Uncertainty Quantification

For Probabilistic Machine Learning in Earth Observation using Conformal Prediction

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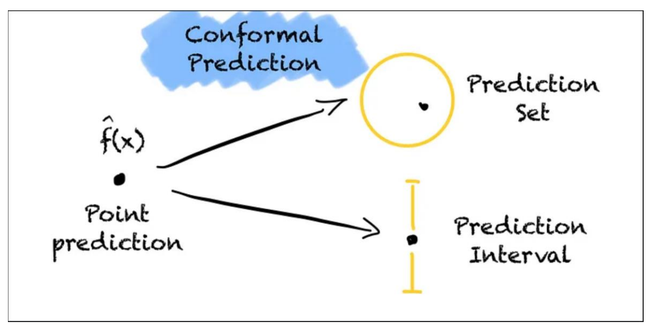


The Problem

Global to national extent earth observation datasets are used in data-driven decision-making, contributing to the characterization, comprehension, and conservation of planet earth. Despite the importance and benefits of uncertainty quantification for decision-making, ~79% of these large-extent datasets do not quantify uncertainty. Those datasets that quantify uncertainty predominantly rely on unreliable methods.

Why Conformal Prediction?

Benefits

- Distribution-free
- Validity guarantee
- Spatially-explicit uncertainty regions
- Applied post-hoc
- Supports numerous machine learning tasks

Assumptions

- Exchangeability

Drawbacks (*Under active research)

- *Marginal coverage
- *Distribution shifts
- *Label errors
- *Missing data
- *Open-source implementations

Code and paper

Interactive Earth Engine app

Satellite Imagery

Research Contributions

- **Systematic literature review** to provide empirical evidence for:
  - Lack of uncertainty quantification
  - Popularity of problematic methods
  - The need for conformal prediction
- Introduces **open-source Google Earth Engine** native conformal prediction **modules** that support:
  - Small to large datasets
  - Classification and regression tasks
  - Traditional machine learning and deep learning workflows
  - **JavaScript** and the **Python API**
- **Case studies** that use the introduced modules to demonstrate:
  - **Scalability** to global datasets
  - Validity despite spatial autocorrelation
  - Applicability to common tasks i.e., Land cover classification, canopy height estimation and invasive species classification.

Results

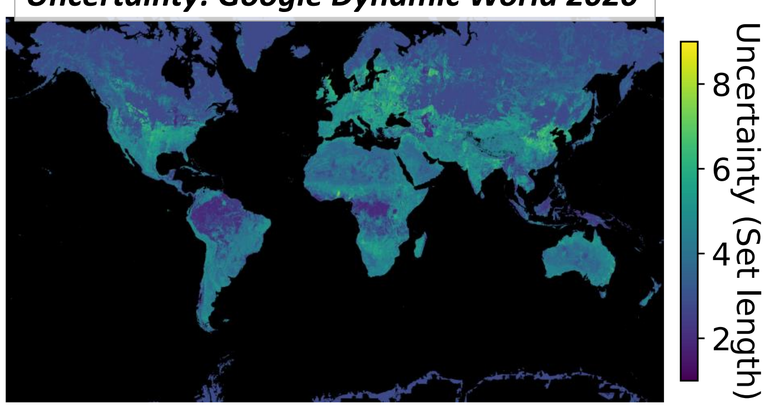
Systematic Literature Review

79% Datasets DO NOT quantify uncertainty

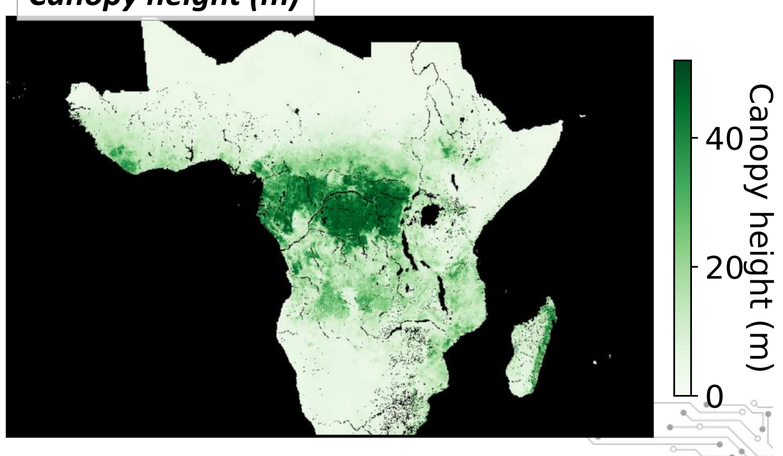
Basic Usage (GEE JavaScript)

```
//import conformal classifier calibration, evluation and inference functions
var calFunctions = require('users/geethensingh/conformal:calibrateConformalFeatureClassifier.js');
var evalFunctions = require('users/geethensingh/conformal:evaluateConformalFeatureClassifier.js');
var infFunctions = require('users/geethensingh/conformal:inferenceConformalImageClassifier.js');

// Configuration parameters
var ALPHA = 0.1; // 1-ALPHA corresponds to required coverage. For example, 0.1 for 90% coverage
var SCALE = 10; // Used to compute Eval metrics
var SPLIT = 0.8; // Split used for calibration (0.8). 20% used for evaluation.
var LABEL = 'label'; //band name for reference label band

// Calibrate conformal classifier on feature collection (points) cotaining (reference label, predicted
label, predicted probability-like score for each candidate class)

var result = calFunctions.calibrate(points, bandNames, QHAT, SCALE, SPLIT, LABEL, 'demo_ICLR24');
var QHAT = 0.0645059604536403; // from calibration print result

// Assess the validity and coverage of the calibrated conformal classifier
var eval = evalFunctions.evaluate(points, bandNames, QHAT, SCALE, SPLIT, 'demo_ICLR24');

// Inference function is mapped over classifier-outpu probability image
var uncertainty = infFunctions.inference(classProbabilityImage, bands, QHAT);
```

Uncertainty: Google Dynamic World 2020



Canopy height (m)



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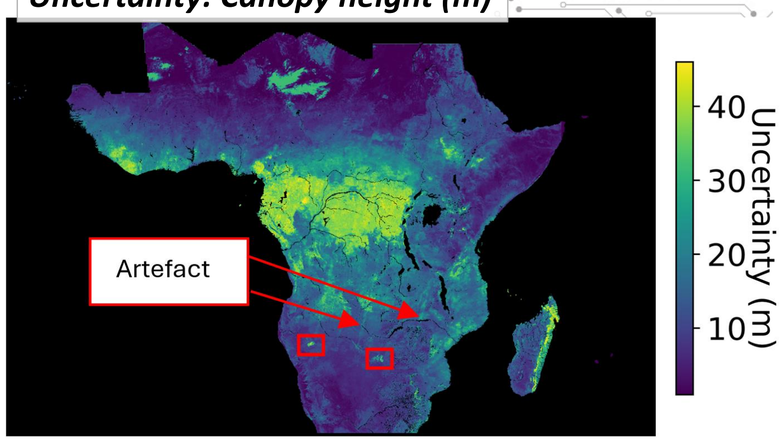

Methods

Google Dynamic World

Each scene contains the probability-like score for each of the nine land cover classes at each pixel. We use the out-of-sample reference labels in the provided validation data to calibrate and evaluate a set-valued conformal classifier. The length of the multilabel sets are presented (alpha = 0.1)

Canopy Height Estimation

A LGBM model is trained on planet NICFI VNIR bands and the GEDI rh98 band across Africa. A out-of-sample partition is then used to calibrate and evaluate a conformal quantile regression model. The presented prediction width is created by subtracting the upper 97.5th quantile from the lower 2.5th quantile (alpha = 0.05).