ECS Lunch and Learn

Supporting internal knowledge transfer within TRCA

October 17, 2022

Toronto and Region Conservation Authority

Site Suitability Analysis Using Fuzzy Logic:

A GIS-Based Application for Agricultural Best Management Practices (BMPs)

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Presented by
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Analyst, Ecosystem and Climate Science

Great Lakes Eutrophication

Source: USGS, 2016

Problem Definition

Eutrophication is the immediate consequence of anthropogenic nutrient loadings

Non-point source pollution is a major threat to surface and groundwater quality

Intensive farming is the primary source of Non-point source pollution

Agricultural Best Management Practices (BMPs): a series of measures intended to maintain water quality by reducing non-point source pollutant loads without compromising productivity (e.g., Reduced tillage, cover crops, crop rotations, diversion terraces, erosion control structures, grassed waterways, and bank and outlet stabilization)

- Location is a critical factor to consider in large-scale water quality management programs
- Determining ideal locations for BMPs implementation is a decision analysis situation
- Acquiring this knowledge requires land suitability assessment

Land Suitability Assessment

A process involving land performance evaluation when it is used for a given purpose.

- Decision: A choice from a set of available options.
- Decision process: The process of determining a subset from the initial set of available options based on a single factor (criterion) or multiple factors (criteria).
- When a decision situation consists of allocating land for a single purpose (or objective), a decision set will be comprised of two subsets: Suitable lands and Unsuitable Lands.
- Overlay analysis: The fundamental method in spatial decision-making whereby an array factors (represented as maps or thematic layers) are overlaid, based on a given rule, to determine the extent to which a location belongs to the set "Suitable"
- Land Suitability Assessment could be a highly subjective process, particularly when a non-realistic spatial homogeneity is assumed for classifying landscape characteristics.

Spatial decision making in land evaluation

Boolean classification of landscape features

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- A simplified illustration of landscape features
- It splits the landscape features into homogeneous, discrete units
- Assign each unit to only one attribute class
- Changes between classes take place at the class boundaries
- No change is considered within individual classes
- Bears the inevitable loss of information by ignoring inherent spatial variability
- Has limited use for land evaluation and allocation purposes

Fuzzy logic approach to land evaluation

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- A quantitative approach utilized to address the imprecision embedded in human decision analysis
- A generalization of Boolean algebra to situations where class boundaries are not sharply defined
- Uncertainty is addressed through the continuous classification of data
- And this makes the fuzzy logic application ideal for characterizing landscape features and their assessment in a GIS

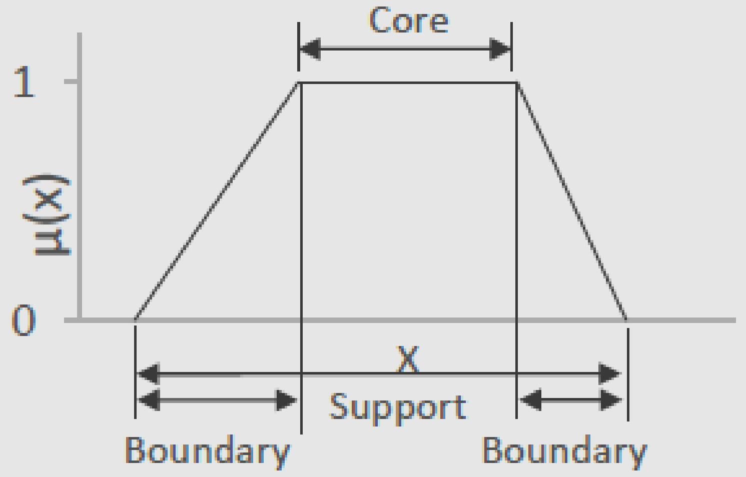
Fuzzy set

- A class of objects with a continuum of grades of membership, A = {(x, μ_A(x)) |x ε X}
- Characterized by a membership function which assigns to each object a grade of membership ranging between zero and one
- The nearer the value of μ_A(x) to unity, the higher the grade of membership of x in A
- μ_A(x) determines the degree to which x can be regarded as an element of A
- The grades of membership illustrate an ordering based on admitted possibility, not probabilities

Membership function

All fuzzy membership functions are defined through the following features:

(i) The Core Region: C(A) = {x ε X | μ_A(x) = 1}.
(ii) The Support Region: S(A) = {x ε X | μ_A(x) > 0)}.
(iii) The Boundary Region: B(A) = {x ε X | 0 < μ_A(x) < 1)}.



A generic Fuzzy membership function

Objectives

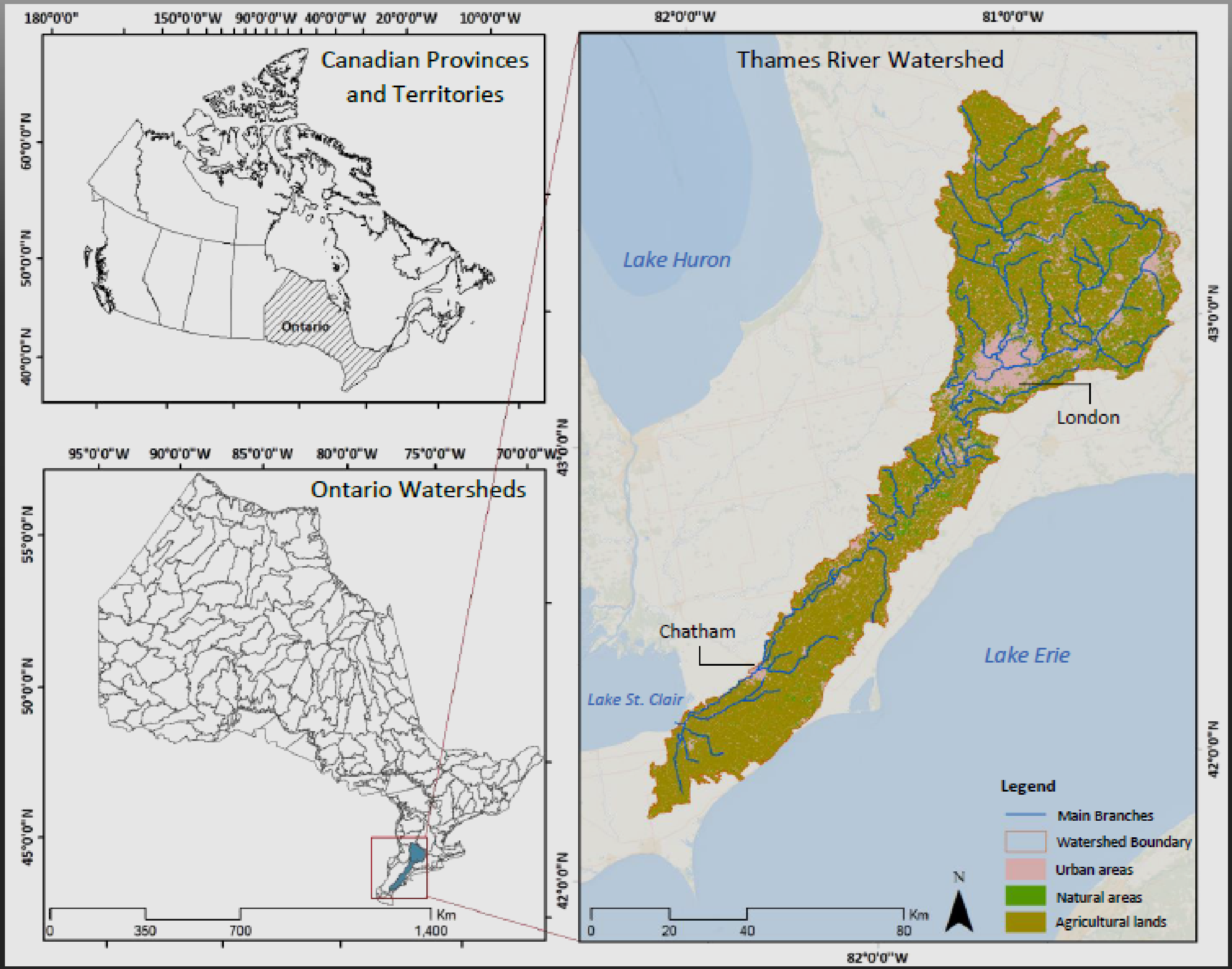
Using fuzzy-logic modeling approach to investigate the land potential, based on hydrological and socio-economic factors, for BMP implementation in the Thames River watershed, an agricultural watershed in southwestern Ontario Canada.

The three main steps employed to achieve this goal are:

(i) identify and prepare the environmental and socio-economic variables as input to the model
(ii) develop a fuzzy logic model for land suitability assessment for BMP implementation
(iii) evaluate the results of the suitability analysis by assessing the sensitivity of thematic layers to different fuzzy membership algorithms

Study area

- Thames River watershed is the second largest watershed in southwestern Ontario (drainage basin 5,825 km²)
- One of the main basins draining to Lake St. Clair, which is connected to Lake Erie by the Detroit River
- The river stretches 273 km and has an average annual discharge of 35.9 m³/s
- The watershed area is comprised mainly of agricultural lands (70%)
- The remaining area is divided between natural features (19%) and urban areas (11%)
- Has one of the highest total phosphorus loads, equal to 0.088 mg/L.
- One of the major contributing factors to water quality decline in Lake Erie



Material and Methods

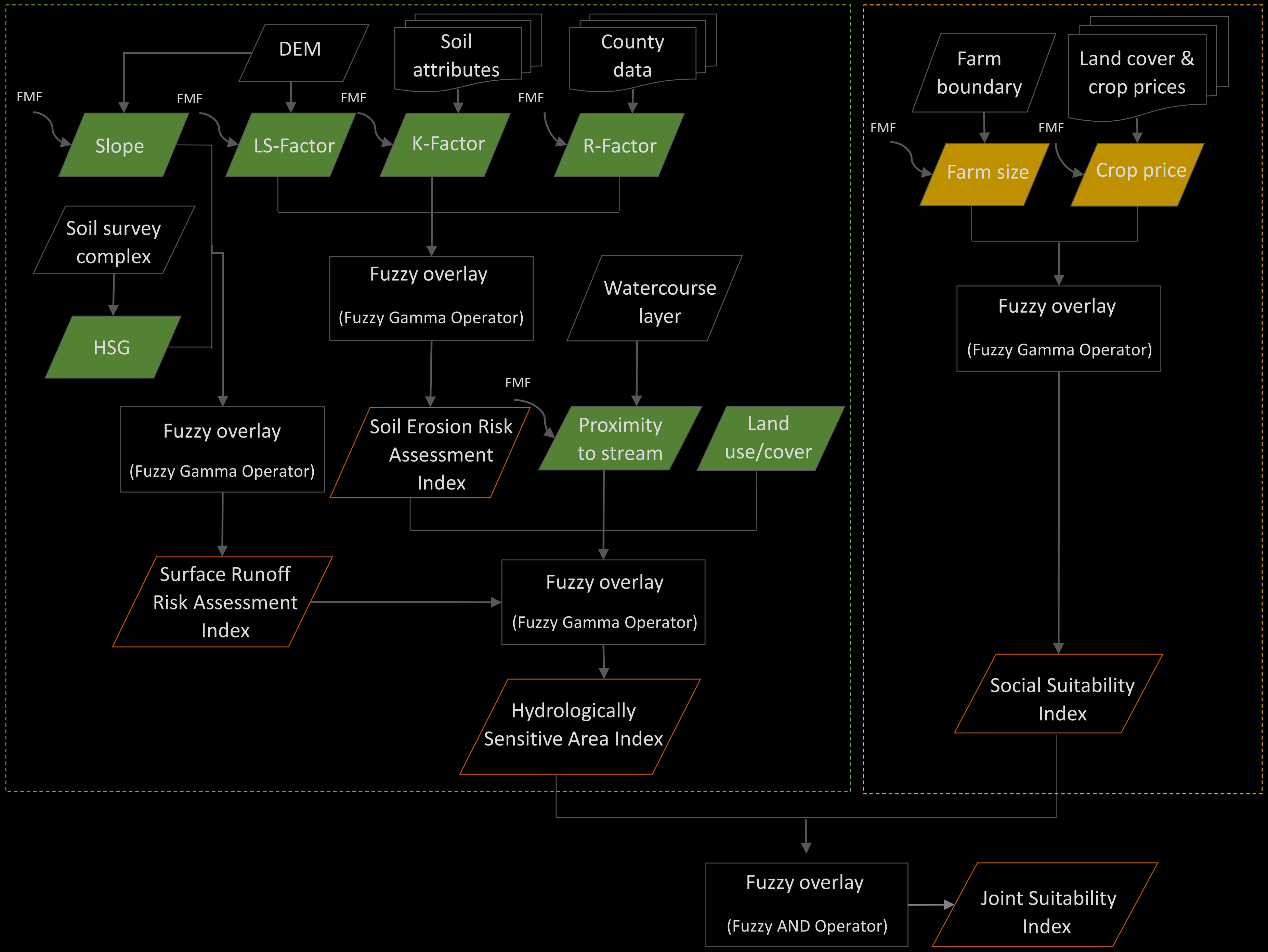
Data Layers

Slope *	Slope is included in the model to increase the accuracy of identifying lands which are prone to a higher volume of surface runoff.
LS-factor *	The LS-factor is used to identify the areas with a higher risk of soil loss, and thus, soil erosion. It was calculated using Stone and Hilborn (2012) equation, which considers flow accumulation and slope to estimate the risk of soil loss.
Land use/cover	Illustrates land use and land cover in the study area. It was used to determine croplands and pasture in the watershed.
Hydrologic Soil Groups (HSG)	It was used to determine soil texture in the study area.
K-factor *	Illustrates soil erodibility factor (soil susceptibility to erosion).
R-factor *	Soil erosivity factor due to rainfall
Proximity to streams *	This spatial data layer represents the risk of surface water pollution based on the distance between the stream and farming activities. This risk is negatively associated with the distance between streams and farmlands.

Crop price *	Price of cultivated crops (cent/lb.)
Agricultural fields *	Boundary of farmlands. Used to determine the size of farmlands in the watershed.

* The thematic layers generated using a combination of multiple data layers

Model structure and component



Fuzzification algorithms for land suitability and sensitivity analyses

Fuzzy Linear (increasing/decreasing)

$$\mu(x) = \begin{cases} 0 & x \leq a \\ \dfrac{x-a}{b-a} & a < x < b \\ 1 & x \geq b \end{cases}$$

- a and b: user-specified minimum and maximum values determining the acceptable ranges of attribute values in the thematic layers

Fuzzy Small/Large

$$\mu(x) = \frac{1}{1 + \left(\frac{x}{f_2}\right)^{\pm f_1}}$$

- f_1 is the spread, and f_2 is the midpoint

Fuzzification algorithms for land suitability and sensitivity analyses

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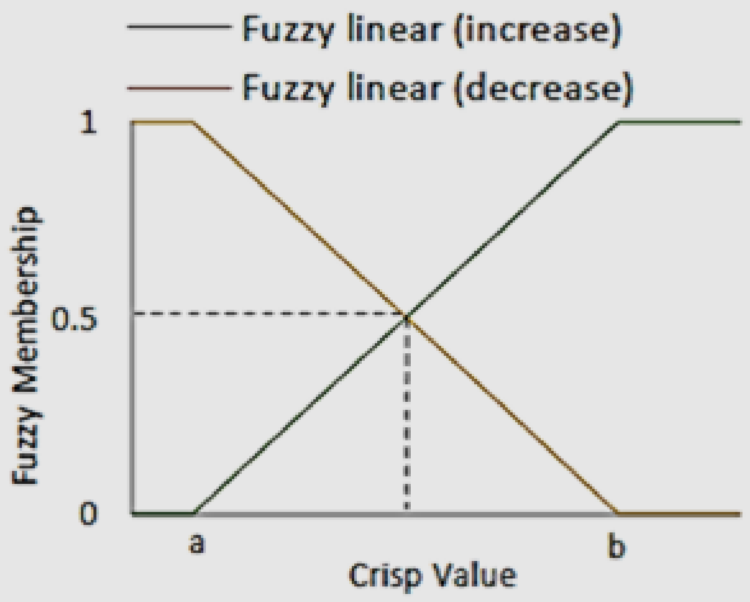
Fuzzy Linear (increasing/decreasing)

- Applies a linear transformation to the values within the user-specified minimum and maximum points
- When the user-specified minimum value in a thematic layer is greater than the maximum value (i.e., a negative linear relationship is in place), the Fuzzy Linear function has a decreasing slope and vice versa
- The defined midpoint identifies the crossover point (assigned a membership value of 0.5)



Fuzzification algorithms for land suitability and sensitivity analyses

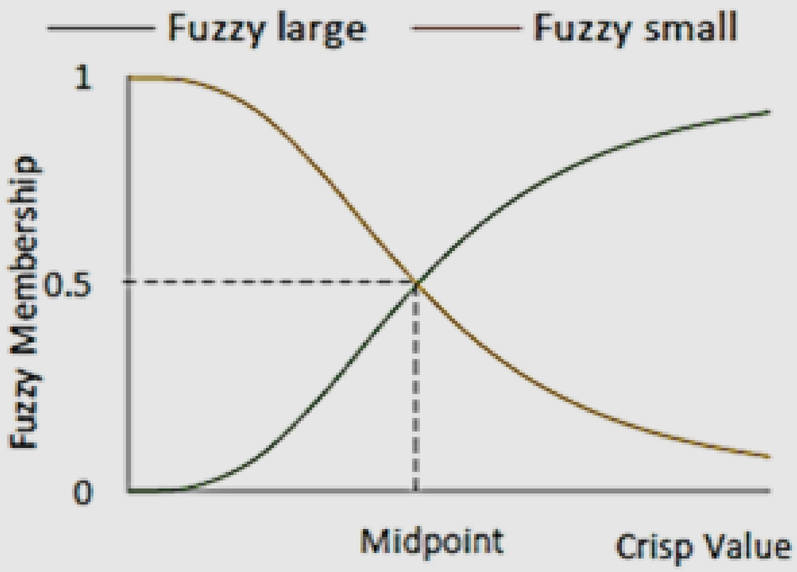
Fuzzy Small/Large

- The Fuzzy Large transformation function is used when the larger input values are more likely to be a member

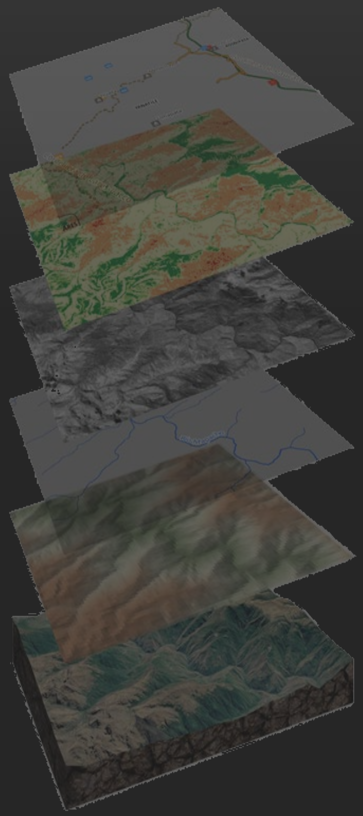
- When the smaller input values are more likely to be a member of the set, the Fuzzy Small membership function is used

- In a Fuzzy Large function, values greater than the midpoint have a higher admitted membership possibility, and those below the midpoint have a lower possibility of membership

- In a Fuzzy Small function, values greater than the midpoint have a lower admitted membership possibility, and those below the midpoint are more likely to be the members of the fuzzy set



Fuzzy Overlay Operators



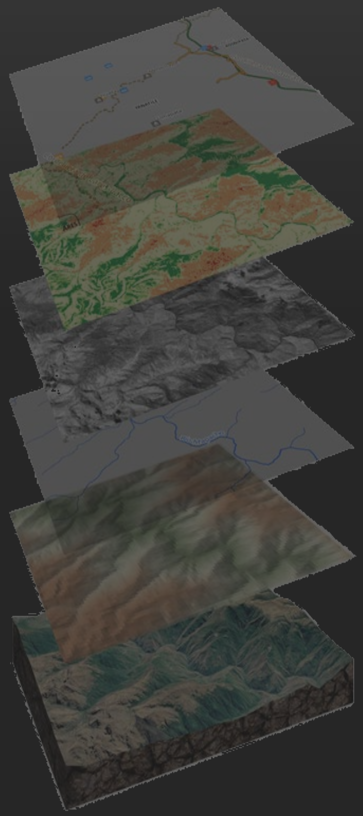
- Combine the fuzzified layers into a single set

- Classified into compensatory and non-compensatory classes considering the tradeoff between the subjective categories in the aggregation procedure

- Incorporating the impact of various phenomena in decision analysis situations necessitates the different combinations of compensation levels

- “Compensatory and” and "minimum operator“ operators are used to overlay multiple fuzzified thematic layers

Fuzzy Overlay Operators



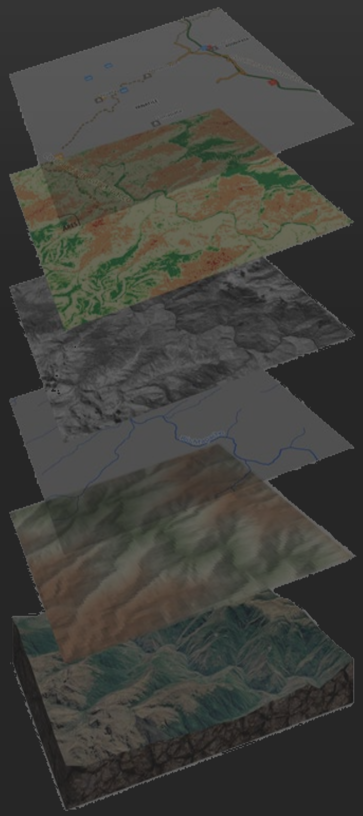
“Compensatory and” operator

$$\mu(x) = \left(1 - \prod_{i=1}^{n}\left(1 - \mu_i(x)\right)\right)^{\gamma} * \left(\prod_{i=1}^{n}\mu_i(x)\right)^{(1-\gamma)} \qquad x \in X \;\; 0 \le \gamma \le 1,$$

- “Compensatory and” is more adequate in human decision-making
- Establishes the relationships between multiple input criteria and allows compensation between the membership values of the aggregated sets
- A combination of the algebraic product (modeling the logical "and") and the algebraic sum (modeling the logical "or")

- To create the hydrological sensitivity and social suitability indices "γ-operator" is used
- Gamma is a user-defined parameter and introduces a degree of subjectivity, even when applied to data-driven models
- In this study, a default value of 0.9 was used for gamma

Fuzzy Overlay Operators



Non- Compensatory Operator (Minimum operator)

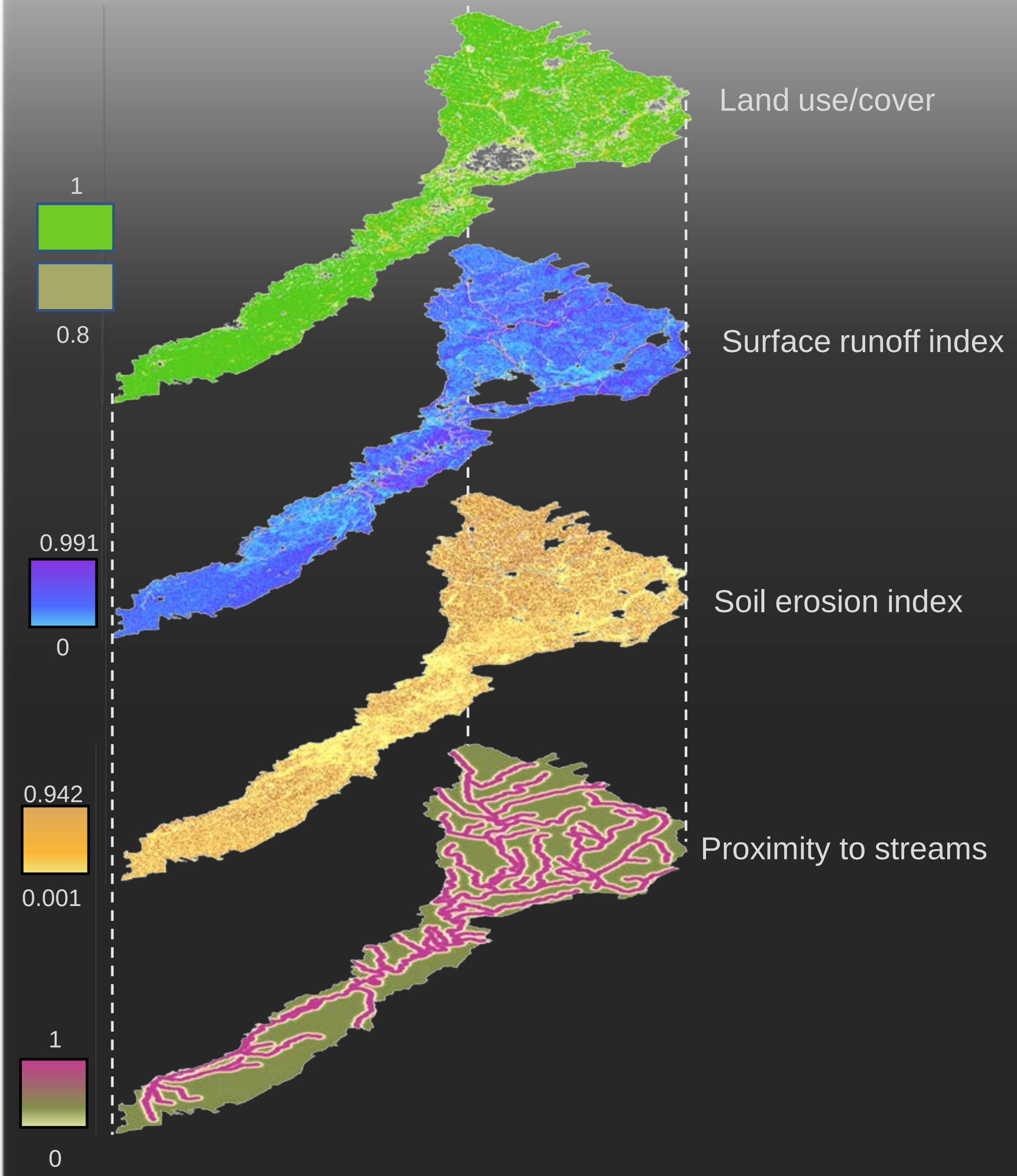
- "fuzzy and" combines the minimum with the arithmetic mean and is defined as:

$$\mu(x) = \gamma \, . \, min\,\{\mu_i(x)\} + \frac{(1-\gamma)\sum_{i=1}^{n}\mu_i(x)}{2} \qquad x \in X \,, \gamma \in [0,1]$$

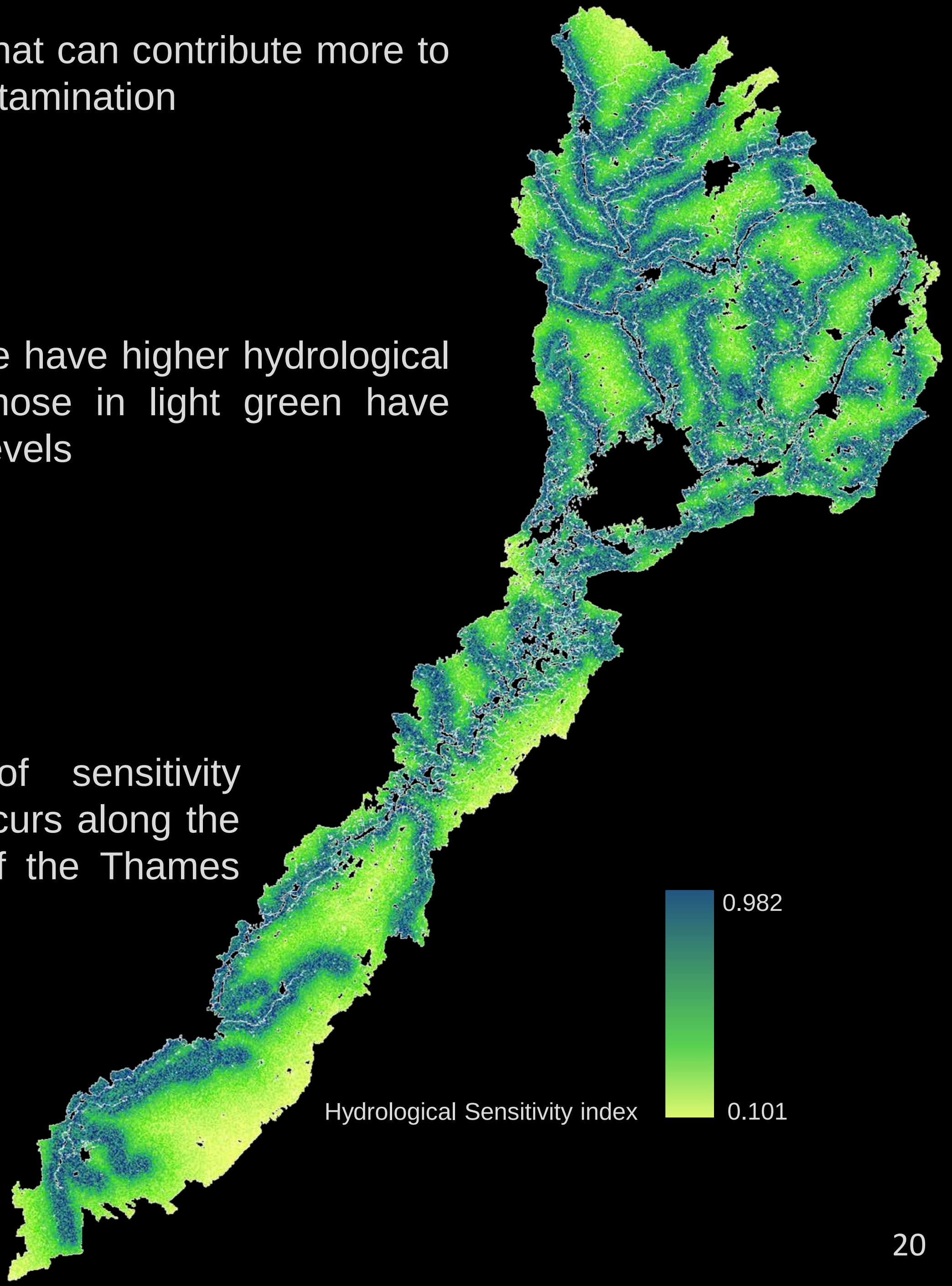
- γ represents the degree of nearness to the absolute, logical meaning of "and"
- γ= 1, the "fuzzy and" becomes the “Minimum operator”, which is non-compensatory in nature
- There is no positive compensation between the membership degrees of the fuzzy sets
- An alternative is rejected on the basis of poor performance with respect to at least one attribute
- The joint suitability map was produced by using the “Minimum operator"
- Areas that have a high joint suitability score are the ones that simultaneously satisfy the hydrological sensitivity and social suitability indices

Results

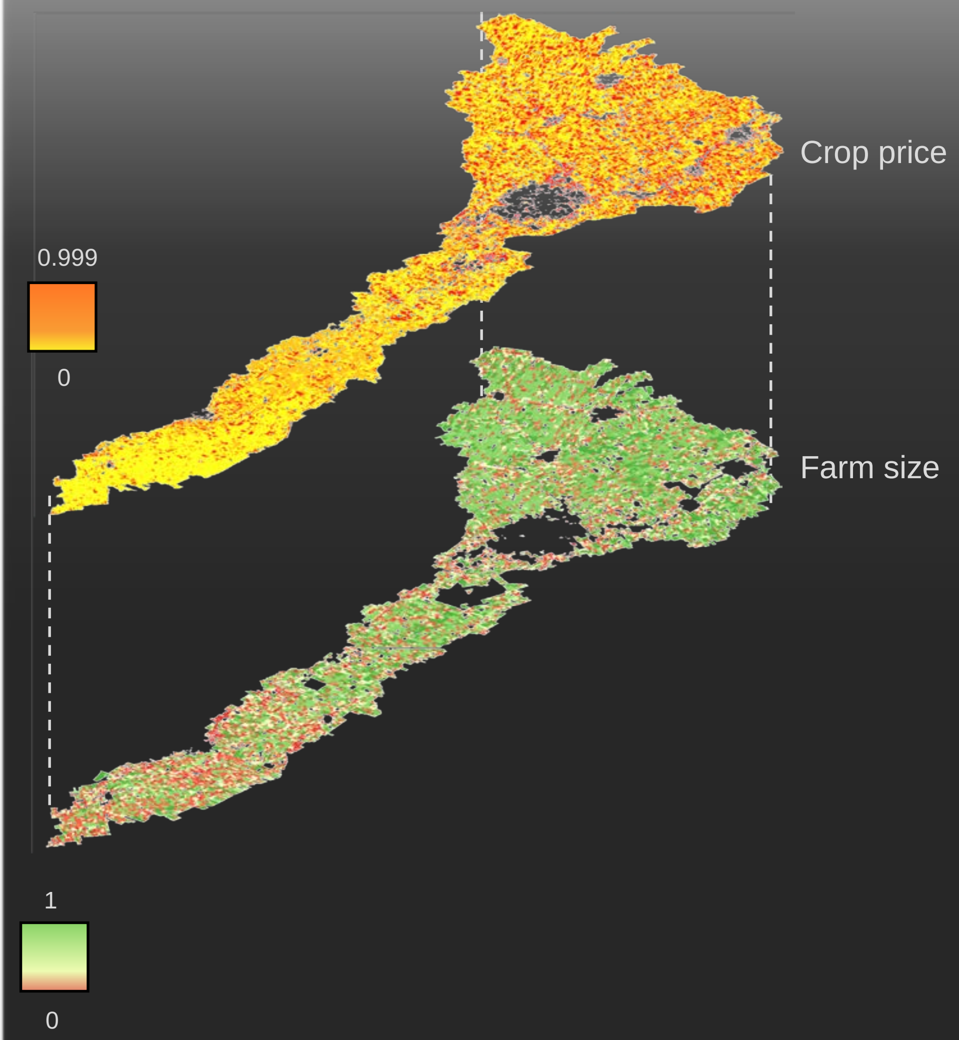
Hydrological sensitivity Index



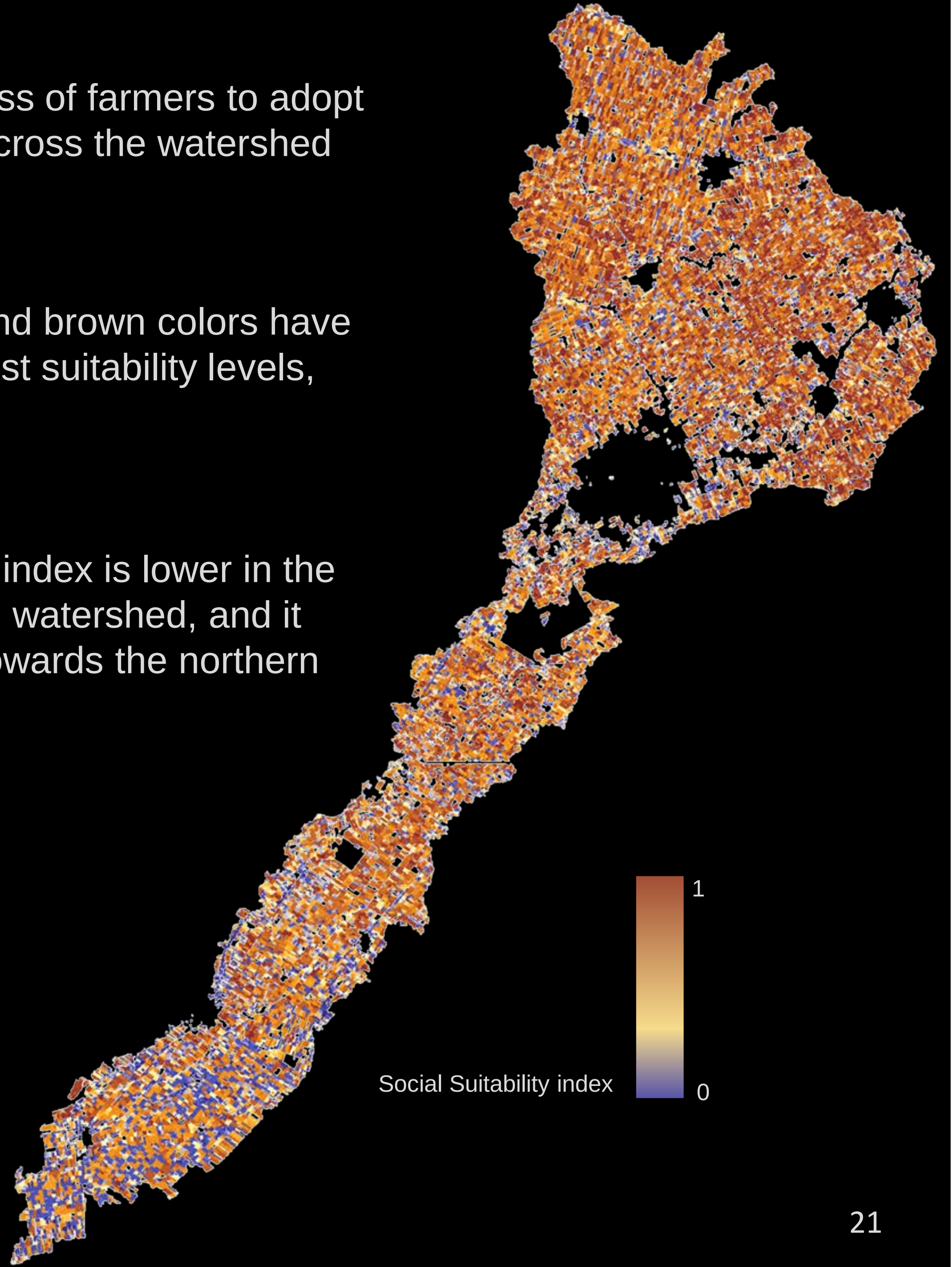
- Illustrates areas that can contribute more to surface water contamination
- Areas in dark blue have higher hydrological sensitivity, and those in light green have lower sensitivity levels
- A high level of sensitivity predominantly occurs along the main branches of the Thames River



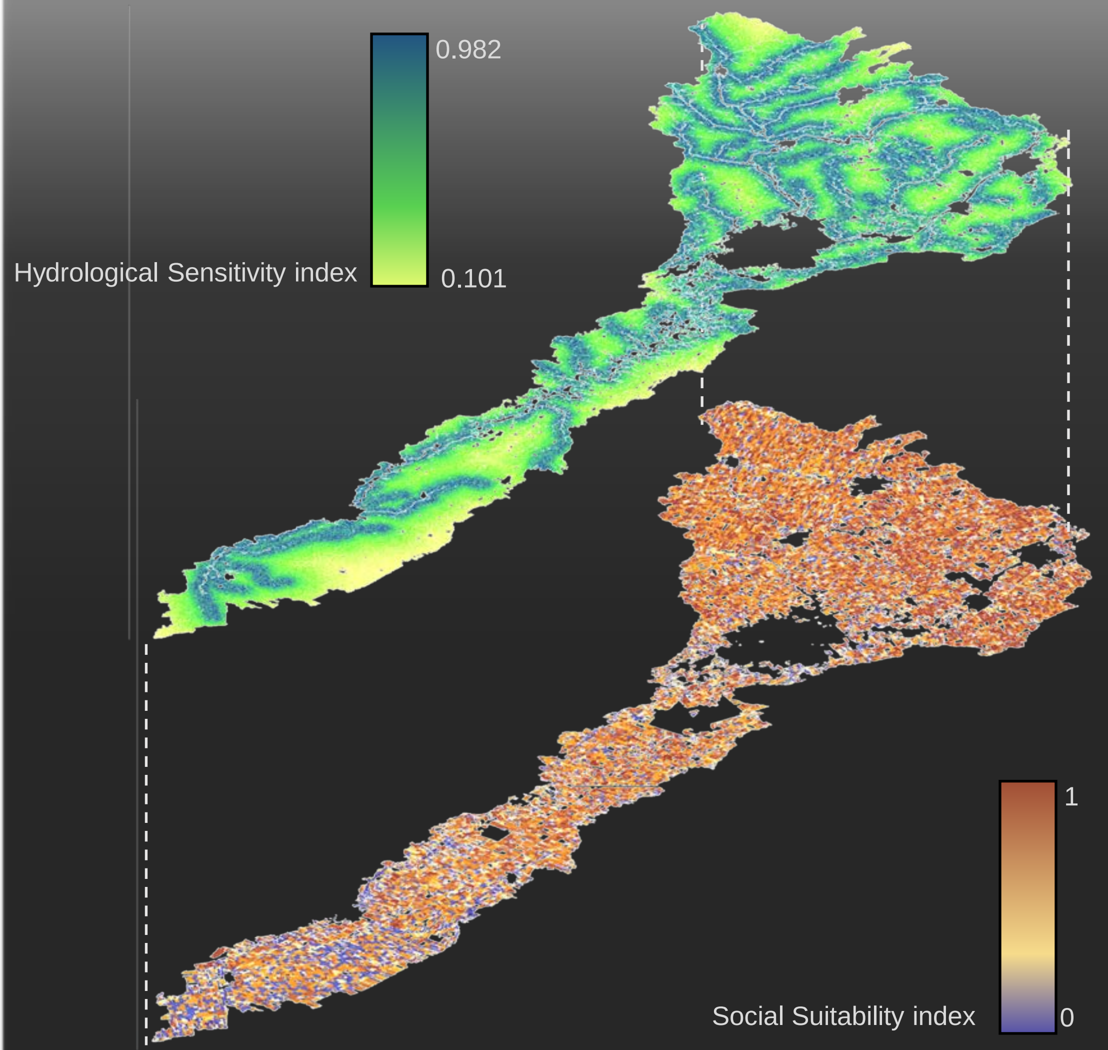
Social Suitability Index

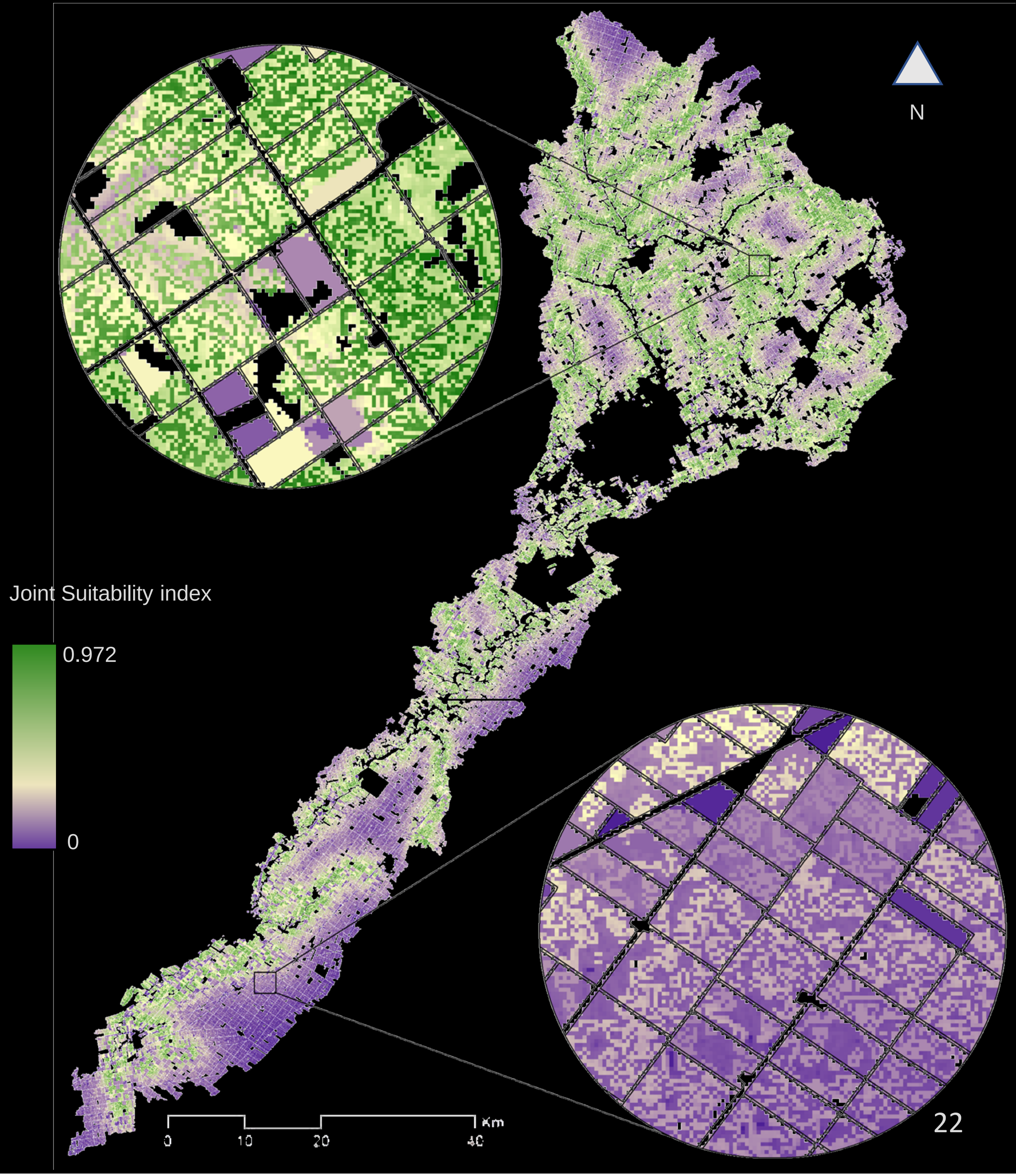


- Shows the willingness of farmers to adopt agricultural BMPs across the watershed
- Areas in dark blue and brown colors have the lowest and highest suitability levels, respectively
- The social suitability index is lower in the southern parts of the watershed, and it begins to increase towards the northern portions of it

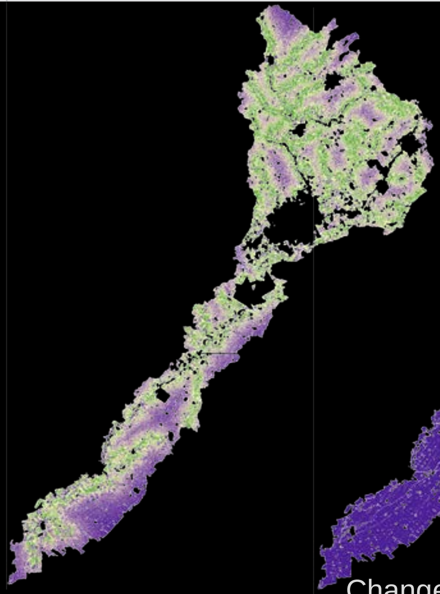


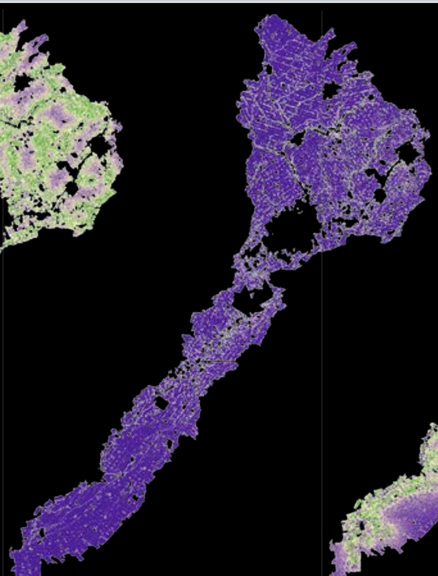
Joint suitability Index



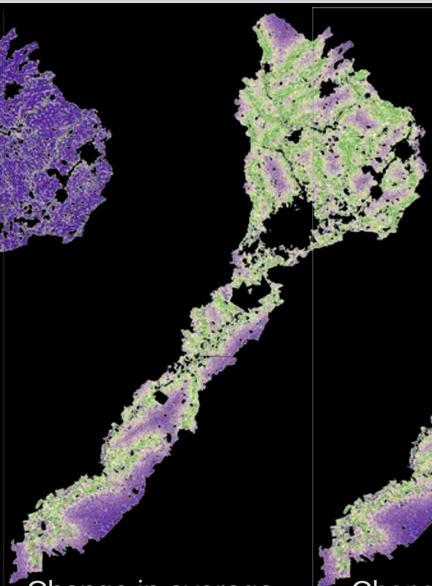


Sensitivity analysis

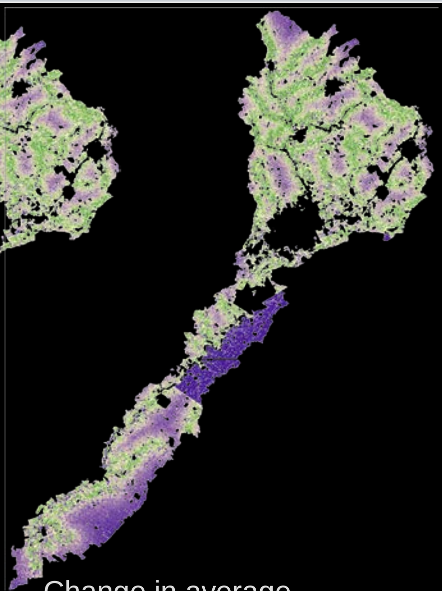




Change in average scores: 43%

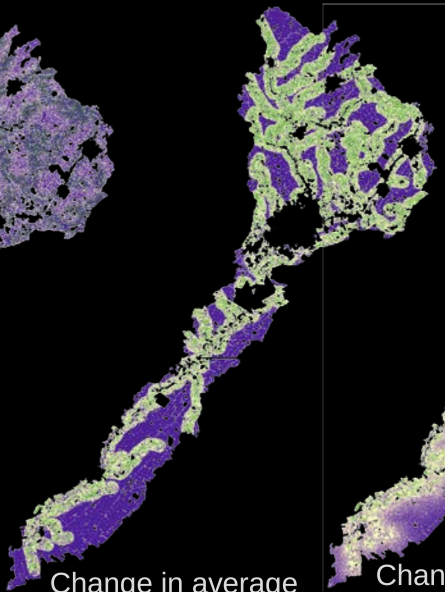


Change in average scores: -1%

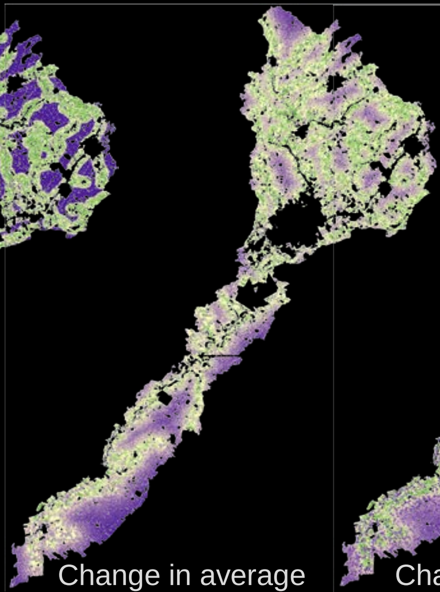


Change in average scores: 3%

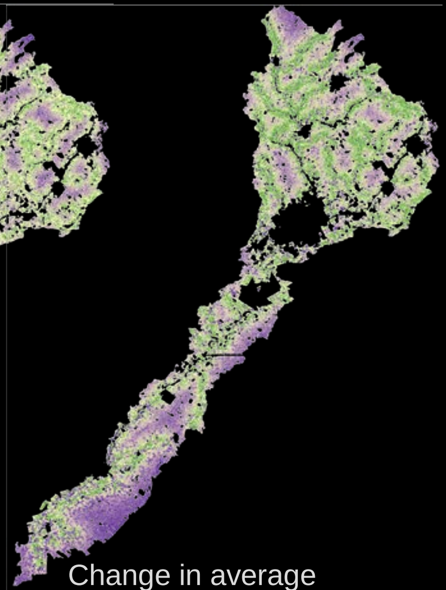
Change in average scores: 25%



Change in average scores: 15%



Change in average scores: 2%



Change in average scores: 2%

Conclusion

- A robust, replicable framework
- Can help streamline the production of farm-to-catchment based suitability maps in many regions and geographies of agricultural production (e.g., across other agricultural watersheds in Canada and the U.S).
- Mitigate the unintended consequences (e.g., excessive costs) associated with “random” or “blanket” approaches to BMP implementation.
- A complementary tool to water quality simulation.

Thank you !

Upcoming ECS Lunch and Learns!

Tuesday, November 1
11:00am-12:00pm

Planning Policy and Regulation

By Mary-Ann Burns
and the PPR team

Wednesday, November 9
11:00am-12:00pm

Planning Ecology (Pt. 1)

By Brad Stephens
and the PE team

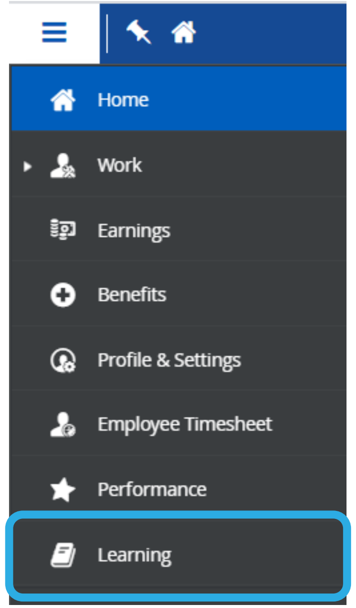
(Tentative)

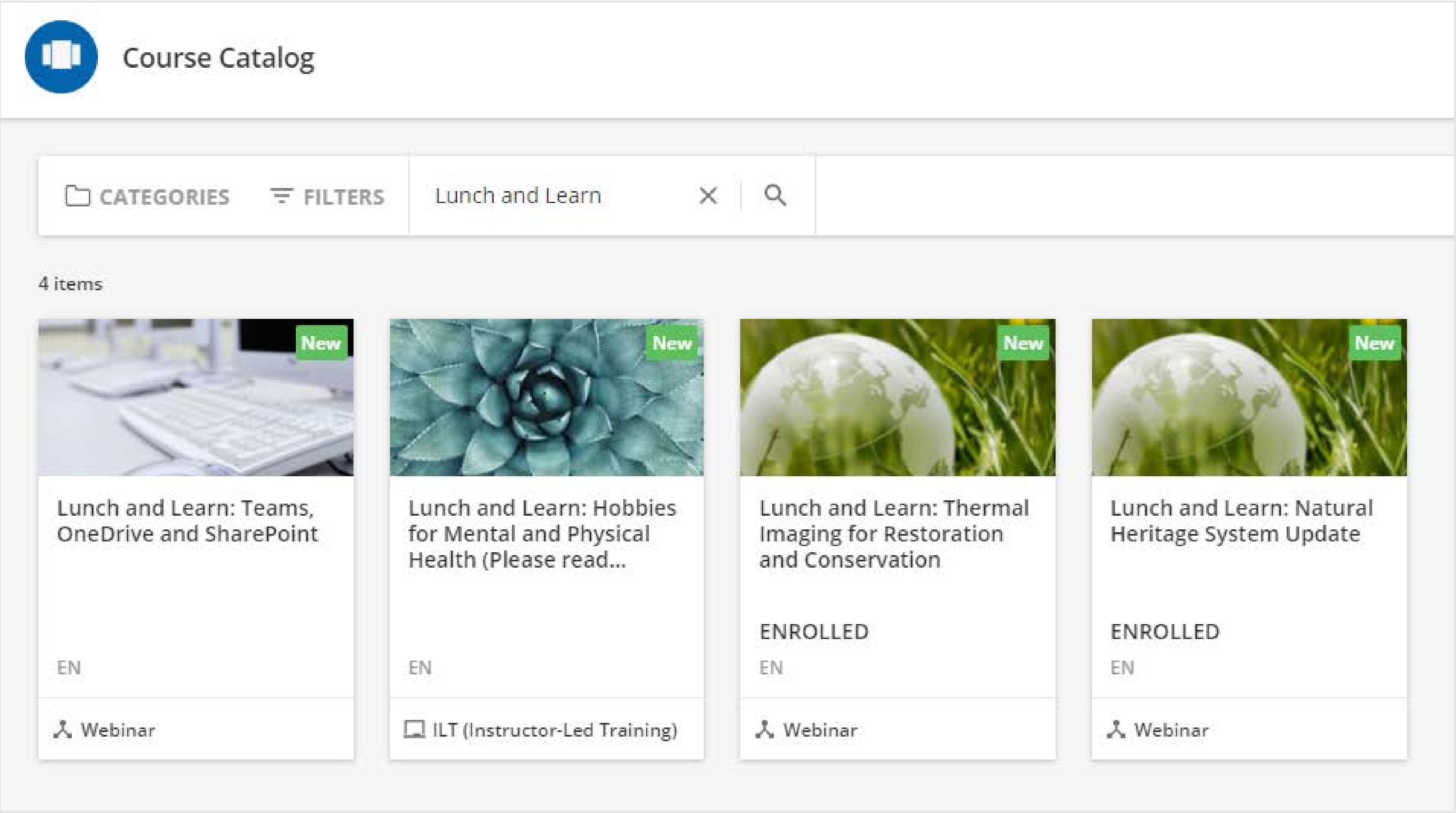
Tuesday, November 15
11:00am-12:00pm

Updated Strategic Plan (2023-2034)

By Jen Moravek

Learning Management System





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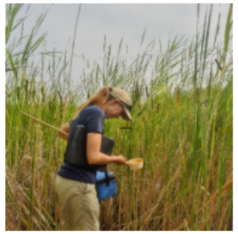
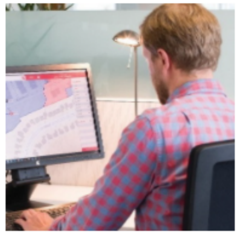
Evidence-based decision making is at the core of what TRCA does. Several of our Business Units engage in generating new scientific knowledge to support watershed management actions and decisions.

It is critical that the knowledge generated is effectively shared.

The Scientific Knowledge Sharing platform is dedicated to sharing the latest scientific knowledge generated by TRCA and our partners. It is a place where staff can learn about and engage in the scientific work TRCA is undertaking.

PLEASE NOTE: *There are several TRCA teams engaged in generating new scientific knowledge. Currently the content on the platform is specific to the Watershed Planning and Ecosystem Science business unit. Additional content from other TRCA teams will be added as the platform develops.*





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Knowledge Sharing – Climate Change Analysis at the Local Scale

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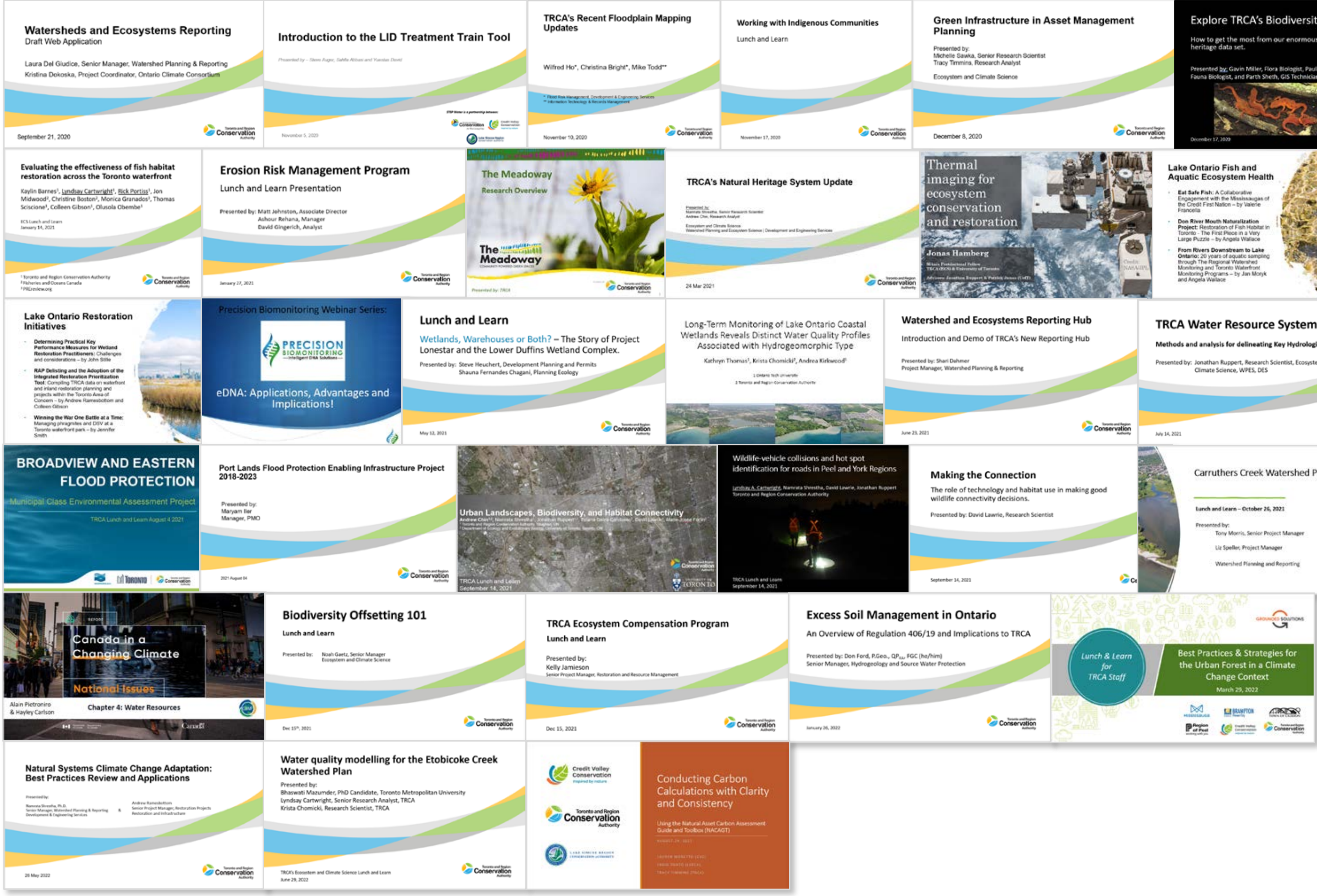

Thank you

For questions about the ECS Lunch and Learn Series, please contact:

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