habitat) with no or low probability of historical occupancy and no evidence of contemporary occupancy, but through which introduction of biota or habitat restoration could provide a desired socioecological service.

Spatial units that do not meet the criteria for either occupied or unoccupied units may be considered as putative service providing units (i.e., service unit). For example, a top trophic level could be stabilized by diversifying lower trophic levels via the introduction of ecologs (a unit that is ecologically exchangeable with another unit; Wood and Gross 2008) to extinct biota (e.g., the introduction of Algonquin Provincial Park blackfin cisco to Lake Michigan in place of *C. nigripinnis*; see Bell et al. 2019) or the establishment of a previously non-existent or unknown intermediate population could serve to generate corridors of dispersal between neighboring populations. Service units may also provide opportunities for stewardship actions where historical records are depauperate and could mitigate potential unknowns in historical species distributions used to designate unoccupied units. To illustrate the notion of a service unit, consider Chinook salmon *Oncorhynchus tshawytscha* in Butte Creek, a tributary to the Sacramento River, California. Historically, spring-spawning Chinook salmon did not occur in Butte Creek, but a dam on a nearby creek diverted cold water into Butte Creek, creating suitable habitat in a place that did not previously provide suitable habitat for this ecotype. As a result, a thriving population of spring-run Chinook was established through natural colonization, thereby providing a valued ecosystem service.

Importantly, environmental conditions continue to change in unprecedented ways due to accelerated warming, shifting disturbance regimes, and extreme events (Schuurman et al. 2020). As changes unfold, suitable habitats will be lost, but some habitats that historically did not support biota may become suitable and offer opportunities to establish ecosystem services that were not previously available (Collingsworth et al. 2017; Feiner et al. 2022). Such regime shifts are more prevalent at the extremes of species distributions. The resist-accept-direct (RAD) framework (Feiner et al. 2022; Lynch et al. 2021; Schuurman et al. 2020) provides a basis for resource managers to respond to ecosystem change through reducing reliance on strategies that resist change towards accepting and directing new management regimes in a changing environment. For instance, conservation efforts to maintain populations or restore habitats that may have historically been effective are becoming increasingly unsustainable. Management responses (accept) towards anticipating, adapting, and directing systems towards desired future states (direct) provide the possibility for new opportunities and ecosystem services where they historically did not occur. It is critical to recognize that where Indigenous Rights may be impacted by adapting to changing environmental regimes, management/stewardship responses need to be made with Indigenous partners.

Candidate service units will be identified through an online survey because it is unlikely that data will be available from the literature to help identify putative service units. Both existing (i.e., previously proposed) and new (i.e., recently realized) putative service opportunities will be sought. Managers/stewards will be asked to identify service-providing opportunities that do not meet the criteria for occupied or unoccupied units (i.e., no or low probability of historical or contemporary occupancy). Putative service units identified via the survey will be evaluated against the service unit criteria (Table 6).

Criteria—Three criteria should be met to designate a service unit: (1) Indigenous Knowledge; (2) low or no evidence of historically viable populations; and, (3) no contemporary colonization (i.e., occupancy) of reproductive habitat.

Indigenous Knowledge (criterion 1) can provide information on historical and contemporary distributions but, importantly, can inform Indigenous-led stewardship efforts to generate desirable services for communities. For instance, some U.S. Tribes operate fish hatcheries on the Laurentian Great Lakes to generate fisheries and economic opportunities for their communities. Indigenous Knowledge of sensitive habitats can inform locations for such efforts, or alternatively, where service units should not be located. The authors note that it is not enough to simply recognize Indigenous Knowledge as a criterion to designate a service unit; the separation of Indigenous Knowledge from Indigenous decision makers is unethical; therefore, Indigenous partners should be included in all aspects of the natural resource management framework.

Low or no evidence of historically viable populations (criterion 2) can be estimated based on an established threshold (e.g., $P<0.5$) generated in species distribution models using historical occurrence and habitat data (see Gap Analysis Task Team methods). For the reasons discussed above, we cannot know definitively whether a habitat did not support a historical population, which is why occupancy modeling is a useful tool to a data-informed criterion evaluation for establishment of service units.

No contemporary colonization (criterion 3) can be assessed using the same methods described above for Unoccupied units.

Evidence—Three lines of evidence can demonstrate *low or no probability of historically viable populations* (criterion 2) for a putative service unit. First, historical capture, harvest, or encounter records or independent survey data can provide information on historical populations. For instance, historical distributions (as described above for unoccupied units) can be modeled where $P>0.5$ above indicated that a habitat was likely occupied historically; conversely, $P<0.5$ indicates that a habitat was not likely historically occupied. Second, historical barriers may have prevented occurrence of a species or form in a particular reproductive habitat, but removal of those barriers in the absence of natural recolonization, post-barrier removal, may afford an opportunity to provide ecosystem service(s). Third, a lack of movement or migration to particular areas during reproductive periods can provide evidence that the habitat was unlikely to have supported a historically viable population. Evidence supporting *no contemporary colonization* (criterion 3) is same as that described above under Unoccupied unit; however, weights may differ in this context. Genetic/omic information is identified as an information source potentially providing evidence of *no contemporary colonization*. This information source could potentially allow inferences to be drawn from ecologs for restoration in comparison to potential source populations or by informing population structure in surrounding habitats. For instance, if neighboring populations show strong population structure as opposed to panmixia, that could support an argument for no contemporary colonization.

*Table 6. Data types that can provide evidence in support of criteria for the designation of **Service** units. Meeting both criteria is required for designation of a **Service** unit. Indigenous Knowledge cannot be broken down into categorical components (i.e., data types per Western Knowledge systems with specific lines of evidence); therefore, IK is considered at the criterion level where it alone could establish or refute delineation of a spatial unit under consideration. Weights were pre-determined using the Delphi approach as described in Section 4.1 and Appendix I.*

Criterion	Indigenous Knowledge	Low or no probability of historically viable populations		No contemporary colonization (i.e., occupancy)			
Evidence	N/A	Presence (non-ephemeral) of target biota in reproductive habitat	Efficacy of barriers	Absence of target biota	Lack of movement/migration through area	Efficacy of barriers	Genetic/ omic
Data type							
Catch, harvest, effort		+		+			
Survey (e.g., harvest-independent, weir, passageway/flyway counts, etc)		++	+	++		+	
Modeled probability of occurrence				+			
Observation (e.g., radar, video, visual, ROV, gamete collection)					++		
Genetic/omic (e.g., epigenetics, genomics, proteomics, transcriptomics, lipidomics)			++			++	++
Telemetry	N/A		++		++	++	
Conventional tagging, banding, marking					+		
Microchemistry					+		
Hydrology/geology/topology			+			+	
Resource partitioning (Trophic ecology/ecological tracers, diet, feeding; stable isotopes; fatty acids, contaminants)			+			+	

4.6 Bounding units

Upon completion of an assessment, spatial units could be bounded geographically and depicted on a map if desirable. Boundary edges are plastic and can change in response to biotic and abiotic variation. Boundary edges can also be updated as new information becomes available. Many variables could be used to define boundary edges depending on availability of information. Information used to bound spatial units should be selected to maximize potential unit size thereby minimizing the risk of excluding potentially occupied reproductive habitat—in other words, we recommend erring on the precautionary side when bounding a spatial unit. We also recommend using the best available information to define unit edges, including: (1) geology (bathymetry or topography); (2) physio-chemical habitat (temperature or chemical composition of water or air masses; scope for activity); (3) behavior (range, movements, imprinting); biology (physio-ecological constraints; metabolism); (4) observation (e.g. trap, harvest, surveys, radar, tagging); and, (5) Indigenous map biographies (e.g., Duncan 2020).

5. IMPLEMENTING A SPATIAL UNIT ASSESSMENT

The following eight steps represent an example of how our recommended spatial unit delineation process could be implemented. These steps can be modified to suit assessment team needs or the intricacies of the system being assessed. Note that weights have already been determined, but if the method is being applied to a new taxon or system, weighting should be re-evaluated. A summary of two test assessments performed by the Task Team can be found in Appendix II.

1. Assemble assessment team—The method is designed to be open and transparent. The assessment team should be tailored to the waterbody being assessed and inclusive of anyone with rights (e.g., Indigenous Peoples), local knowledge of the system and/or range-wide knowledge of the biota under consideration, scientific expertise, or management authority, for example.
2. Identify putative units—Putative units can be identified using local knowledge and gap analysis for the target species and lake.
3. Compile relevant information—Information for an assessment will be garnered from sources including the CORHIST database, publications, and agency databases and archives (some of which have been compiled by other task teams). Modeled probability of occurrence data will be compiled as evidence of historical presence or absence of target biota. Data acquisition, compilation, and synthesis will be undertaken.
4. Identify Indigenous Knowledge—Partners from Indigenous Nations/Tribes or organizations will serve as liaisons with other Nations who may have a shared interest in the spatial units being assessed. Indigenous Peoples or representatives can join the assessment team as they desire. Indigenous Knowledge holders are not often paid to be part of processes like this, so, resources will be sought to include Indigenous knowledge holders in any assessment.
5. Evaluate data to determine evidentiary support for each criterion—Apply the IDEA approach to determine average level of support (DD, NS, Low, Moderate, or High) for each evidence type under consideration.
6. Apply weights—Pre-determined weights will be applied to each information type and the overall assessment of evidence in support of each criterion will be compiled.
7. Apply decision rules—Decision rules will be applied to each putative unit assessment to obtain a decision: accept as a spatial unit, reject, or deem data deficient.

8. Delineate units—Where desirable, boundaries for each identified spatial unit can be delineated using the best available information and spatial units can be depicted geographically via polygons.

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APPENDIX I: THE PROCESS OF WEIGHTING DATA TYPES

***Using the Delphi method to weight data types on* relevance*,* strength*, and* reliability—** A structured approach to expert elicitation known as the Delphi method (Hanea et al. 2017; Hemming et al. 2018) was used to weight the data types that were identified as supporting evidence and criteria for unit delineation. Here, the process involved a four-step approach to refining an overall weight for each data type: (1) a panel of experts (the Task Team) independently weighted data type properties based on the *relevance*, *strength*, and *reliability* of those data types to the lines of evidence they can support using the qualitative scores of +, ++, +++ (see Section 4.1); (2) compiled results from independent weightings were discussed as a group, including points of consensus and divergence; (3) a second round of independent weighting was then undertaken; and, (4) rounded average weight from the second independent evaluation was assigned to each data type as an overall weight.

Virtual expert elicitation for reviewing and weighting data types— Data type weighting with the Delphi method may take considerable time depending on the number of data types originally identified as informative to lines of evidence for Spatial Unit criteria. The importance of having established overall weights in place prior to a Spatial Unit assessment made practical options for performing this process virtually and/or over multiple days appealing. The weights for data types presenting here were generated over multiple 2-hour virtual meetings of the Task Team.

To facilitate this process, an online spreadsheet with Google Sheets was created with column fields for relevance, strength, and reliability for each data type under consideration for each line of evidence. Rows were created for each member of the Task Team to score each field and for Task Team score averages, and filter views were created for each member of the Task Team. When a Team member's filter view was enabled, only the evidence and data type fields, the individual's scores, and the Task Team score averages were visible. The qualitative scores of +, ++, and +++ were translated to the numerical scores of 1, 2, and 3 for ease of use and averaging within a spreadsheet.

The Delphi method of evaluating and qualitatively weighting each data type also enabled the Task Team to review and refine data types prior to proceeding with Unit assessments. During this process, some of the originally identified data types were removed, renamed, or combined for consistency. For example, under evidence for *Differences in reproductive time/location/behavior/morphology* supporting the criterion *Reproductive isolation*, "Gonadosomatic indices/maturity schedules/histology" was originally listed as a data type, while under evidence for *Life history variation* supporting the criterion *Important in evolutionary legacy of the species (i.e., product of past and current evolutionary events),* "Size and age at maturity" and "Fecundity" were originally identified as separate data types. After evaluation, these data types were combined in a single, comprehensive data type "Reproductive status (e.g., fecundity; gonadosomatic indices; maturity schedule)" that could be used for both lines of evidence.

The weighted data types in the Spatial Unit delineation methods presented here were designed to be comprehensive and applicable both to and beyond the aquatic ecosystem for which they were originally developed, however, we recommend an expert review of suggested data types and overall weights to assess their suitability prior to a Spatial Unit assessment in a new ecosystem. Future assessments in the Great Lakes or other ecosystems could easily adopt the process described here to review the need for changes or additions to data types.

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APPENDIX II: A TEST OF OCCUPIED AND UNOCCUPIED UNITS IN LAKE ONTARIO CISCO

We assessed the performance of our described Spatial Unit methods using a test case of Great Lakes Cisco (*Coregonus artedi*). The purpose of this assessment was two-fold: first, to evaluate the comprehensiveness of designated data and evidence types, and second, to test the functionality of assigned weights and scoring of Western science data types in support of evidence and criteria for Spatial Units.

Of the four Great Lakes containing extant Cisco populations, Lake Ontario was selected for testing Spatial Unit methods. Lake Ontario was once home to a thriving commercial fishery for Cisco and spawning was documented in the numerous shallow water habitats around the lake (Figure 1a). Over the past century, intense exploitation, invasive species, and habitat degradation and destruction have had a substantial impact on the Cisco populations in Lake Ontario (Scott and Crossman, 1973; Goodyear et al. 1982). Today, Cisco spawning populations are restricted to the eastern end of the lake and are a fraction of the historic populations once present (Figure 1b; George et al., 2017; George et al., 2018; Paufve et al., 2021; Brown et al., 2022; Brown et al., 2023, Gatch et al., 2023). The combination of both 1) habitat that continues to support spawning Cisco populations and 2) habitat that historically supported Cisco

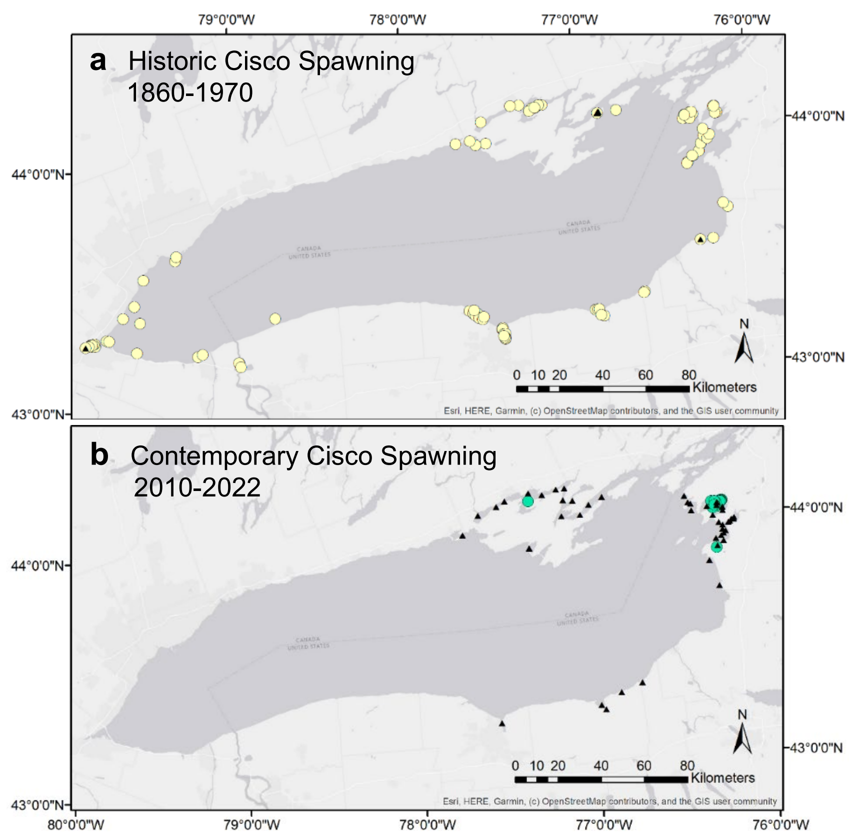

Figure 1. Historic (a) and contemporary (b) spawning occurrences of Cisco in Lake Ontario. Colored circles represent spawning areas (based on catching spawning adults OR collecting cisco eggs from substrate). Black triangles represent locations where cisco larvae were collected.

spawning populations but no longer supports contemporary Cisco spawning populations makes Lake Ontario an ideal candidate for assessing Occupied and Unoccupied Unit methods. Additionally, Cisco spawning habitat in Lake Ontario is fairly well-studied (Pritchard, 1931; George et al., 2017, Paufve et al., 2021) but only moderately complex relative to other Great Lakes that support multiple extant and extirpated Cisco populations such as Lake Huron. This provided a good balance of available information on which to assess the performance of Spatial Unit methods without requiring extensive time to compile the data required to do a robust test assessment.

Two test assessments were run through virtual workshops in early 2023: 1) a test of Occupied Unit methods, and 2) a test of Unoccupied Unit methods. Methods developed for Unoccupied Unit delineation and Service Unit delineation are extremely similar, with the major difference between the two hinging on the probability of historical occurrence of the taxa under consideration. Given this similarity, it was determined that a Service Unit method test would be unnecessary following a test of Unoccupied Unit methods. Occupied and Unoccupied Unit test assessments focused specifically on the performance of Western science-based criteria, evidence, and data types, and used the same virtual platform for employing the Delphi method of expert elicitation as described for data type weighting in Appendix I.

Occupied Units Test

Science Team Participants: Amanda Ackiss, Andrew Muir, Ralph Grundel, Jory Jonas, Ryan Lauzon, Brian O'Malley*, Breanna Redford, Mark Ridgway, Jason Smith

Regional Expert Participants: Jeremy Holden (Ontario Ministry of Natural Resources and Forestry), Tim Johnson (Ontario Ministry of Natural Resources and Forestry), Brian Weidel (USGS Lake Ontario Biological Station), *Team member Brian O'Malley is also a regional expert.

On February 14th, 2023, a test assessment of the Occupied Units methods was held remotely via Zoom. Participants included members of the Resolve Taxonomy Task Team as well as invited regional experts with knowledge of Cisco populations in Lake Ontario. The assessment was facilitated by Science Team member Ackiss, and the assessment team stepped through each available *data type* that had been identified to support or refute *evidence* for the two Western science-based *criteria* supporting the delimitation of Occupied Units: Criterion 2) *Reproductive isolation*, and Criterion 3) *Importance in the evolutionary legacy of the species*.

Unoccupied Units Test

Science Team Participants: Amanda Ackiss, Andrew Muir, Ralph Grundel, Ryan Lauzon, Nick Mandrak, Brian O'Malley*, Tom Pratt, Mark Ridgway

Regional Expert Participants: Jeremy Holden (Ontario Ministry of Natural Resources and Forestry), *Team member Brian O'Malley is also a regional expert.

On April 24th, 2023, a test assessment of the Unoccupied Units methods was held remotely via Zoom. Participants included members of the Resolve Taxonomy Task Team as well as invited regional experts with knowledge of Cisco populations in Lake Ontario. The assessment was facilitated by Science Team member Ackiss, and the assessment team stepped through each available *data type* that had been identified to support or refute *evidence* for the two Western science-based *criteria* supporting the delimitation of Unoccupied Units: Criterion 2) *Reproductively isolated and/or historically viable population*, and Criterion 3) *No contemporary colonization.*

ASSESSMENTS SUMMARY

Prior to the assessments, data informing evidence supporting or refuting Occupied and Unoccupied Unit criteria were compiled by Task Team co-leads. Ranking weighted data types as data deficient or No, Low, Moderate, or High Support was run remotely through Google Sheets using the Delphi method following the same protocol outlined in Appendix I. Once all participants independently evaluated available data supporting or refuting a line of evidence, all assessment participants undertook a discussion about the available data facilitated by the Task Team co-leads, specifically focusing on areas where scores across participants may have strongly varied. After discussion, a second and final, independent evaluation occurred whereby participants could modify their original score. The average score across all participants was used to generate a weighted, overall score of No Support, Low Support, Moderate Support, or High Support for each data type supporting or refuting a line of evidence.

Since preliminary data compilation was not fully comprehensive and the Lake Ontario Cisco test assessments were meant to evaluate the performance of Occupied and Unoccupied Unit methods, specific Spatial Unit outcomes are not reported here. The process of performing test assessments overlapped with data type weighting (though data types for a specific Spatial Unit had overall weights assigned prior to the start of the specific test assessment), which allowed for the refinement of data and evidence types within the context of a real-world example. The outcomes were reached using the semi-quantitative methods outlined in this paper, but feedback from regional experts indicated that the results aligned well to expectations. Overall, the assessment panel consensus was that the methods performed well to synthesize available data and expert knowledge in a structured approach to providing guidance on regional conservation, restoration, and service units.

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