BIOS 35502: Practicum in Field Biology

A landscape position analysis of UNDERC lakes and a determination of its crayfish diversity is related to landscape position

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Abstract

Landscape position, generally defined as a lake's position within the groundwater and/or surface flow system, has proven to be an effective way to explain much limnological variation. The lake order metric is a very efficient tool for explaining landscape position and is easy to measure using solely geographical information. I analyzed each of the 38 permanent lakes and bogs on the UNDERC property in order to determine how they fit into the lake order model using the following variables: lake area, perimeter, shoreline development factor, maximum depth, pH, conductivity, chlorophyll *a* concentration, crayfish abundance and Secchi depth. It was hypothesized that each of variables would each follow the trends predicted by the lake order model. Additionally, the relationship between crayfish richness and lake order was investigated at UNDERC as a novel variable to the model. Of the nine variables, only three (maximum depth, chlorophyll *a* and Secchi depth) were not significantly related to lake order, indicating that the UNDERC lakes most fit into the lake order model and further significance was limited by the small sample size of lakes on the property. In only one lake (of the highest order) was more than one crayfish species found. This indicates that more lakes need to be analyzed before any conclusive judgments of richness can be made. UNDERC may benefit from future

landscape position analyses as they provide insight to proximate mechanisms, and how they may react to future external forces.

Introduction

Lakes within the same lake district share similar origins, climates and catchment areas but differ in many physical, chemical, and biological aspects. Understanding the underlying causes of this heterogeneity has been a recurrent theme of regional limnology. However, efforts to select the best predictors and to identify proximate causes have tended to obscure the spatial linkages among lakes in the landscape and have thus hampered a landscape perspective on lake districts (Riera *et al*. 2000). Only recently, in fact, have lakes been viewed along a spatial gradient, interconnected through groundwater and/or surface water pathways (Kratz *et al*., 1997; Soranno *et al.,* 1999; Riera *et al*., 2000; Quinlan *et al.,* 2003, Martin & Sorrano 2006). The studies that have identified and evaluated the importance of spatial structure across lakes have found that variability of some lake features follow a pattern consistent with the position of the lake within the landscape. The basis of this categorization is two-fold. First, lake features within a lake district are not randomly distributed in space but reflect a spatial pattern (Riera *et al*., 2000). Furthermore, each lake district displays a characteristic spatial organization, and different metrics of landscape position can reveal different aspects of this spatial pattern within a lake district, or among lake districts (Riera *et* al., 2000). Second, dissimilar lake features such as those included in the categories of morphological variables, water optical properties, major ions, biological variables, nutrients, and human-use variables, which may seem apparently unrelated to each other, are nonetheless related to a lake's landscape position (Riera *et al*. 2000). Thus, landscape position is related to a broad array of lake properties.

Lake landscape position, as defined by Kratz *et al*. (1997) is a "combination of the hydrologic description with information on the spatial placement of a lake within a district." Three predominant metrics for measuring lake landscape position have been described. The first is based on the relative position of a lake within the ground water system. The higher a lake is in the landscape the less groundwater input it has and as a result, less calcium and magnesium concentrations (Kratz *et al*., 1997). The second metric, developed by Soranno *et al*. (1999), is known as "lake chain number" and it measures lake landscape position with regard to lakes connected along a linear chain through primary surface-flow systems (Martin & Soranno 2006). Therefore, as lake chain number increased, not only did non-reactive weathering products such as calcium and magnesium increase, but so did concentrations of total nutrients and chlorophyll *a* (Martin & Soranno 2006). The final landscape metric, and the one focused on by this study, is known as "lake order." Developed by Riera *et al*. (2000), lake order is an extension of the river-continuum concept developed by Vannote *et al*. (1980) and is based on the type and strength of the connections between a lake and the surface drainage network. In a study looking at 71 lakes in northern Michigan, Marin & Soranno (2006) found that lake order was the landscape position metric that explained the most overall variation amongst limnological variables compared to three other metrics based on different aspects of lake surface hydrologic connections.

Lake order provides lake researchers with a novel perspective in analyzing changes in lake characteristics along a gradient of landscape position (Quinlan 2003). Riera et al. (2000) found that 21 of 25 lake variables which included measures of lake morphometry, water optical properties, major ions, nutrients, biology, and human settlement patterns were explained by lake order. Thus, this classification can be beneficial in many ways.

The first objective of this study was to determine if the lakes on the UNDERC property fit into the lake order model. As shown, this model has been used to explain many patterns of limnological properties and thus an examination of how these characteristics of UNDERC lakes compare to previously observed patterns may offer many benefits to the property as suggested by Riera *et al*. (2000). First, it would reveal how lakes are related to each other across the landscape. Second it would provide information of how the lakes may respond to external forces in the future. Third, it would provide a framework for regionalization, allowing better predictions and better management decisions with scant data. Finally, it would provide a framework for the synthesis of regional analyses of lakes, streams, and the terrestrial landscape. The hypothesis of this study is that the lakes on the UNDERC property fit into the lake order model, meaning that physical, chemical and biological characteristics follow a predictable pattern based on the order of the lake.

The lake physical properties chosen to be analyzed in this study were: lake area, lake perimeter, shoreline development factor and maximum depth. Conductivity and pH were chosen as lake chemical properties to be analyzed. Chlorophyll *a* and crayfish abundance were chosen as biological properties. Finally, the Secchi depth was chosen as a water optical property. Since both Riera's study and my own study were conducted in the Northern Highland Lake District, I hypothesized that the lakes on the UNDERC property would follow the same trends as those observed by Riera et al. (2000).

The second objective of this study was to test the presence and strength of the relationship between crayfish diversity and lake order. Fish richness has been shown to be correlated with lake order (Riera *et al*., 2000) but crayfish diversity has not yet been examined. Capelli & Magnuson (1983) found that crayfish abundance in the Northern Highland Lake District of Wisconsin was best predicted by calcium concentration, the quality of the littoral substrate, and lake size. All three of these variables were shown by Riera *et al.* (2000) to be related to lake order. Whether diversity is related to these variables and therefore related to lake order has not been assessed. I hypothesized that crayfish richness will increase with increasing lake order as suitable habitat and calcium concentrations increase. Additionally, higher order drainage lakes are connected to other lakes by streams and rivers and thus crayfish should have been able to naturally colonize adjacent lakes.

Methods

Study area

The UNDERC property resides in the Northern Highland Lake District on both sides of the state line between Wisconsin and Michigan's Upper Peninsula in Vilas County (Wisconsin) and Gogebic County (Michigan). The landscape was formed approximately 12,000 years ago as a result of the Wisconsin glaciation and the altitude of the area ranges between 500 m and 520 m. The UNDERC property encompasses a land area of 6150 acres with nearly 40 permanent lakes and bogs with a combined surface area of 1350 acres. The property also lies in an area where the glacial deposits are young and the drainage system is poorly developed although this district serves as the headwaters for many major river systems such as the Wisconsin and Menominee (UNDERC 2004)

Lake order

Lake order is based solely on geographical information (Riera *et al*. 2000). For lakes with both surface inlets and outlets, lake order was defined as the order of the stream that drains the lakes. For lakes with a surface outlet but no inlet (headwater lakes) a lake order of 0 was assigned. Lakes connected to the surface drainage network by weak or intermittent streams were assigned a lake order -1. Lakes that were connected to the drainage system by a wetland where channelized flow was absent were assigned a lake order -2. Finally, closed-basin lakes which were hydrologically unconnected to the drainage network by surface water were assigned an order -3. Lake order on the UNDERC property was obtained in two ways. The first was through the analysis of USGS (U.S. Geological Survey) topographical maps. The scale of these maps was 1:24,000 and 1:100,000. Riera *et al.* (2000) found however that lake order values are sensitive to map scale and accuracy. Therefore, each accessible lake to be assigned an order on the property was thoroughly examined by boat for inlets and outlets. This examination proved important in a study done by Quinlan *et al*. (2003) which found that a certain lake showed no outlet streams on a 1:50,000 map but field sampling notes described the presence of an outlet. For all other non-accessible lakes, only USGS topographical maps were used. The list of lakes on property that were assigned a lake order are shown on Table 1.

Data collection

For each permanent lake and bog listed in Table 1, the following variables were taken from bathymetric maps provided from the UNDERC visitor's guide

(2004): lake area, maximum depth, lake perimeter, and shoreline development factor (SDF). For each physically accessible lake, Secchi depth, pH, and conductivity were taken 1-3 times throughout the summer and an average was taken. Chlorophyll *a* was taken once throughout the summer in each of the accessible lakes. Each chlorophyll *a* water sample was collected approximately one foot below each lake's surface using a Van Dorn sampler. Fifty to 150 ml of lake water was filtered through a GF/F Whatman filter. These filters were later placed into a film canister with 10 ml of methanol and allowed to sit for 24 hours at -4 C in the dark. The chlorophyll *a* concentration in the solute from each canister was then analyzed using the fluorometric method (American Public Health Association 1999). Crayfish trapping took place in accordance with the methods described by Lodge *et al*. (1986) once during the summer for each of the accessible lakes using modified minnow traps (hole diameter ~5cm) which were allowed to sit in 3 – 5 ft of water over a 24 h period. Traps were spaced equally around each lake's perimeter and contained approximately 80g of beef liver as the bait. The number of trapped ranged from 5 (North Gate bog) to 25 (Bay lake), depending on the size of the lake.

Statistical analysis

The relationships between landscape position and lake response variables were tested by first inspecting the relations with lake order on box-and-whisker plots. These gave a visual representation of the distribution properties of a sample based on nonparametric measures of central tendency, dispersion, and skewness and aided in visualizing statistical distribution as well as the presence, strength and shape between the variable and lake order (Riera *et al*. 2000). Next, one-way analysis of variance (ANOVAs) tests were employed with lake order as the categorical variable to determine if there was a statistical significance in the values of a limnological variable amongst lake orders. If an ANOVA suggested that lake orders differed significantly, a multiple means of comparisons with the Bonferroni correction was employed to test for differences among individual lake orders. Thick lines were added to the base of each box-and-whisker plots based on the multiple means comparison tests in effort to examine trends between lake order and variable. If the ANOVA suggested the lakes orders did not differ significantly, the orders were divided into drainage lakes (order ≥0) and seepage lakes (order <0) and two-sample t-tests were performed in order to identify any significant differences between the lake types. Furthermore, if abnormality was expected from box-and-whisker plots, a Kolmogorov-Smirnov normalcy test was used in order to identify significance amongst the lake orders. As recommended by Riera *et al*. (2000) linear regression analyses were not used because lake order is not continuous, but ordinal. Additionally it was not expected that all relationships would be linear.

Results

A list of each lake's order is provided in Table 2. The number of each lake class decreased as order increased (see Fig. 1).Of 38 permanent lakes and bogs, 26 (68%) were seepage lakes (order < 0) whereas only 12 (32%) were drainage lakes (order ≥ 0).

A list of descriptive statistics for each of the variable tested is shown in Table 2. Of the 9 variables tested, only 3 (maximum depth, Secchi depth, and chlorophyll *a* concentration) did not show significant differences among lake orders. One variable (shoreline development factor) was marginally significant ($p=0.068$) and the others differed significantly based on one-way ANOVAs or the Kruskal Wallis test used for crayfish abundance (see Table 4 and Figs. 2-5).

Upon subdividing the non-significant variables (maximum depth, Secchi depth, and chlorophyll *a*) into seepage lakes (order < 0) and drainage lakes (order ≥ 0), a two-sample t-test showed no significant difference between lake types ($p=0.48$ for maximum depth, $p=0.55$ for Secchi depth, and $p=0.15$ for chlorophyll *a* concentration)

Of each lake in which trapping occurred, Tenderfoot Lake (order 3) was the only lake to have crayfish of more than 1 species (see Table 5). There was a significant difference in trap catch between lake types ($p=0.04$; Fig.5b) with trap catches ranging from 0 - 3.75 crayfish per trap.

Discussion

It was expected that as lake order increased, the number of lakes found on the property in each class would decrease because lake order is based upon position along the drainage network.

Lake morphological variables

Riera *et al*. (2000) found that lake area, lake perimeter, and shoreline development factor of lakes in the Northern Highland Lake District in north-central Wisconsin lakes all strongly increased with lake order. Maximum depth differed significantly among lake orders with a slight tendency to increase with lake order but no significant differences were found between individual orders. At UNDERC, of the four morphological variables tested, lake area, lake perimeter, and the shoreline development factor all increased with lake order (see Fig. 2). The relationship between lake area and lake perimeter was strongly influenced by Palmer and Tenderfoot Lake (both order 3) which were much larger than any other lake on the property. These results support the findings by Riera *et al*. (2000) who described highland lakes as typically being numerous, small, and circular in shape while lowland lakes are less common, large, and tend to have convoluted shorelines. This relationship may have been more evident with a larger sample size which included lakes of the order 2.

Maximum depth was the only morphological variable lake that did show a significant relationship to lake order. These results are not surprising however as the lake depth in this area is limited by the 30 m thickness of the layer of glacial sediments over bedrock (Riera *et al*. 2000).

Chemical variables

Riera et al. (2000) found conductivity and pH to be strongly related to lake order with significant increases in both as lake order increased. Differences here were highest between seepage lakes (classes -3, -2 and -1) and drainage lakes (classes 0 and higher).Similar results were found at UNDERC as shown by marked increases in conductivity and pH as lake order increased (Fig. 4). Kratz *et al*. (1997) found that lakes higher in the landscape had relatively lower ground water inputs, and therefore lower calcium and magnesium concentrations, than lakes lower in the landscape. Furthermore, Riera *et al*. (2000) found that total catchment area increased sharply with lake order for drainage lakes while lakes of lower order had consistently small catchments. Additionally total catchment area has been used as an indicator of terrestrial inputs to lakes and therefore the higher conductivities found in higher order lakes are most likely a direct result of both greater proportions of ground water and allochthonous input. Riera *et al*. (2000) found that silica, calcium, carbonates, and magnesium, ions whose presence are a direct function of groundwater input, were each strongly related to lake order. I would expect to make similar findings at UNDERC had the presence of specific ions been examined.

The relationship between pH and lake order was also very strong for similar reasons. Additionally, the presence of sphagnum moss surrounding the perimeter of many of the isolated seepage bogs strengthened this relationship. According to Cole (1994) among its many functions, sphagnum replaces calcium and magnesium cations with hydrogen ions, lowering both the pH as well as the conductivity. Sphagnum's presence has been noted on the UNDERC property and during this study, it was found on nearly 70% of the perimeter of order (-3) lakes or bogs.

Water optical variables

There was no significant relationship found between Secchi depth and lake order (see Fig. 3). Secchi depth is the net result of chlorophyll concentration, colored dissolved organic carbon (DOC), and suspended sediments (Soranno *et al*. 1999) and it was predicted that Secchi depth would decrease with increasing lake order as a result of each of these variables increasing. Partially contributing to a lack of any relationship was that chlorophyll *a* concentration was not related to lake order. Additionally Riera *et al*. (2000) found DOC was not related to lake order. These non-significant factors most likely contributed to non-significance for Secchi depth. More specifically, in my study, sphagnum dominant seepage lakes (Cranberry, North Gate etc.) showed very low Secchi depths as made evident by much suspended and dissolved organic carbon. On the other hand, seepage lakes void of sphagnum (Roach, Crampton, etc.) showed very high Secchi depths. These intra-order contrasting lake types added much Secchi depth variation into the lake order comparison. In contrast to my findings, Soranno *et al*. (1999) found that Secchi depth showed a very consistent decreasing pattern as lake chain order increased. It may be possible that in my study, not enough drainage lakes were analyzed to make up for the variation created by seepage lakes.

Biological variables

Chlorophyll *a* concentrations did not increase significantly with increasing lake order. Conversely, Riera *et al*. (2000) found a significant difference although their data was relatively sparse and a post-hoc analysis found no differences. Silica, phosphorus and nitrogen are each essential phytoplankton nutrients. It has been previously shown that silica concentration increases with lake order as ground water input increases. Additionally the major source of nitrogen and phosphorus in this forest dominated region is likely to be precipitation (Wentz *et al*., 1995; Riera *et al*., 2000). It may be expected that a larger catchment areas and more ground water inputs (characteristic of high order drainage lakes) would translate to larger nutrient inputs and therefore greater amounts of chlorophyll *a* biomass. This was not seen for the UNDERC lakes but a lack of a significant difference between lake orders may have been a result of uptake processes in the catchment and in-lake processes which induce considerable variability into the relationship (Riera *et al*. 2000). Additionally, chlorophyll *a* was sampled only once throughout the summer and it is possible that presence or absence of algal blooms in certain lakes created extra variation.

The relationship between crayfish abundance and lake order was shown to have a significantly positive relationship (p=0.04) according to a Kruskal-Wallis test. This was expected as crayfish abundance has been best predicted by calcium concentration, the quality of the littoral substrate, and lake size (Capelli & Magnuson, 1993; Lodge *et al*., 1998; Riera *et al*., 2000) which are each related to lake order. Calcium is important to crayfish because it is necessary for growth and structure and concentrations below a ~ 4mg/l do not sustain crayfish populations (Riera *et al*., 2000). Additionally most crayfish species prefer cobble as it provides the most suitable habitat against predators (Capelli & Magnuson, 1983; Riera *et al*., 2000) and larger lakes will most likely provide more places for suitable habitat to occur. It is no surprise then that crayfish abundance was related to lake order at UNDERC even though crayfish were only found in nine of the twenty-two lakes in which trapping took place. The only seepage lakes in which crayfish were found were Tuesday Lake and Bogpot Lake (both order -2) and abundance in these lakes was relatively low (0.46 and 0.1 crayfish/trap respectively).

Crayfish diversity

Fish richness has been shown by Riera et al. (2000) to increase significantly with increasing lake order. This is due to higher order lakes being larger and thus allowing for more area of suitable habitat, more winter oxygen and more connection to streams thus allowing for invasions (Tonn & Magunson, 1982; Riera *et al*. 2000). The same logic was used in predicting crayfish richness on the UNDERC property and it was expected that higher order lakes would have greater species richness than lower order lakes. However, only Tenderfoot Lake (order 3) had more than one species of crayfish caught, *O. virilis* and *O. propinquus* (see Table 5). Since Tenderfoot and Palmer Lake are connected by the Ontonagon River, it is possible that extensive trapping would reveal both species as well. My hypothesis here was supported from this data since Tenderfoot is of the highest order at UNDERC, but there was not enough evidence to make the conclusive judgment that higher order lakes in the area foster more crayfish richness. Many more lakes, especially drainage lakes, must be examined in the future to fully support this hypothesis. Additionally, it is difficult to test this hypothesis because there were three species of crayfish found: *Orconectes virilis, Orconectes propinquus* and *Cambarus diogenes* on property. The first two species were found only in drainage lakes (order ≥ 0) while *C. diogenes* was found only in lakes of order -2. This was expected as *C. diogenes* is a semi-terrestrial, primary or secondary burrower that occurs for the most part in wetlands in contrast to fast water streams, rivers or lakes (Guiasu *et al*., 1994). With only these three species present in the area, a relationship between species richness and lake order may prove especially difficult to determine.

Lake order at UNDERC

Lake order has proven itself to be a very useful tool for examining how a lake's landscape position constrains the expression of limnological features, some directly (morphometry and chemistry) by geomorphological or hydrological factors, and some indirectly (biological variables) (Riera *et al*. 2000). Despite the low sample size of lakes and few variables tested, I suggest that UNDERC does in fact fit into the lake order model. As suggested by Riera et al. (2000), further knowledge of this relationship will help advance an understanding of how the lakes in the area will react to external forces in the future such as drought, invasive species, eutrophication, logging, etc. Additionally, it will provide a framework for regionalization, allowing us to make better management decisions with limited data. Landscape perspectives are becoming increasingly more useful for ecologists worldwide and UNDERC would benefit from further landscape position analyzes in the future.

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Tables and Figures

Table 1 List of all permanent lakes and bogs on the UNDERC property given an order and what limnological variables were used to examine how they relate to the lake order model

Lake	Assigned an order	Area	Maximum depth	Perimeter	S.D.F. *	Secchi depth	pH	Conductivity	Chlorophyll *a*	Crayfish abundance
Cranberry	X	X	X	X	X	X	X	X	X	X
Bogpot	X	X	X	X	X	X	X	X	X	X
Forest Service Bog	X	X	X	X	X	X	X	X	X	X
Raspberry	X	X	X	X	X	X	X	X	X	X
Bergner	X	X	X	X	X	X	X	X	X	X
Paul	X	X	X	X	X	X	X	X	X	X
Roach	X	X	X	X	X	X	X	X	X	X
Bay	X	X	X	X	X	X	X	X	X	X
Long	X	X	X	X	X	X	X	X	X	X
Tuesday	X	X	X	X	X	X	X	X	X	X
Peter	X	X	X	X	X	X	X	X	X	X
Crampton	X	X	X	X	X	X	X	X	X	X
Hummingbird	X	X	X	X	X	X	X	X	X	X
Tender Bog	X	X	X	X	X	X	X	X	X	X
North Gate Bog	X	X	X	X	X	X	X	X	X	X
Moccasin	X	X	X	X	X	X	X	X	X	X
Plum	X	X	X	X	X	X	X	X	X	X
Inkpot	X	X	X	X	X	X	X	X	X	X
Kickapoo	X	X	X	X	X	X	X	X	X	X
Morris	X	X	X	X	X	X	X	X	X	X
Palmer	X	X	X	X	X	X	X	X	X	X
Tenderfoot	X	X	X	X	X	X	X	X	X	X
Brown	X	X	X	X	X	X	X	X		
Ward	X	X	X	X	X	X	X	X		
Nansen	X	X	X	X	X	X	X			
Bolger	X	X	X	X	X	X	X			
Ziesnis Bog	X	X	X	X	X	X	X			
Ed' Bog	X	X	X	X	X	X				
Mullahy	X	X	X	X	X	X				

Gilbert	X	X	X	X	X					
Gillen	X	X	X	X	X					
Reddington	X	X	X	X	X					
Firestone	X	X				X				
Beaver Bog	X					X	X			
Donut Bog	X					X				
Craig Bog	X									
Trout Pond	X									
Lacey	X									

***Shoreline development factor, calculated as SDF= P/(2√πA), where *P* is lake perimeter and *A* is lake area**

Table 2 Orders assigned to all permanent lakes and bogs on the UNDERC property

Lake	Order
Bay	1
Beaver Bog	-3
Bergner	-2
Bogpot	-2
Bolger	-1
Brown	0
Craig Bog	-3
Crampton	-3
Cranberry	-3
Donut Bog	-3
Ed' Bog	-3
Firestone	-1
Forest Service Bog	-3
Gilbert	-2
Gillen	-2
Hummingbird	0
Inkpot	0
Kickapoo	1
Lacey	-2
Long	-3
Moccasin	-2
Morris	1
Mullahy	-1
Nansen	0
North Gate Bog	-3
Palmer	3
Paul	-1
Peter	0
Plum	1

Raspberry	-2
Reddington	-1
Roach	-3
Tender Bog	-3
Tenderfoot	3
Trout Pond	-3
Tuesday	-2
Ward	0
Ziesnis Bog	-3

Table 3 List of variables used in this study, with descriptive statistics and data sources. Meaning of Acronyms below

Variable	Units	N	Min	Max	Mean (SD)	Data Sources
a) *Morphological Variables*						
Lake area	ha	34	0.085	256.8	24.3 (56.3)	UNDERC, WDNR
Lake perimeter	m	32	64	10783	1881 (2758)	UNDERC, WDNR
Maximum depth	m	32	1.1	19.6	8.6 (5.1)	UNDERC, WDNR
Shoreline Development Factor	Unitless	32	1.04	3.6	1.41 (0.38)	UNDERC, WDNR
b) *Variables related to optical properties*						
Secchi Depth	m	28	0.48	5.13	2.35 (1.18)	PC, UNDERC
c) *Water chemistry variables*						
Conductivity	$\mu S\ cm^{-1}$	24	10.8	153	49.2 (49.8)	PC, UNDERC
pH		32	3.6	9.15	6.35 (1.51)	PC, UNDERC
d) *Biological variables*						
Chlorophyll a	$\mu g\ L^{-1}$	22	2.92	20.5	6.72 (3.9)	PC
Crayfish abundance	ind./trap	22	0	3.75	0.27 (0.8)	PC

UNDERC – Data taken from the UNDERC visitor's guide

WDNR – Data taken from the Wisconsin Department of Natural Resources (Palmer Lake)

PC – Data was personally collected during the 2007 summer

Table 4 Results of ANOVA tests used to analyze the relationship specific variables and lake order

Variable	N	df	F- ratio	P-value
a) *Morphological Variables*				
Lake area	34	5, 32	4.71	<0.0001
Lake perimeter	32	5,26	1.56	<0.0001
Maximum depth	32	5, 26	0.22	0.949
Shoreline Development Factor	32	5, 26	2.37	0.068
b) *Variables related to optical properties*				
Secchi Depth	28	5, 22	2.37	0.89
c) *Water chemistry variables*				
Conductivity	24	5, 18	4.66	0.0066
pH	32		1.15	<0.0001
d) *Biological variables*				
Chlorophyll a	22	5, 22	0.97	0.46
Crayfish abundance*	22	5, 17	1.16**	0.041

*Non-parametric Kruskal-Wallis test was used rather than an ANOVA to analyze the relationship between crayfish abundance and lake order

**Kruskal-Wallis test statistic value

Table 5 List of crayfish species caught on each lake trapped.

Lake	**Species**		
	O. virilis	***O. propinquus***	***C. diogenes***
Bay			
Bergner			
Bogpot			X
Brown	X		
Crampton			
Cranberry			
Forest Service Bog			
Hummingbird			
Inkpot	X		

Kickapoo	X		
Long			
Morris	X		
North Gate Bog			
Palmer	X		
Paul			
Peter			
Plum	X		
Raspberry			
Roach			
Tenderfoot	X	X	
Tuesday			X
Ward			

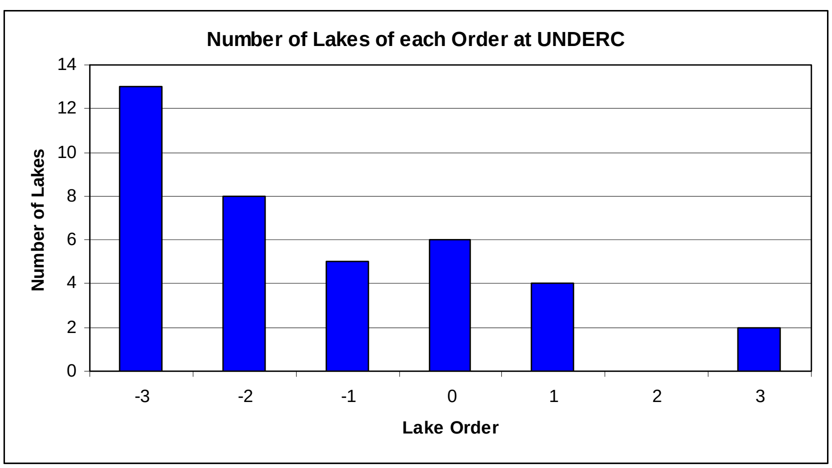

Figure 1 Distribution of lakes by lake order on the UNDERC property.

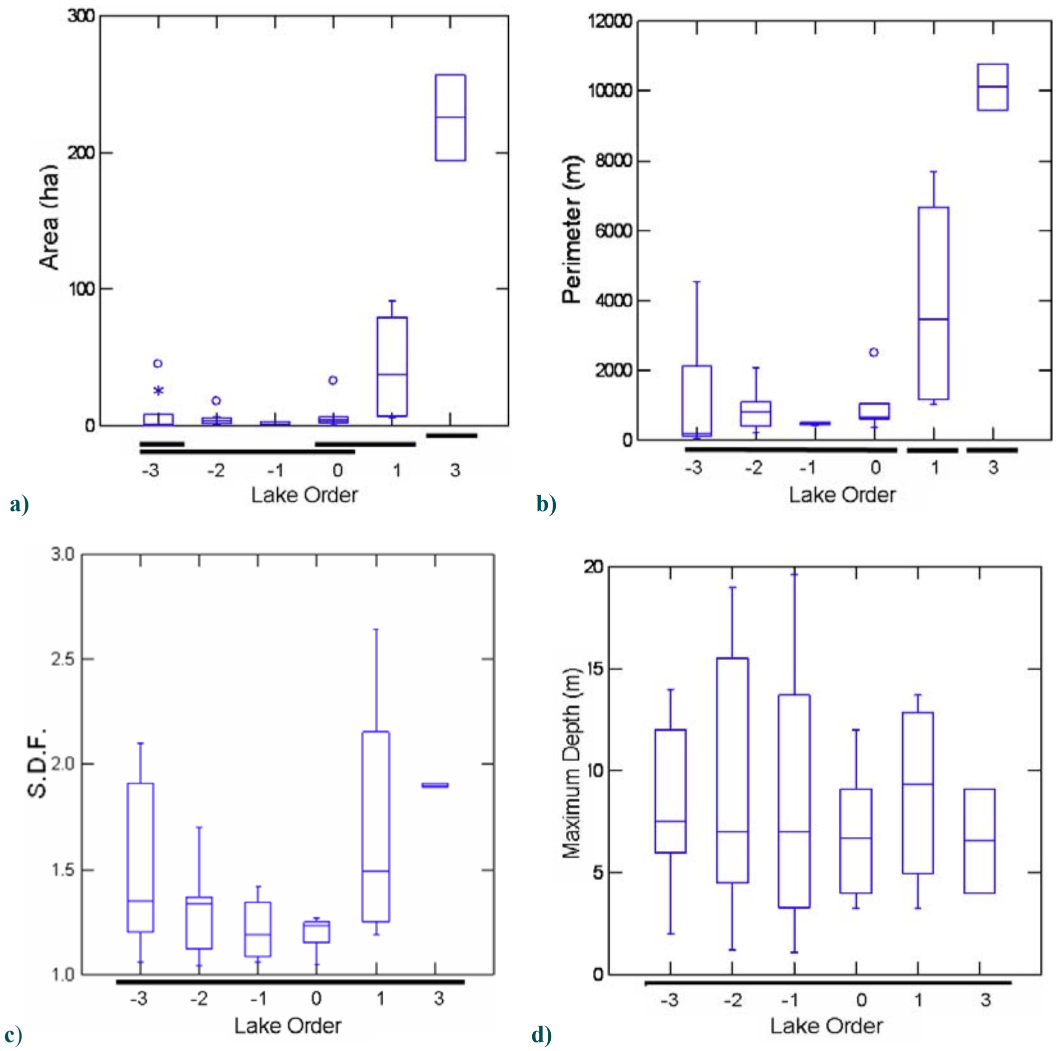

Figure 2 (a-d) Box plots for each of the morphometric variables: lake area, maximum lake depth, lake perimeter and shoreline development factor (SDF). Thick lines at the bottom of each graph group lake orders not significantly different according to multiple means comparison tests.

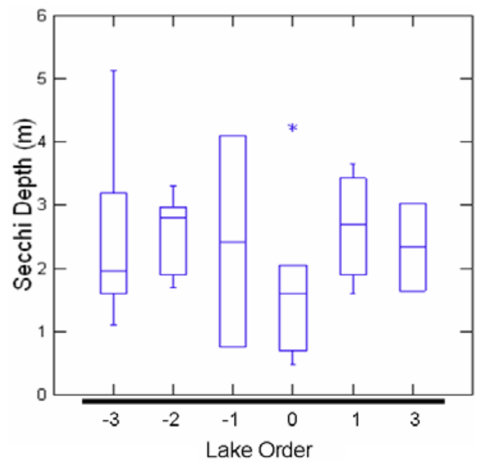

Figure 3 Box plot for Secchi disk depth. The thick line at the base of the graph groups lake orders not significantly different according to multiple means comparison tests.

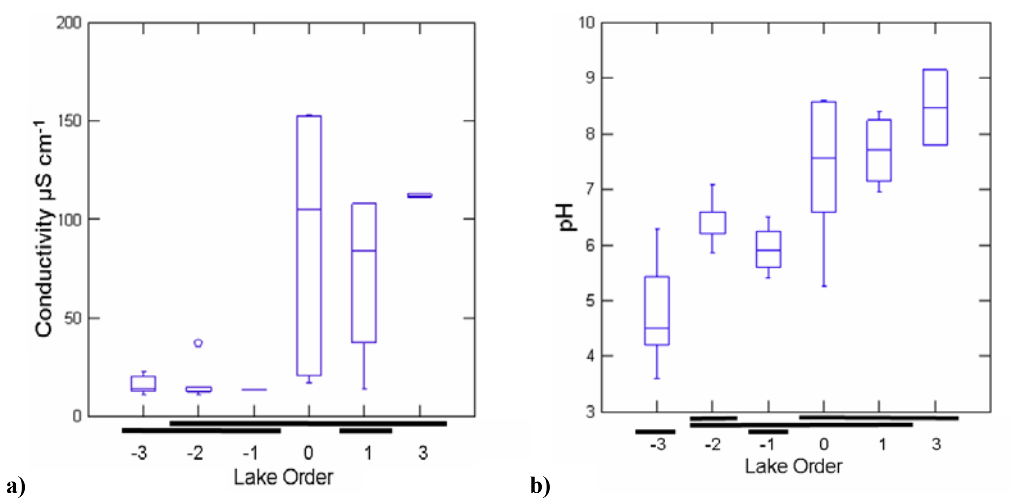

Figure 4 (a-b) Box plots for each of the water chemistry variables, conductivity and pH. Thick lines at the bottom of each graph group lake orders not significantly different according to multiple means comparison tests.

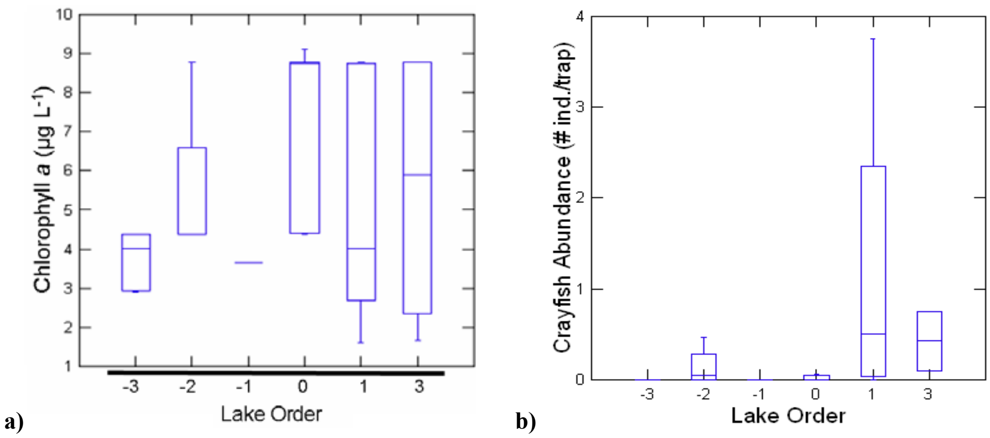

Figure 5 (a-b) Box plots for each of the biological variables, chlorophyll *a* concentration and crayfish abundance. Thick lines at the bottom of the chlorophyll *a* graph group lake orders not significantly different according to multiple means comparison tests. The non-parametric Kruskal-Wallis test used to analyze the relationship between crayfish abundance and lake order was unable to differentiate significant differences between individual lake orders.