**Appendix S1:** **Ranking accessibility on British Columbia and Yukon lake trout lakes using multivariate statistics: a proxy for fishing effort and exploitation pressure**

*Background*

Fishing effort and exploitation pressure was expected to vary across lakes for the BC and Yukon lake trout fishery. This variation was thought to be driven, in part, by biological conditions of the lake, e.g., size of the catch (Johnson and Carpenter 1994), and also by infrastructure and other features related to accessing the lake (Hunt 2006; Post et al. 2008; Kaufman et al. 2009; Hunt et al. 2011). These two components are inherently intertwined. Conditional on environment, variation in fishing effort is expected to lead to variation in life history traits, especially growth, by altering size-structure and reducing fish abundance via harvest and catch-and-release mortality. This is due to compensatory growth arising from inverse density-dependence changing per capita resource availability (Post et al. 1999). Conditional on environment, lakes with high fishing effort should have higher growth rates and vice versa. Hence, descriptions of exploitation pressure (or proxies) would help to understand and predict clinal life-history responses expected from exploitation.

The frequency that a lake is chosen as a fishing site likely depends on how difficult or easy it is for anglers to access that lake. This includes the relative ability for anglers to: (1) drive to that lake (e.g., paved road, close to town, or fly in lake via float plane), (2) stay near that lake after a long day of driving and fishing (e.g., lodging or camping), (3) launch a boat into the water (e.g., boat launches or marinas on lake), and/or (4) whether guiding operations exist for that lake. The positive relationship between access features, like road access, and fishing effort are empirically supported in other spatially structured lake trout fisheries (Kaufman et al. 2009), and is an important assumption for modelling the numerical response of anglers to fishery resources in many data-limited and spatially-structured fisheries.

*Objectives*

Unfortunately, direct information on effort and fishing mortality was not available on most lakes in the lake trout fishery. To circumvent this lack of information, we developed a proxy ranking of exploitation pressure for BC and Yukon lakes based on their relative accessibility. Specifically, we used a multivariate statistical approach to describe how lakes cluster based on features of the lake such as: predominant road type, minimum travel time from nearest town, number of campgrounds, etc. Hence, our specific hypothesis was that access ranks can be described by multivariate clustering analyses (Legendre and Legendre 2012), and that exploitation pressure is associated with these access ranks (see Kaufman et al. 2009). If lakes with similar access features clustered together, then we can construct a hierarchical decision tree to rank exploitation pressure on BC and Yukon lakes based on access and infrastructure data. While only a crude approximation of effort, we attempted to validate such an approach by comparing these ranks both to expert opinion (i.e., where fishery managers are already most concerned with high exploitation) and to available creel data on 30+ Yukon lakes.

The different jurisdictions (British Columbia management regions, and Yukon) had different data available to conduct this analysis and ranking. Some metrics have been quantified more rigorously in one jurisdiction than in others. Generally, BC geospatial databases have much more quantitative data available on access. However, Yukon had more effort data available to validate our approach, but only has qualitative or occurrence type data on access/infrastructure. See Table S1.1 for example data that was used in both the clustering analyses (excluding Yukon data) and on ranking the lakes *post hoc* to analyses (including Yukon data).

*Access on British Columbia Lakes*

Direct measurement of exploitation pressure on British Columbia lake trout populations was unavailable. However, access information was available and could be used in a multivariate, hierarchical clustering framework to help rank likely exploitation on BC lakes. The data available for this analysis on accessibility included: (1) predominant road type (e.g., the major road access to get onto the lake: paved road, forestry road, or no road access), (2) whether a lake was within 0.5 hour drive of the nearest town (i.e., short day trip), (3) whether a lake was between 0.5–2.5 hours of the nearest town (i.e., long day trip), (4) presence/absence of reported guiding (i.e., registered Freshwater Guided Recreation, mostly related to licenced commercial guiding activity in backcountry lakes), (5) the number of provincial park campgrounds and recreational sites, (6) the number of private lots (i.e., fee simple parcels and rural crownland leases), (7) the number of fishing lodges and marinas, (8) the number of permits and leases for hunting camps, fishing camps, and cabins, (9) the number of nearby reserves, and (10) the historical and contemporary presence of First Nations’ gillnetting. The data for the above metrics were collected from BC provincial databases. Registered BC angling guides annually report on fishing operations within the province, including species captured and which lakes were fished. Provincial GIS and spatial databases (GeoBC) document the degree of fisheries-related development including: fee simple parcels, lodges, marinas, and lots.

*Access on Yukon Lakes*

Accessibility data for Yukon lake trout populations was much less quantitative than BC lakes, composed of mostly the presence or absence of certain types of infrastructure. The data was composed of: (1) predominant road type (e.g., the major road access to get onto the lake: paved road, unpaved road, or no road access), (2) whether a lake was within 0.5 hour drive of the nearest town (i.e., short day trip), (3) whether a lake was between 0.5–2.5 hours of the nearest town (i.e., long day trip), (4) presence/absence of known guiding operations, (5) presence of territorial park campgrounds and recreational sites, (6) presence of fishing lodges, resorts, and marinas, (7) presence of fishing camps and cabins, (8) presence of nearby First Nations, and (9) the historical and contemporary presence of First Nations’ gillnetting operations.

Yukon lakes were not used in the hierarchical clustering analysis. However, this data was used to rank Yukon lakes *post hoc* based on the decision tree created from analyses of BC data (see section *Decision tree* below). Note that if lakes were considered not road accessible, hence they were considered accessible only from fly-in or hike-in users, then the travel time for those lakes was not included. This was done to penalize travel time for those lakes as, anecdotally and logically, fly-in/hike-in lakes receive far less fishing effort than lakes with road access. While fly-in lakes might have less than a 2.5 hour travel time, this penalty had the added benefit of ensuring these types of lakes grouped together in the clustering analysis for the two drive time variables (e.g., fly-in lakes did not vary in travel time penalties from other fly-in lakes).

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| Table S1.1 – Subset example of the available access information used in hierarchical clustering analysis to partition and rank British Columbia and Yukon Lakes. Note – if the region included the Yukon, the data input changes from quantitative to qualitative (i.e., occurrence of access feature). | | | | | | | | | | |
| Name | Region | Road Type | Minimum Drive Time (hrs) | Guides? | Camping and Recreational Sites | Private Lots | Lodges and Marinas | Permits for Camps and Cabins | Nearby FN reserves | FN netting? |
| Aconitum | Skeena | None | (Fly-in) | Yes | 0 | 0 | 0 | 1 | 0 | No |
| Adams | Thompson | Paved | 0.72 | No | 9 | 145 | 1 | 1 | 3 | No |
| Aeroplane | Peace | None | (Fly-in) | Yes | 0 | 0 | 0 | 1 | 0 | No |
| Aiken | Omineca | Paved | 8.07 | Yes | 0 | 3 | 0 | 1 | 0 | No |
| Airline | Omineca | None | 3.28 | Yes | 0 | 0 | 0 | 1 | 0 | No |
| Aishihik | Yukon | Paved | 1.83 | No | Yes | Yes | No | Yes | Yes | Yes |
| Allan | Skeena | Paved | 0.54 | No | 0 | 0 | 0 | 0 | 0 | No |
| Alligator | Yukon | None | (Fly-in) | No | No | No | No | Yes | No | No |

*Data standardization*

The BC access data had mixed variable types (i.e., categorical discrete rank, occurrence, and numerical continuous) which could be standardized on a common axis (see Gelman 2008) for use in a multivariate, hierarchical clustering analysis. We standardized occurrence data by centering this vector on the mean for that variable as recommended in Gelman (2008). For example, in the ‘Road Access?’ categorical data vector: ‘No Road’ was scored as a 0, and all other road access types were scored a 1. For the ‘Paved Road’ category, both ‘No Road’ and ‘Forest Road’ were scored as a 0, and ‘Paved Road’ was scored as a 1. Lastly, we standardized all numerical continuous data types by centering on the mean and dividing by twice the standard deviation.

Lakes were capped at a maximum value of 1.5 for any given standardized attribute (Table S1.2). This cap was required because a few lakes can dominate the point variability for certain infrastructure attributes, and because increases in any given infrastructure attribute would likely lead to diminishing returns for increases in fishing effort due to density-dependent crowding. This removed the effect of extreme outliers on the clustering analysis. The real-world value for this threshold cap depends on the mean and standard deviation for that attribute (Table S1.2). An example is that Shuswap Lake has over 3,000 private parcel lots, whereas no other lake has more than 912 lots, and only 47 lakes have as many as 5 lots. With a mean of 41 lots per lake and a standard deviation of 225, Shuswap Lake gets a standardized value of 7.11; this is an exceedingly extreme outlier. If not capped at some cutoff, clustering model would place Shuswap in its own cluster. The consequences for this would be that these outlier lakes share no commonality with other ‘well-developed’ lakes. On a lake-by-lake basis, this lack of commonality might be indicative of abnormally high fishing pressure. However, the effect of extreme outliers precludes generalizations of the effort–access relationship and confounds the clustering analysis. Furthermore, the dominance of any one category to create a single-lake cluster is also outside the expectations of fisheries experts in the region (BC FLNRO personal communication). In the case of private parcel lots, capping at 1.5 is explicitly stating that all lakes with ≥ 716 private lots are considered equivalent in number of lots (i.e., they will have the same effect on fishing effort); only Shuswap Lake and Cluculz Lake ≥ 716 private lots. In this instance, capping helped bring Shuswap Lake closer to lakes that were considered similar to it *a priori*, like Lac La Hache or Moberly Lake.

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| Table S1.2 - Various thresholds that can be used to cap extreme outliers for different access attributes, the confidence intervals that cap would, and the value of that cap in unstandardized units of that attribute. *Note* – numbers in ***bold*** were the thresholds used in the multivariate clustering analysis. | | | | | | | | | |
|  | Threshold used to cap standardized access attributes  (and associated confidence intervals) | | | | | | | | |
|  | 1 | 1.25 | ***1.5*** | 1.75 | 2 | 2.25 | 2.5 | 2.75 | 3 |
| Access Attribute | (0.95) | (0.9876) | ***(0.997)*** | (0.9995) | (0.99993) | (0.999993) | (0.999999) | 1.0 | 1.0 |
| Private lots | 491 | 604 | ***716*** | 829 | 942 | 1054 | 1167 | 1279 | 1392 |
| Lodges and marinas | 2.32 | 2.84 | ***3.37*** | 3.89 | 4.42 | 4.94 | 5.47 | 5.99 | 6.51 |
| Provincial parks and campgrounds | 3.37 | 4.06 | ***4.74*** | 5.43 | 6.12 | 6.81 | 7.50 | 8.18 | 8.87 |
| Permits for camps or cabins | 1.99 | 2.38 | ***2.77*** | 3.16 | 3.55 | 3.94 | 4.32 | 4.71 | 5.10 |
| Nearby First Nation's reserves | 3.77 | 4.60 | ***5.43*** | 6.26 | 7.09 | 7.92 | 8.75 | 9.57 | 10.40 |

*Analyses*

Determining the optimal number of clusters in a clustering analysis is relatively subjective, and is as much art as science (see Hennig 2014). We assessed the optimal number of unique rankings to use in ranking of BC and Yukon lakes using a hierarchical clustering analysis *hclust* in R (R Statistical Community 2016) across a range of *k* number of clusters for the BC dataset, following advice from Hennig (2014). The standardized BC access dataset was used to calculate a Euclidian distance matrix ***D***. The matrix ***D*** was then fed into the hierarchical clustering analysis, using Ward’s clustering criterion (Ward 1963; Murtagh and Legendre 2014), and the reconstructed cluster tree was then cut into *k* clusters. Each lake was then assigned a rank from 1 to *k*. For each value of *k*, we calculated summary statistics such as the normalized gamma, Dunn’s index, average silhouette width, widest within-cluster gaps, within-cluster sum of squares residuals, cluster stability, and cluster separation. The optimal number of clusters corresponds to when the gamma, Dunn index, silhouette width, and widest within-cluster gaps are maximized. The optimal number of clusters is also indicated by correspondingly steep decline in the slope of the within-cluster SS against cluster size *k*. Furthermore, sufficient number of clusters is indicated when clusters are relatively stable (after a randomized bootstrap approach), and this sufficient *k* occurs before a steep decline in the cluster separation index.

After finding the optimal number of clusters, we then conducted an ANOVA to describe how a variable *i* varies across lake-access type *j*. We then conducted Tukey’s HSD on that ANOVA outcome to evaluate how the mean and variation of variable *i* compares across different lake types. For example, are two different lake types similar across all access variables except one, or are they different in every access variable? Lastly, we conducted a MANOVA for all access variables *i* across each lake-type cluster to have a holistic measure of accessibility to see how these correlated standardized access variables combine to vary across all cluster types.

*Results*

The various summary statistics for diagnosing optimal clustering generally found a range of optimal *k* from 2–8, but disagreed on any one particular value for *k* (Figure S1). While a *k* = 8 was supported in several diagnostic metrics, the stability of the clusters was seriously reduced (see Figure S1) suggesting it was not an optimal *k* according to Hennig (2014). Based on combinations of these statistics, intermediate values of *k* indicating about 3–6 unique lake-types were supported, and different diagnostics were all high or above average when *k* = 5. Figures S2–S5 explored and diagnosed the cluster tree, and how the access variables varied across those cluster-types when *k* = 5. We constructed a decision tree to rank BC and Yukon lakes into ordinal ranks 1–5 based on either quantitative or qualitative measures of accessibility and fishing activity, including fisheries-related infrastructure developed (Figures S4 and S5).

Figure S1.1 – Various metrics to diagnose optimal number of *k* cluster for a clustering analysis. Example *k* indicated with filled dots range from 3 to 10.

Figure S1.2 – Clusters-wise comparison of principal components 1 and 2 when *k* = 5. These two components explain 50% of the point variability.



Figure S1.3 – Hierarchical cluster dendrogram when *k* = 5.

The five lake types varied in the composition of their access attributes (Figures S1.4 and S1.5, Tables S1.3 and S1.4). Types *a*–*c* were lakes with roads and moderate to high amounts of infrastructure, but these lakes varied from one another in travel time, paved road access, private lots, and fishing lodges and marinas. Lake type *a* were mostly unroaded with heavy guiding activity, and also had intermediate amounts of some infrastructure, but lacked lodges, private lots and were generally far away from the nearest towns. Lake type *b* were the most well-developed in infrastructure being typically close to towns, with lodges and private lots while scoring high in most other attributes. Lake type *c* were lakes that were moderately developed. They tended to be close to towns, but were located on unpaved roads and lacked lodges and some other attributes. Lake type *d* lakes were also moderately developed. They differ from *c*-class lakes in that they are further away (98% of *d*-class lakes are located 0.5–2.5 hours drive time), and lacked reported guiding activity. Type *e* lakes were not developed. They had no road access, and generally lacked any other infrastructure.

*Lake classification*

After choosing an optimal *k* of 5, we ranked accessibility, and hence, exploitation pressure on British Columbia and Yukon lake trout lakes into the following five classifications based on the outputs from Figures S1.4–S1.5 above:

1. Pristine (lake-type ‘e’) – while all lakes see some level of human visitation, the remote wilderness lakes in this category would be those that don’t have known regular hunting outfitter use (lack a cabin or tent camp tenure) and generally appear infrequently visited
2. Semi-pristine (lake-type ‘a’) – remote backcountry and wilderness lakes without road access but that do experience regular use by anglers, hunters and hunting outfitters; would usually have one or more outfitter cabins or camps by crown lease
3. Backcountry (lake-type ‘d’) – lakes farther from highways which lack paved road access and private residences but have some kind of public facilities like a road accessed park or rec site with boat launch
4. Semi-developed (lake-type ‘c’) – lakes with good road access and not overly far from the highway, but with a lower amount of residences and/or lacking commercial development
5. Developed (lake-type ‘b’) – lakes having paved road access near a town (< 30 minutes), hundreds of private lots and lots of infrastructure often including lodges/resorts or busy Provincial Park(s)

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| Table S1.3 – Mean number of attributes present, and two standard deviations, in British Columbia across each lake-type. Values are from lakes in the British Columbia dataset. | | |
| Lake-Types | Mean No. of Attributes Present | 2σ |
| 1 | 0.18 | 0.78 |
| 2 | 2.03 | 1.74 |
| 3 | 1.70 | 2.45 |
| 4 | 1.28 | 2.16 |
| 5 | 4.29 | 2.43 |

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| Table S1.4 – Mean occurrence of access attributes across each lake type in British Columbia lakes. | | | | | | | | | | |
| Lake Type | Camp-grounds | Private Lots | Lodges | Cabins | First Nation reserves | Road? | Paved? | Travel  (≤0.5 h) | Travel  (0.5–2.5 h) | Guided? |
| 1 | 0.00 | 0.02 | 0.00 | 0.16 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2 | 0.14 | 0.17 | 0.00 | 0.63 | 0.10 | 0.40 | 0.00 | 0.03 | 0.17 | 1.00 |
| 3 | 0.68 | 0.44 | 0.07 | 0.30 | 0.21 | 1.00 | 0.18 | 0.00 | 0.96 | 0.00 |
| 4 | 0.39 | 0.41 | 0.10 | 0.11 | 0.11 | 1.00 | 0.38 | 0.52 | 0.02 | 0.15 |
| 5 | 0.82 | 0.94 | 0.88 | 0.41 | 0.76 | 1.00 | 0.88 | 0.71 | 0.18 | 0.47 |



Figure S1.4 – Cluster-wise comparisons of class type to unstandardized access variables.



Figure S1.5 – Cluster-wise comparison of the mean (points), 95% confidence intervals (solid lines) and total range (dashed lines) across standardized access variables. Colors of lines and the letters above each cluster indicate significantly similar clusters for that variable according to pairwise ANOVA and Tukey HSD. Bottom right panel indicates the relative accessibility across all attributes sorted by increasing mean accessibility (according to MANOVA results)

*Decision tree*

Below is the hierarchical decision tree followed to rank effort and exploitation on lake trout lakes based on the lake-types resulting from the clustering analyses:

1. Does the lake have road access?
   1. Yes – Is the lake within 30 minutes of the nearest town?
      1. Yes – Does it have 3 or more attributes, including private lots and lodges?
         1. Yes (Class 5 lake)
         2. No (Class 4 lake)
      2. No – Does it have at least 5 attributes, including private lots and lodges?
         1. Yes (Class 5 lake)
         2. No – Is it paved with at least 4 attributes, including private lots and lodges?
            1. Yes (Class 5 lake)
            2. No – Does it have at least 2 attributes, but isn’t 0.5–2.5 hours away, and lacks fishing cabins?

Yes (Class 4 lake)

No – Does it have at least 1 attribute, is within 0.5–2.5 hours away from the nearest town, and lacks guiding

Yes (Class 3 lake)

No – Does it have no more than 2 attributes, is more than 2.5 hours away, is not paved, and has a fishing cabin?

Yes (Class 2 lake)

No (Class 4 lake)

1. No, the lake does not have road access
   1. Does the lake have any access attributes?
      1. Yes (Class 2 lake)
      2. No (Class 1 lake)

*Model Validation – Comparisons to creel data in Yukon*

We used the average occurrence of any access attributes, and the occurrence of each access attribute, associated with the five lake classes to construct a decision tree and rank the 152 Yukon lakes (see *Decision Tree* above). The proportion of each rank class observed was similar between the two jurisdictions, with the exception that there were more pristine lakes in Yukon and comparatively more backcountry lakes in British Columbia (Table S1.5). Historical differences in infrastructure development between the two jurisdictions explain this discrepancy. British Columbia has a more developed highway network due to its larger and more dispersed population which has led to more paved and unpaved roads connected towns and lakes, especially for towns and lakes more distant from mainland BC (i.e., Vancouver metropolitan area) compared to Yukon. The population in Yukon is concentrated in and adjacent to Whitehorse. Hence, lakes with road access tend to be clustered around Whitehorse and tend to be more well developed (i.e., class 4–5 lakes) due to demands for fishery resources. Conversely, more distant lakes remain, more often than not, inaccessible and undeveloped (i.e., class 1 lakes). Given the scope of undeveloped areas in Yukon, it is no surprise that there are proportionally more pristine, inaccessible lakes at the expense of moderately developed lakes compared to British Columbia.

Effort data was available in 33 Yukon lakes, and the access ranks for these lakes ranged from semi-pristine (class 2) to developed (class 5). Using a generalized linear model with a Gamma distribution and inverse link function we assessed the relationship between access ranks and effort density. There was a significant and positive relationship between effort and lake class (Figure S6). On average, there was an increase of ~1.25 angler hours per hectare per increase in accessibility rank (*p* = 0.013). This supports our prediction of a positive relationship between access and effort, and that we can approximate effort with the accessibility ranks resulting from our clustering analysis approach.

Catch data was available in 30 Yukon lakes, and the access ranks for these lakes ranged from backcountry (class 3) to developed (class 5). Using a generalized linear model with a Poisson distribution we assessed the relationship between access ranks and total catch (number of lake trout caught per summer season). There was a significant and positive relationship between total catch and lake class (Figure S1.7). On average, there was an increase of ~0.25 on the log(λ) of the Poisson in total catch per increase in access rank (*p* << 0.001) – back-transformed, this manifests a difference in expected total catches of 557 and 331 lake trout between developed (class 5) and backcountry lakes (class 3), respectively. This supports our prediction of a positive relationship between access and catch, and that we can approximate fishing pressure and mortality with the accessibility ranks resulting from our clustering analysis approach.

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| Table S1.5 – The number of lakes and proportion of lakes within each lake class for each of the jurisdictions in the lake trout fishery. | | | | | | |
|  |  | Lake Class | | | | |
| Jurisdiction | N | 1 | 2 | 3 | 4 | 5 |
| British Columbia | 262 | 0.21 | 0.27 | 0.22 | 0.23 | 0.06 |
| Yukon | 152 | 0.39 | 0.24 | 0.09 | 0.18 | 0.10 |



Figure S1.6 – Effort density (angler hours per hectare) across each lake class for Yukon lake trout populations using decision tree from hierarchical clustering analysis. Statistical relationship between effort and lake class indicated from best-fit lines using (1) generalized linear model with gamma distribution and log-link function (red solid), (2) smoothing line (dashed blue), and (3) polynomial spline (dashed orange line).



Figure S1.7 – Total catch (number caught per year) across each lake class for Yukon lake trout populations using decision tree from hierarchical clustering analysis. Statistical relationship between total catch and lake class indicated from best-fit lines using (1) generalized linear model with Poisson distribution and log-link function (red solid) and (3) polynomial spline (dashed orange line).

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