High-Performance Programming and Execution of a Coral Biodiversity Mapping Algorithm Using Chapel

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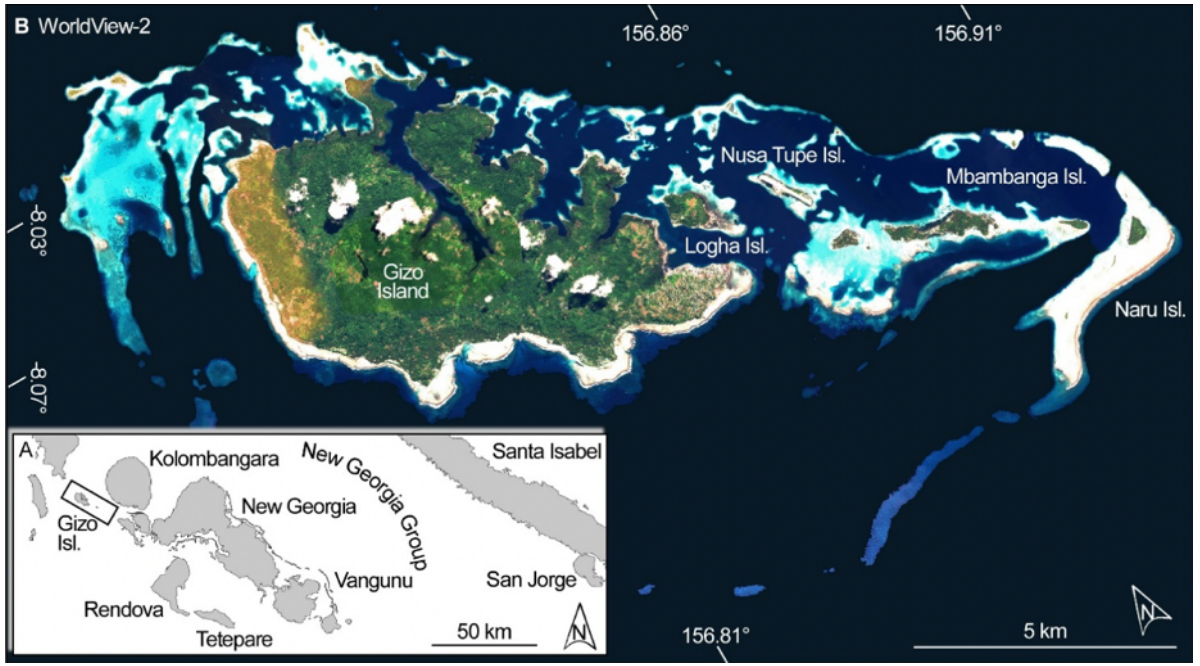
4. Hewlett Packard Enterprise Spring, Texas, USA

Coral Reef Biodiversity (image analysis)

Background

- **Problem:** Coral reefs are widespread, but small and hard to reach. Surveying and measuring is difficult, time-consuming, and expensive.

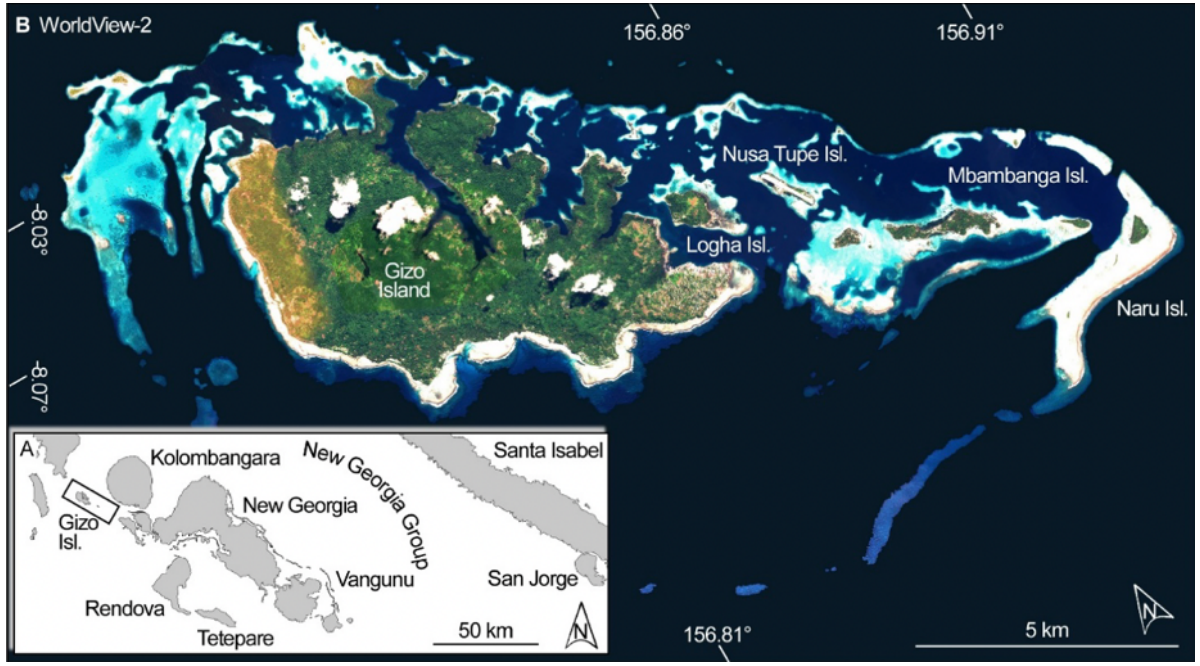
Do corals and fish correspond to seascape patterns in the reef as seen by satellite?



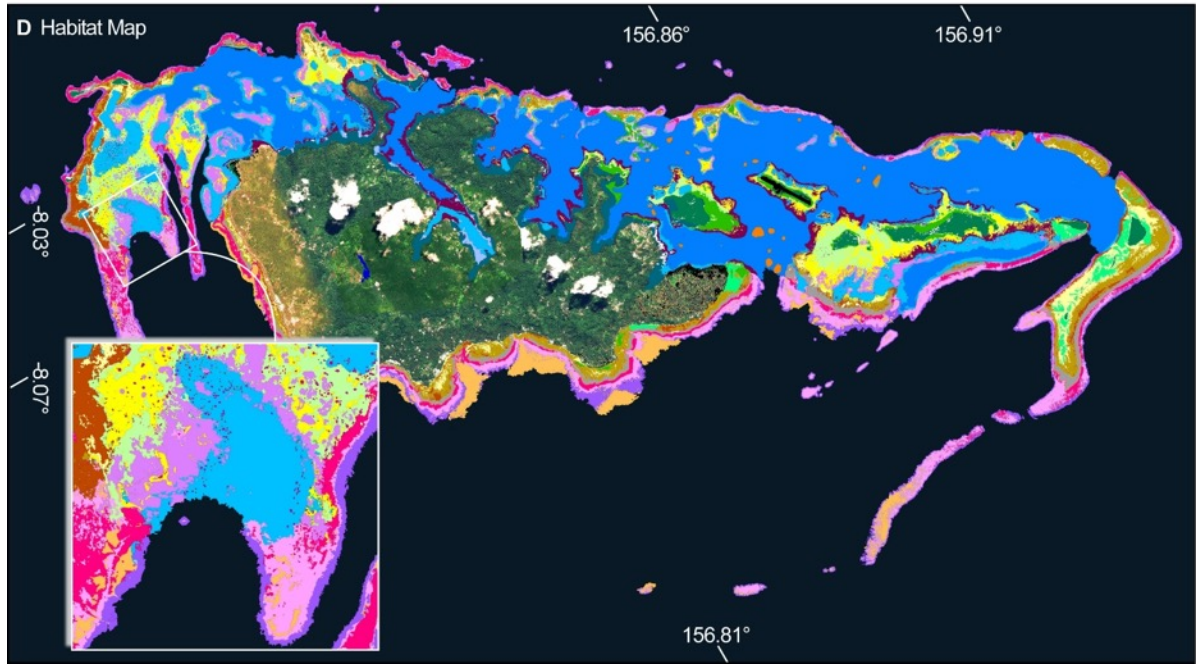
Coral Reef Biodiversity (image analysis)

Background

Satellite image

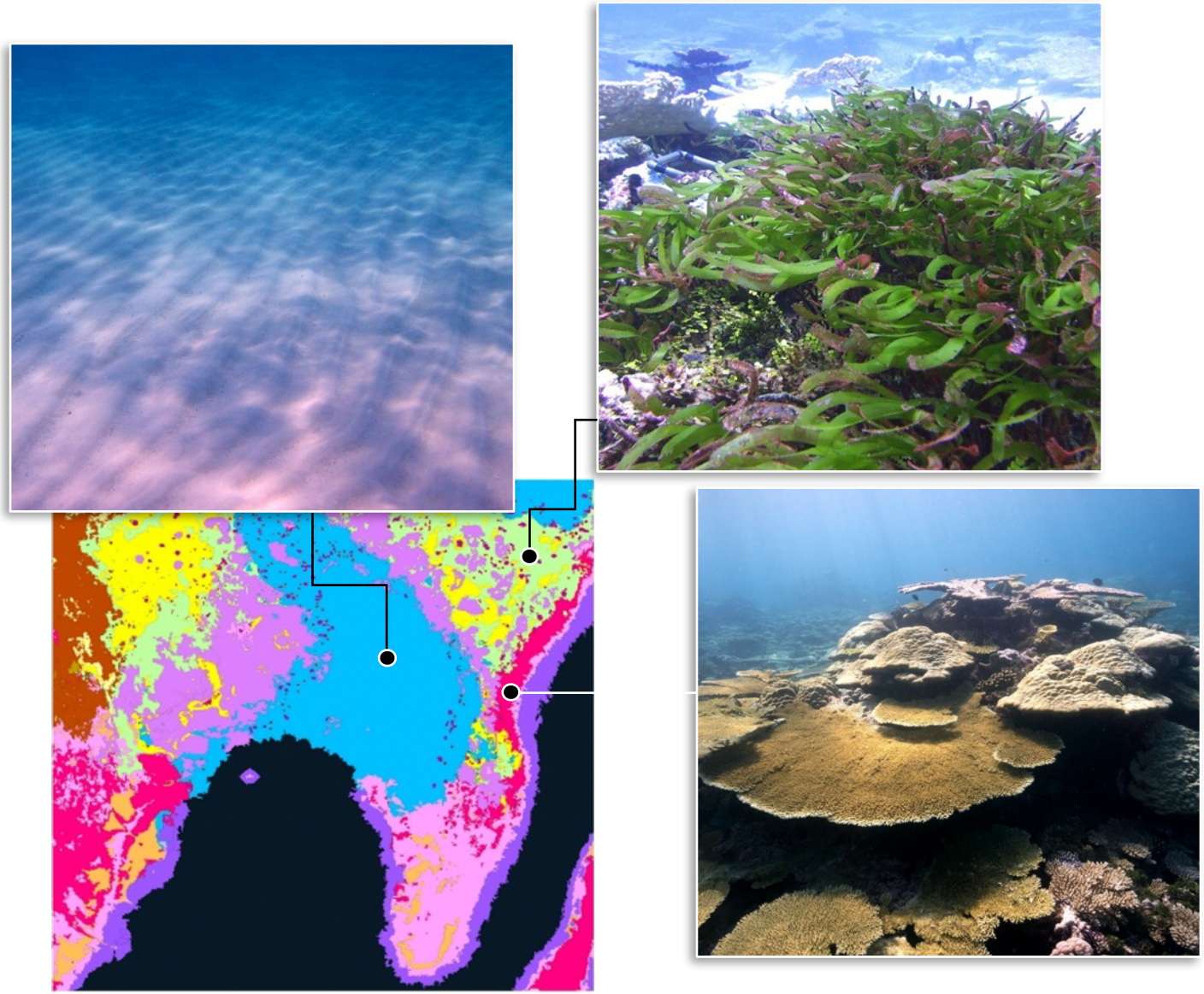


Rasterized habitat map



Coral Reef Biodiversity (image analysis)

Background

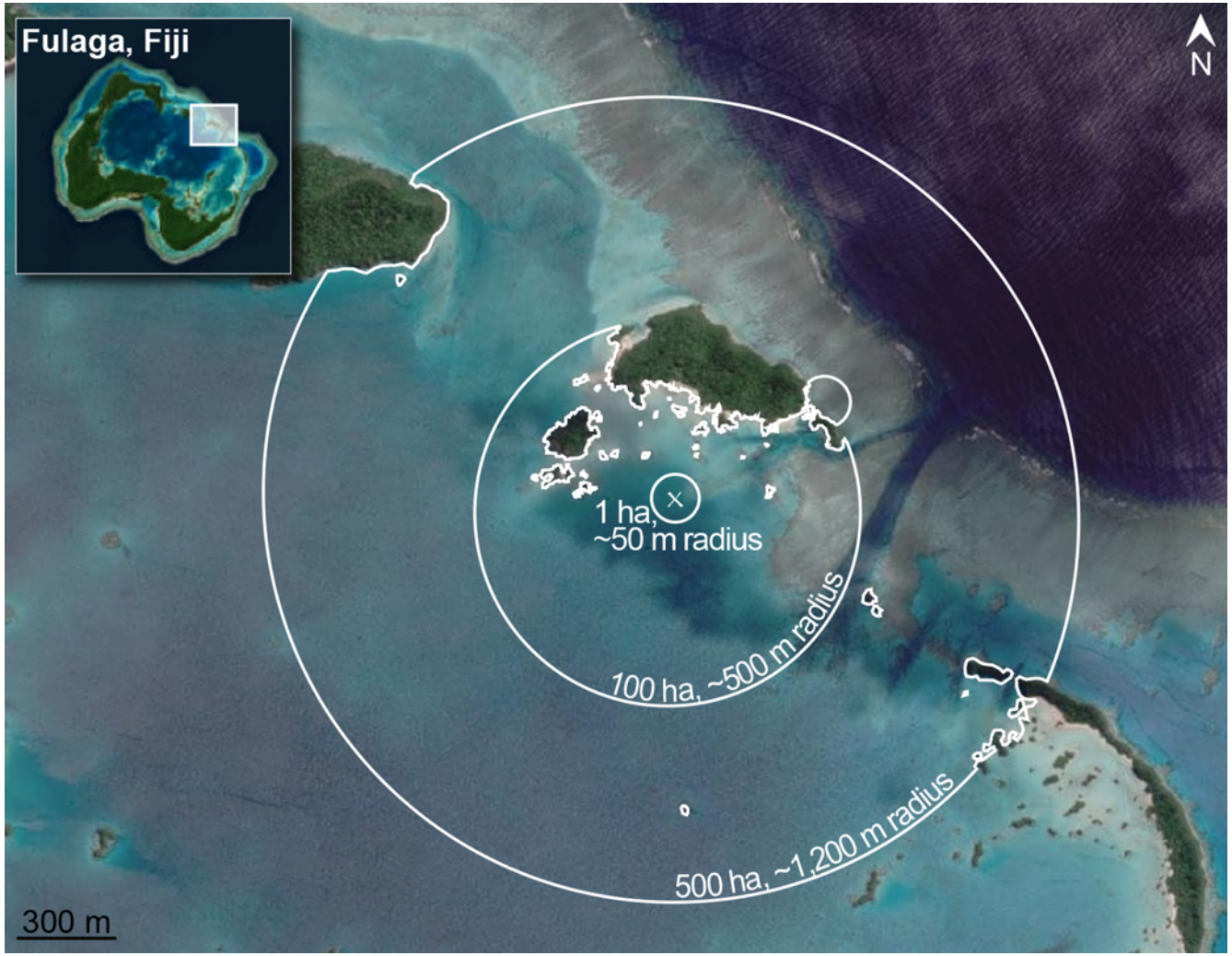


Coral Reef Biodiversity (image analysis)

Background

Challenge: How much habitat diversity occurs in a circle of size X?

Need to perform this calculation for each point in the image.



Coral Reef Biodiversity (image analysis)

This Effort

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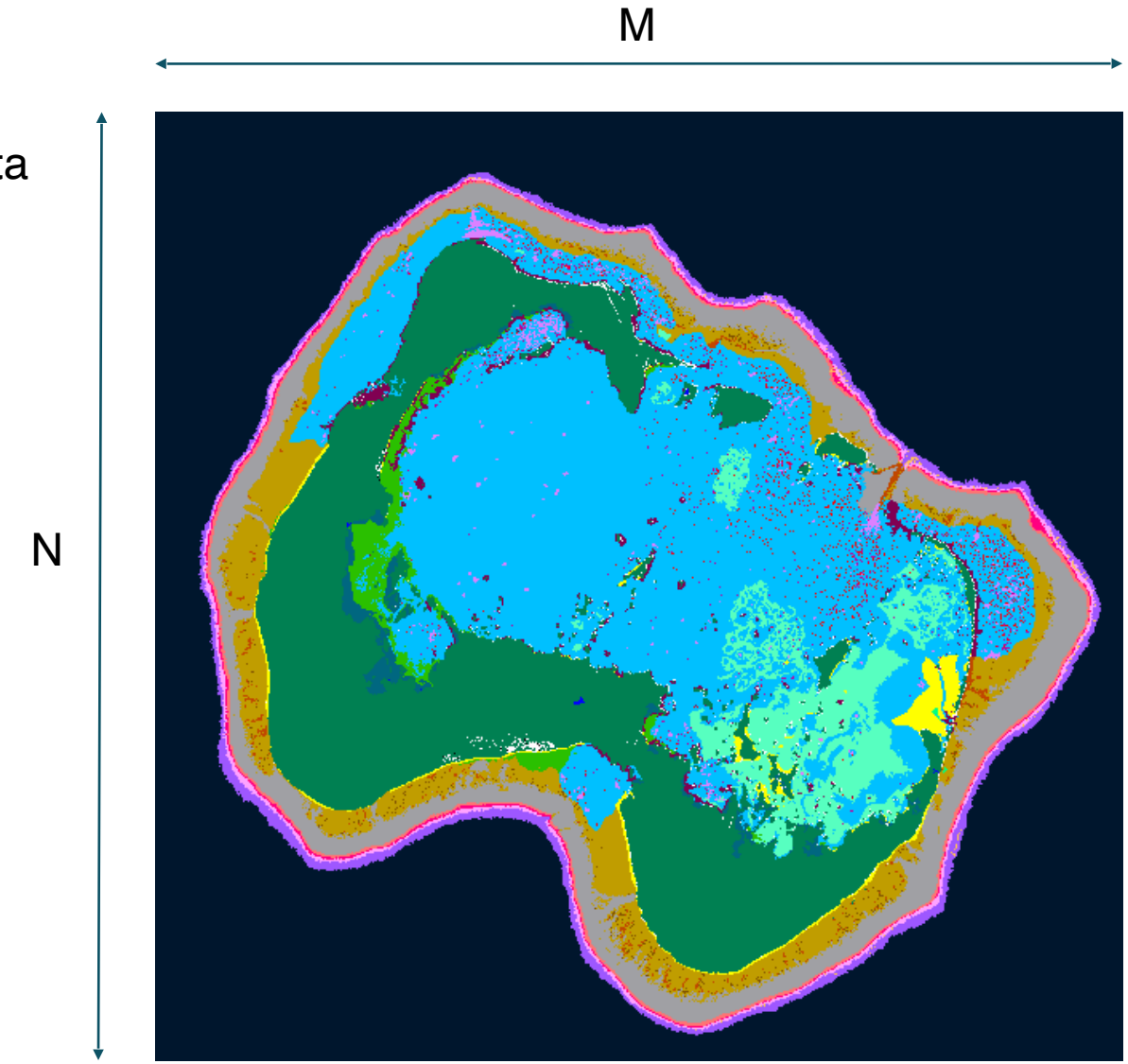

Coral Reef Biodiversity (image analysis)

This Effort

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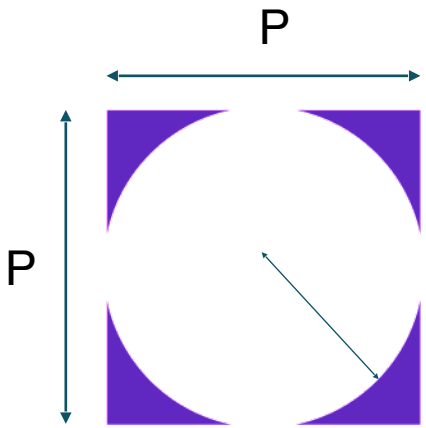
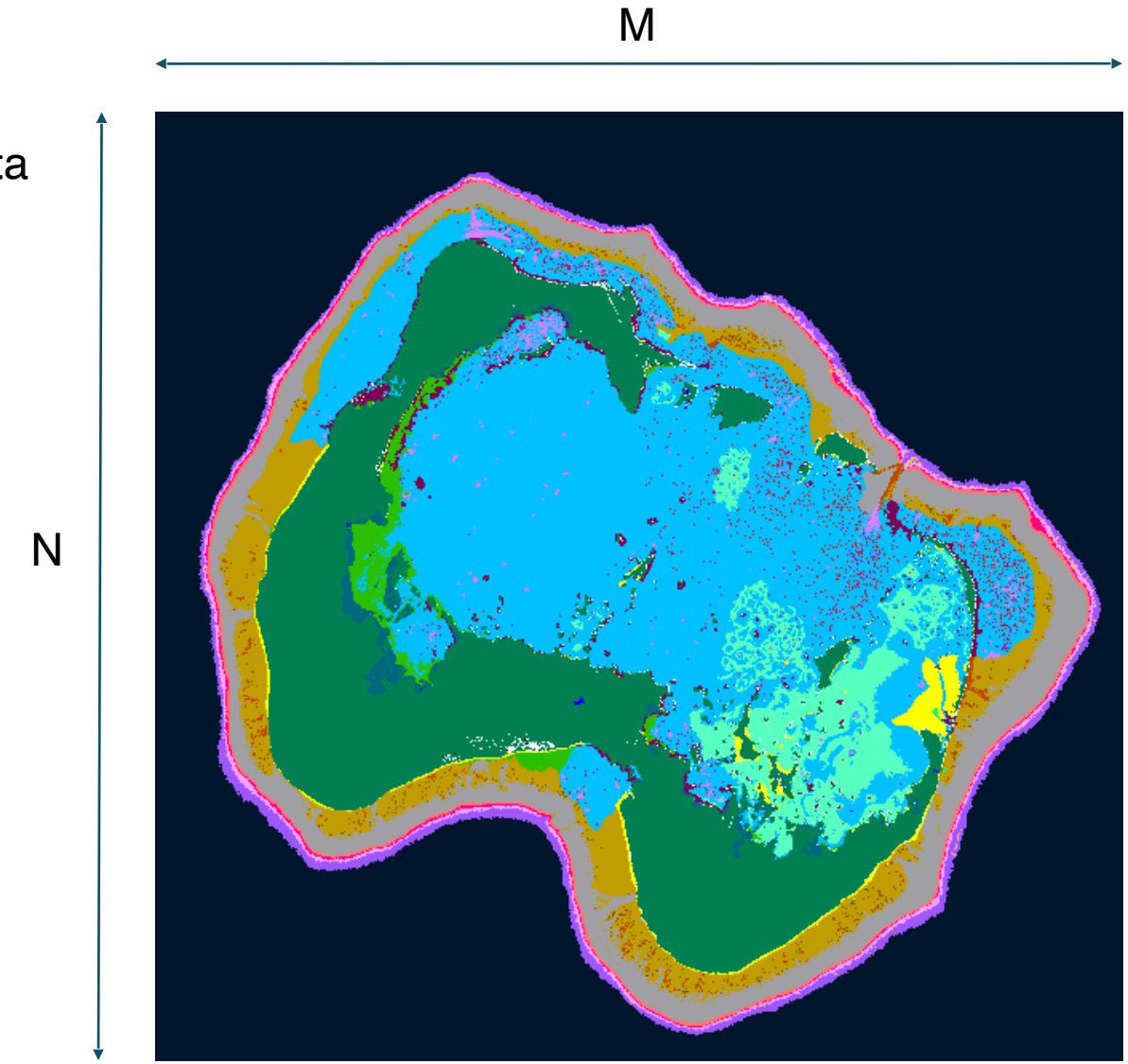
2. Create a (P x P) mask to find all points within a given radius.





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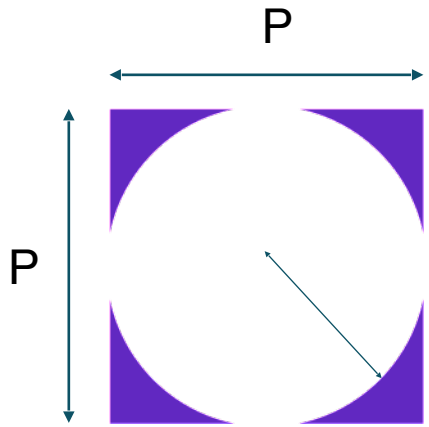
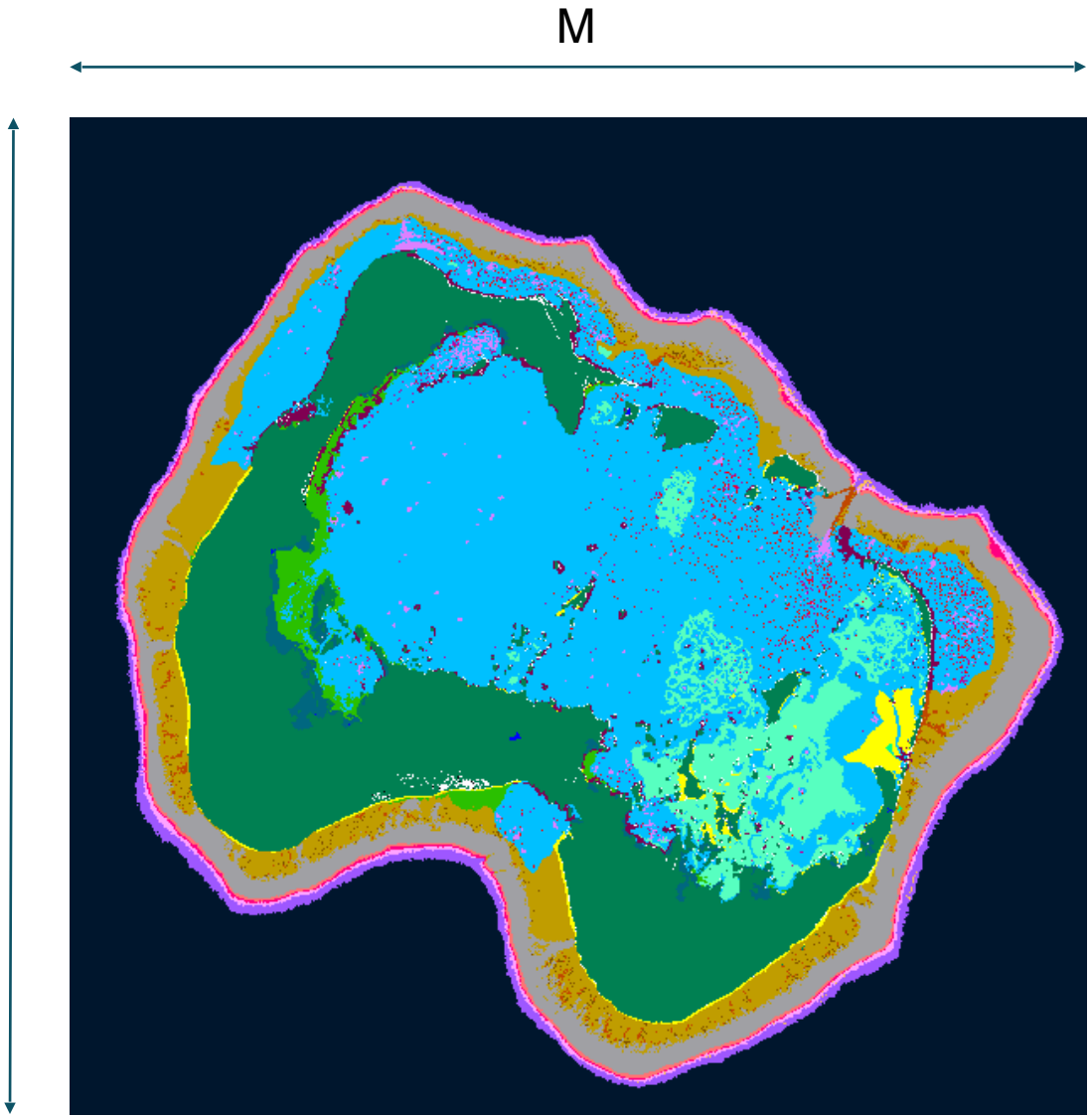
1. Read in a (M x N) raster image of habitat data
2. Create a (P x P) mask to find all points within a given radius.
3. Convolve this mask over the entire domain and perform a weighted reduce at each location.





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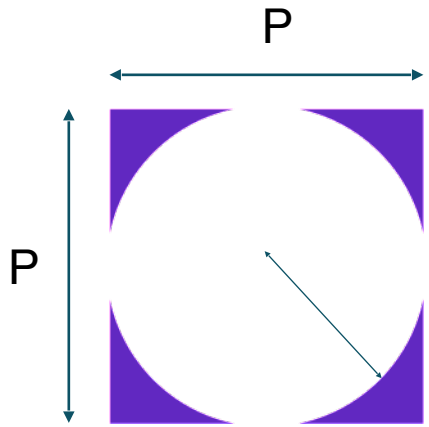

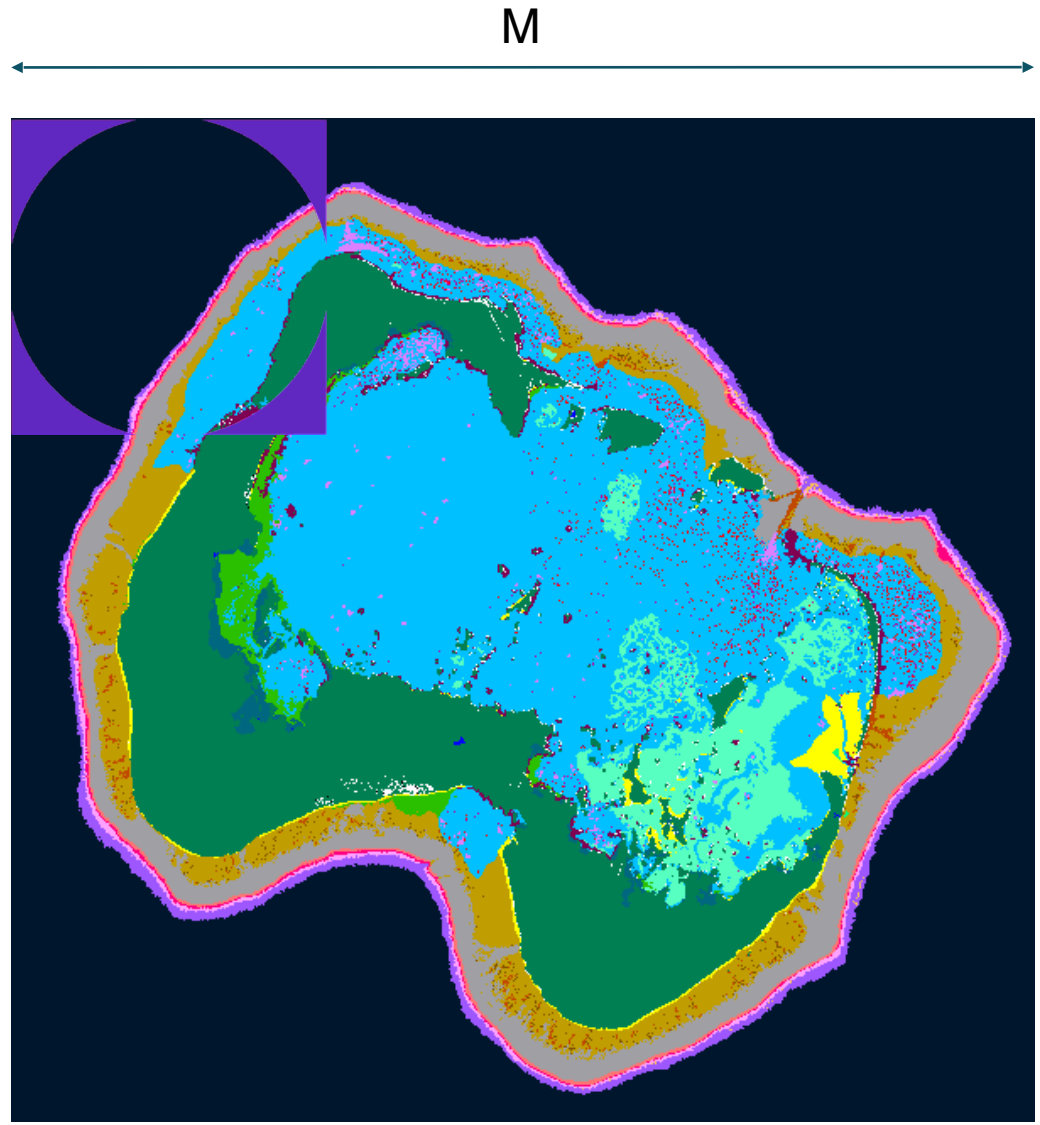

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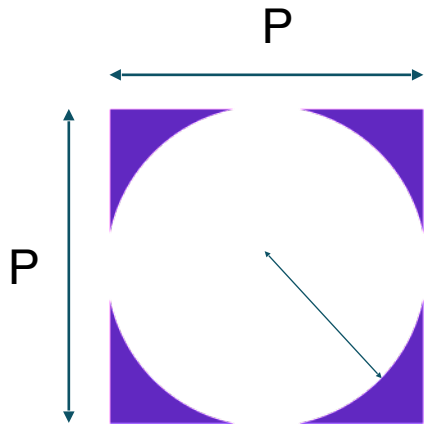

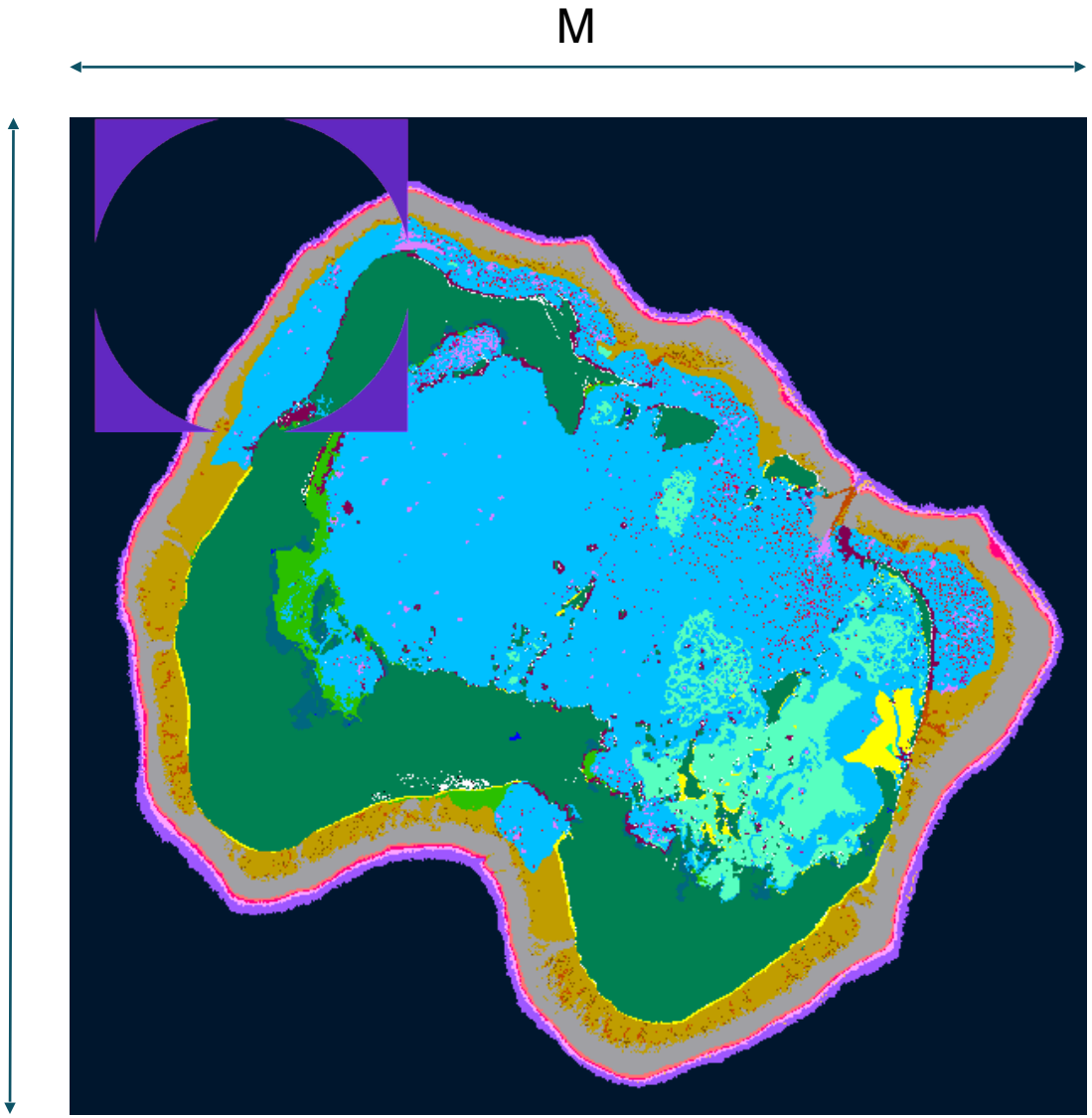

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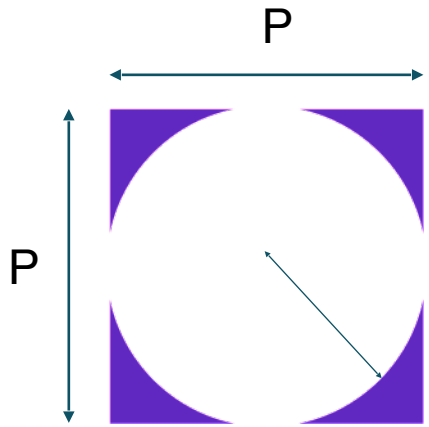

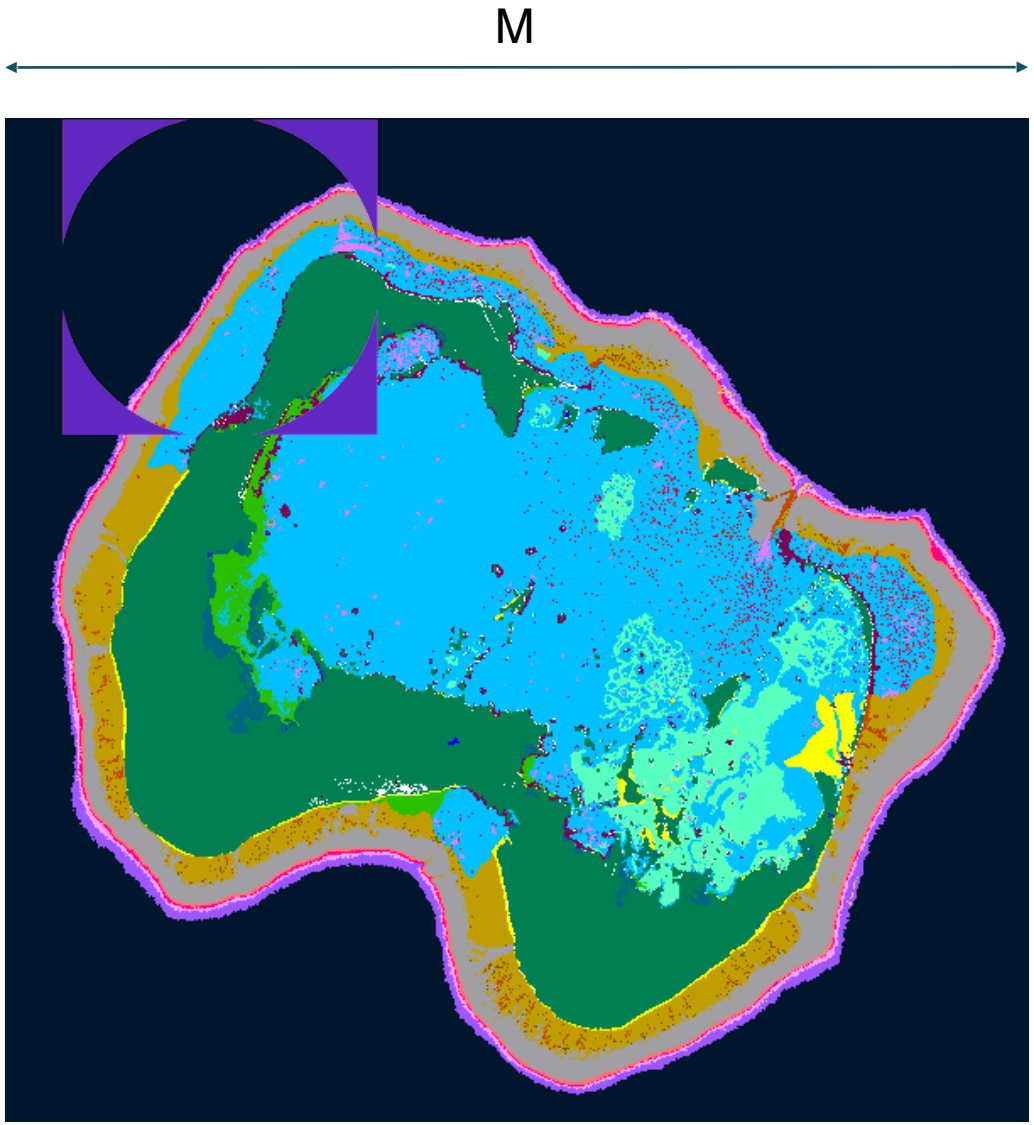

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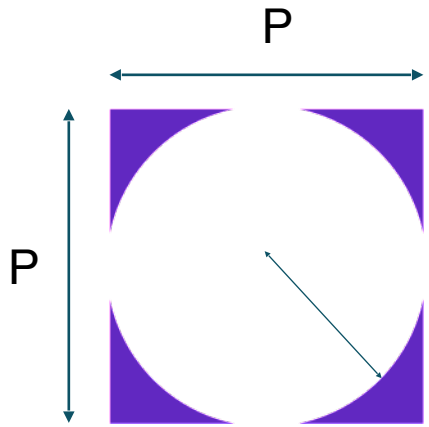

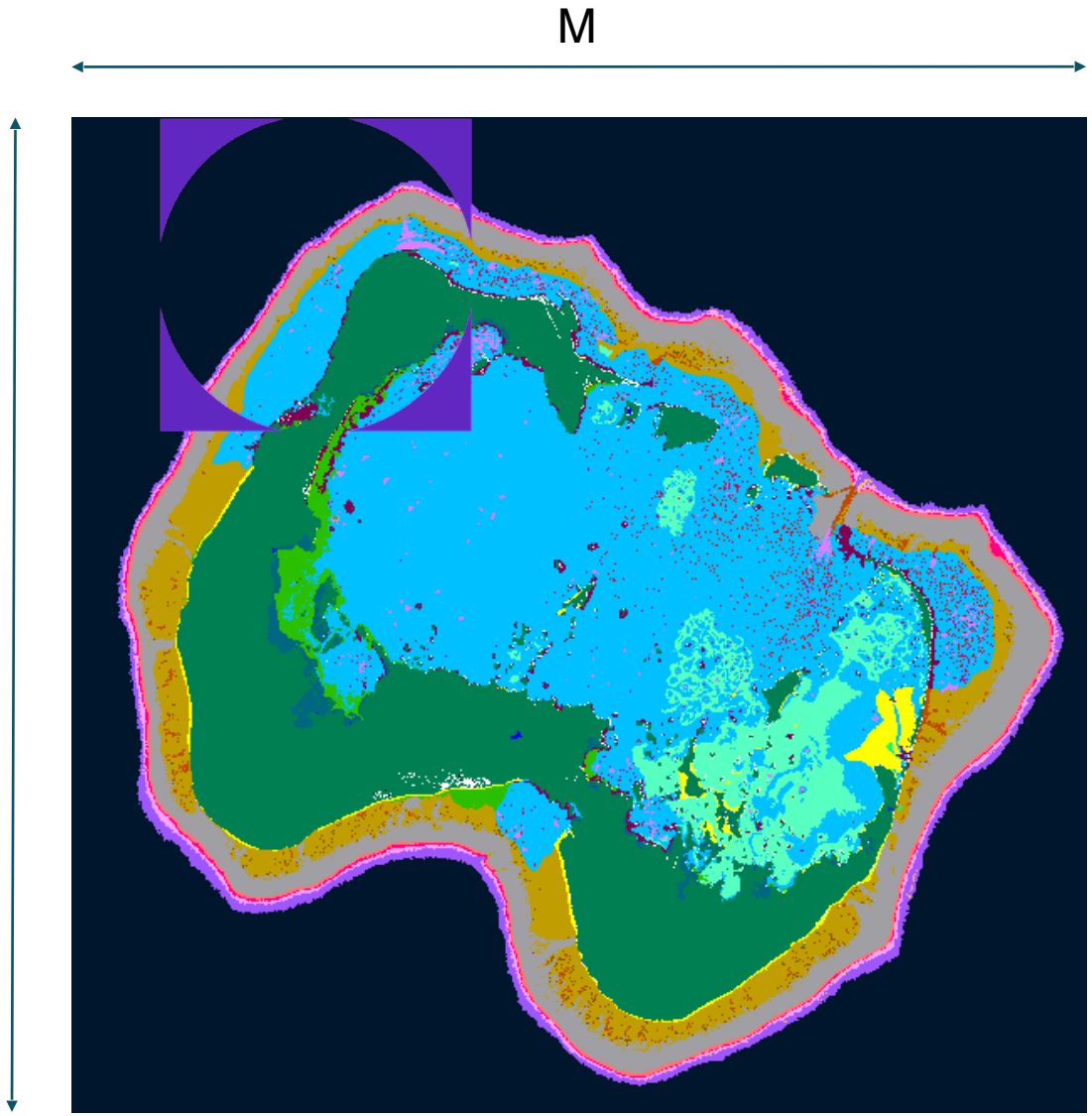

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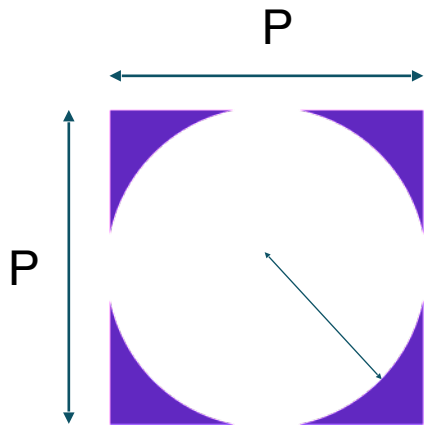

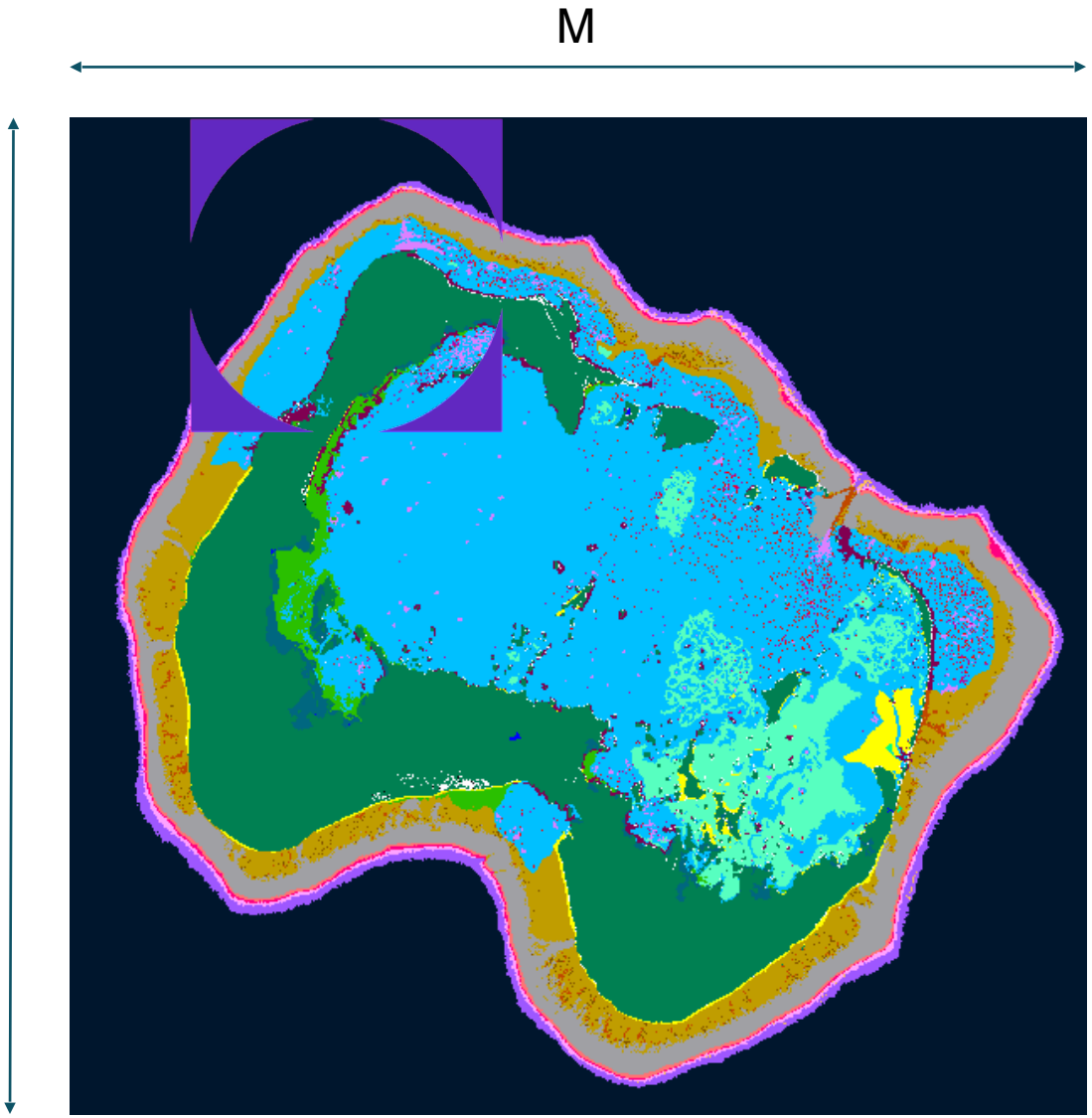

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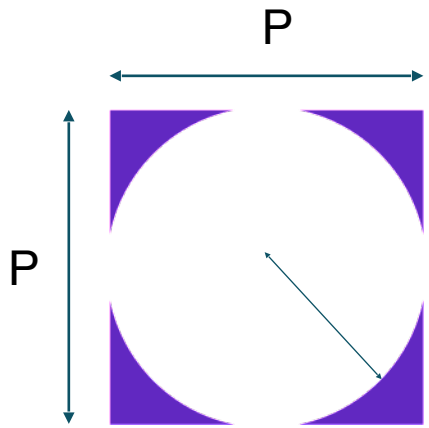
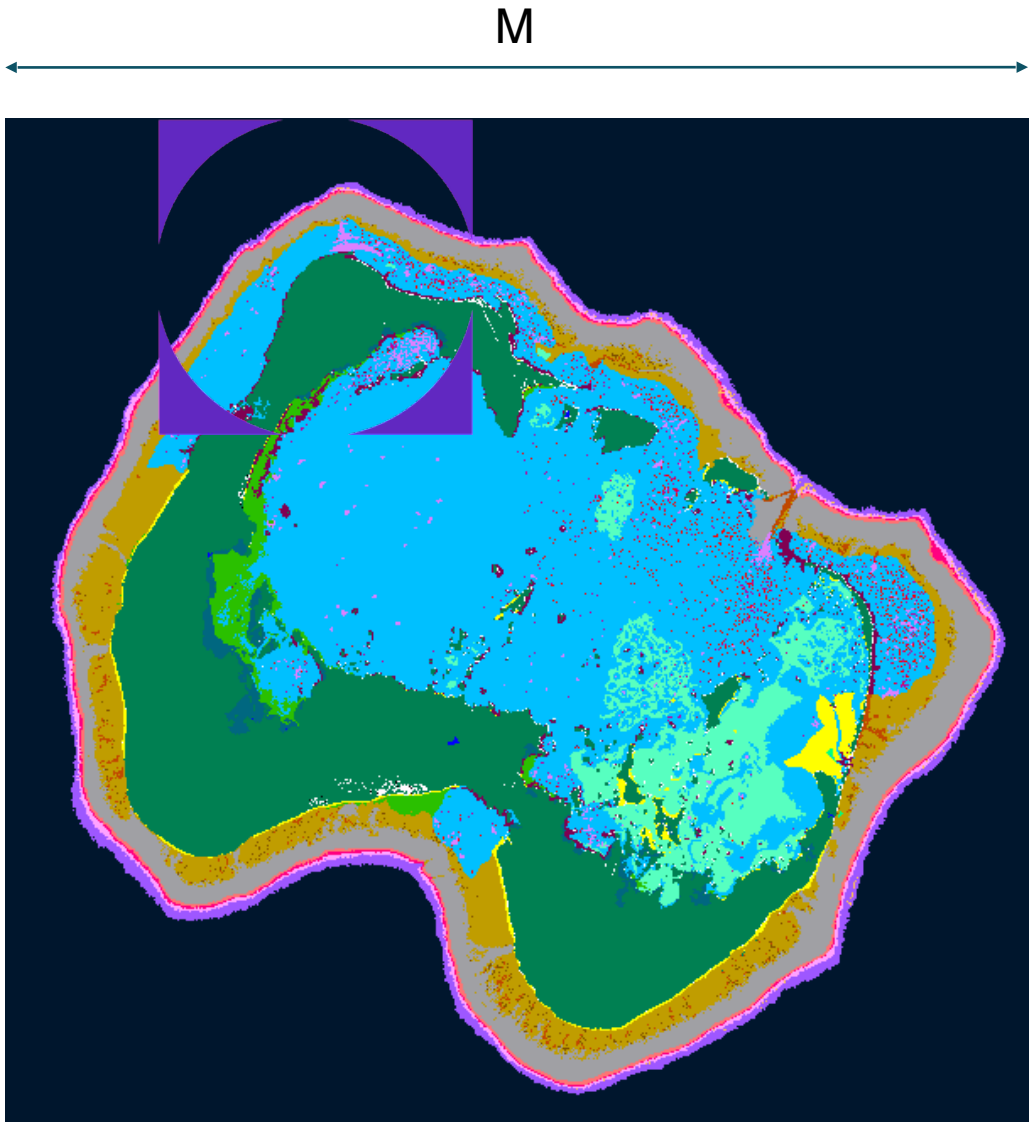


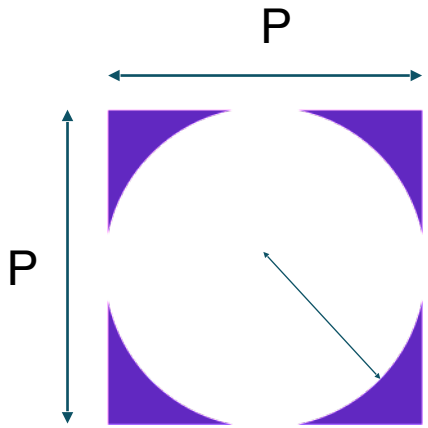


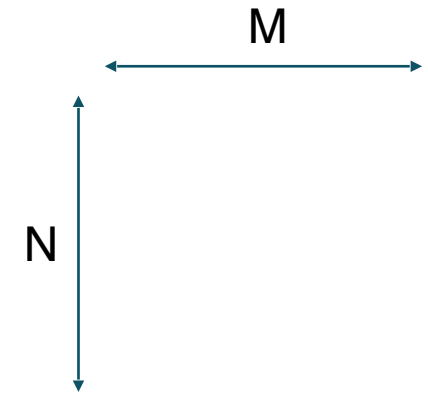
Coral Reef Biodiversity (image analysis)

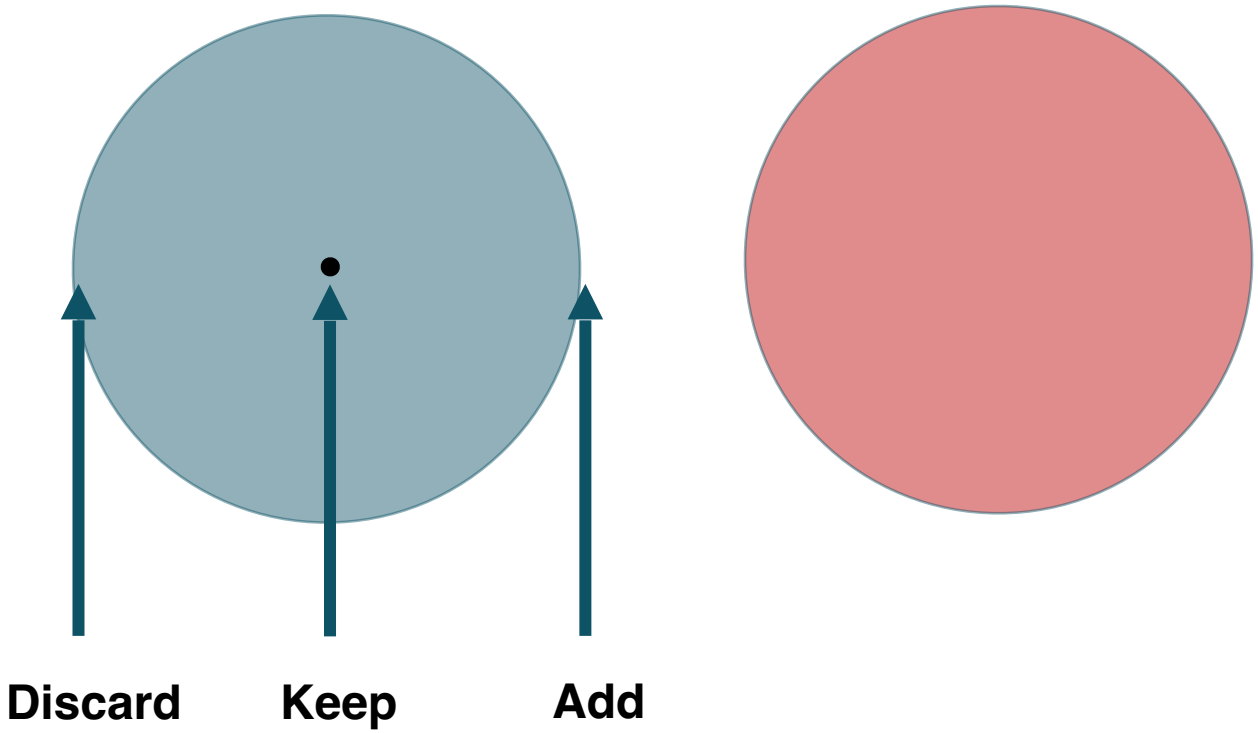
The Code

The basic algorithm essentially involves calculating a histogram at each point.

"How many habitats of each type are in the neighborhood?"







- Saves roughly a factor of P calculations.

Overall algorithm is $O(MNP)$ instead of $O(MNP^2)$

Coral Reef Biodiversity (image analysis)

The Code

```
proc create_distance_mask(radius : real, dx : real, nx : int) {

  const D : domain(2, int) = {-nx..nx, -nx..nx};
  var D_center : sparse subdomain(D);
  var D_left : sparse subdomain(D);
  var D_right : sparse subdomain(D);

  var dist : [D] real;

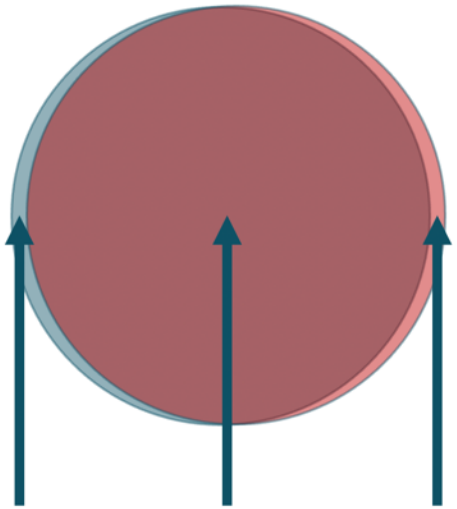
  var center_mask : [D_center] bool;
  var left_mask : [D_left] bool;
  var right_mask : [D_right] bool;



                ...



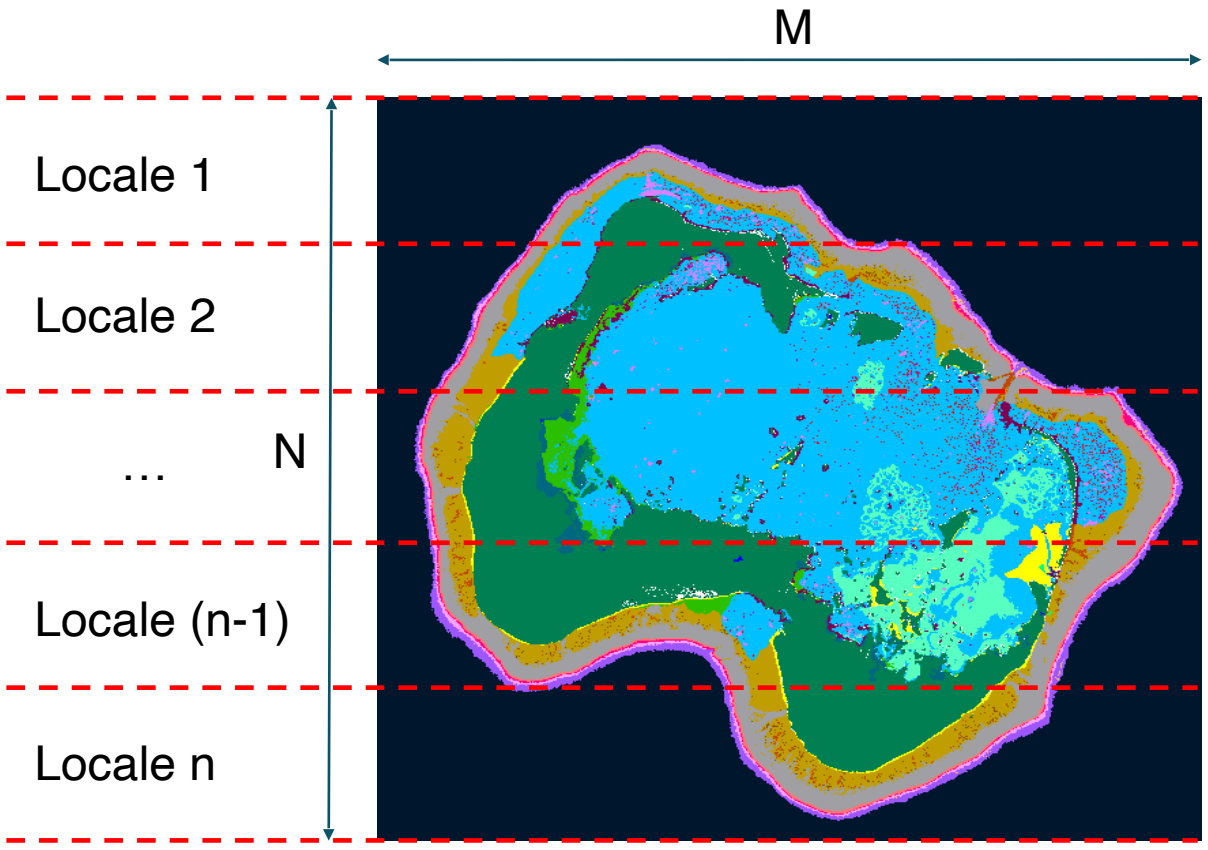
  // Define center mask.
  for (i,j) in dist.domain do {
    dist[i,j] = dx * sqrt(i**2 + j**2);
    if (dist[i,j] < radius) {
      D_center += (i,j);
    }
  }
```



Discard (D_left) **Keep** (D_center) **Add** (D_right)

Coral Reef Biodiversity (image analysis)

The Code




```
// Create Block distribution of interior of PNG
const offset = nx;
const Inner = ImageSpace.expand(-offset);
const myTargetLocales = reshape(Locales, {1..Locales.size, 1..1});
const D = Inner dmapped Block(Inner, targetLocales=myTargetLocales);
var OutputArray : [D] real;
```

Coral Reef Biodiversity (image analysis)

The Code

```
coforall loc in Locales do on loc {

  const locImageDomain = Image.domain;
  const locImage : [locImageDomain] Image.eltType = Image;

  const locLeftMaskDomain = LeftMask.domain;
  const locCenterMaskDomain = CenterMask.domain;
  const locRightMaskDomain = RightMask.domain;

                        • • •

  // If we are on a reef point, calculate beta diversity

    var num_habitat_pixels = (+ reduce B[1..(d_size-2)]) : real;
    var habitat_frac = num_habitat_pixels / Mask_Size;

    var P = B / num_habitat_pixels;

    var beta = + reduce (dissimilarity * outer(P,P));
    Output[center,point] = habitat_frac * beta + eps;
```

$$B_d = \alpha \sum_i \sum_j (D_{ij} P_i P_j)$$

α - fraction of window covered by valid habitat pixels

D_{ij} - dissimilarity coefficient

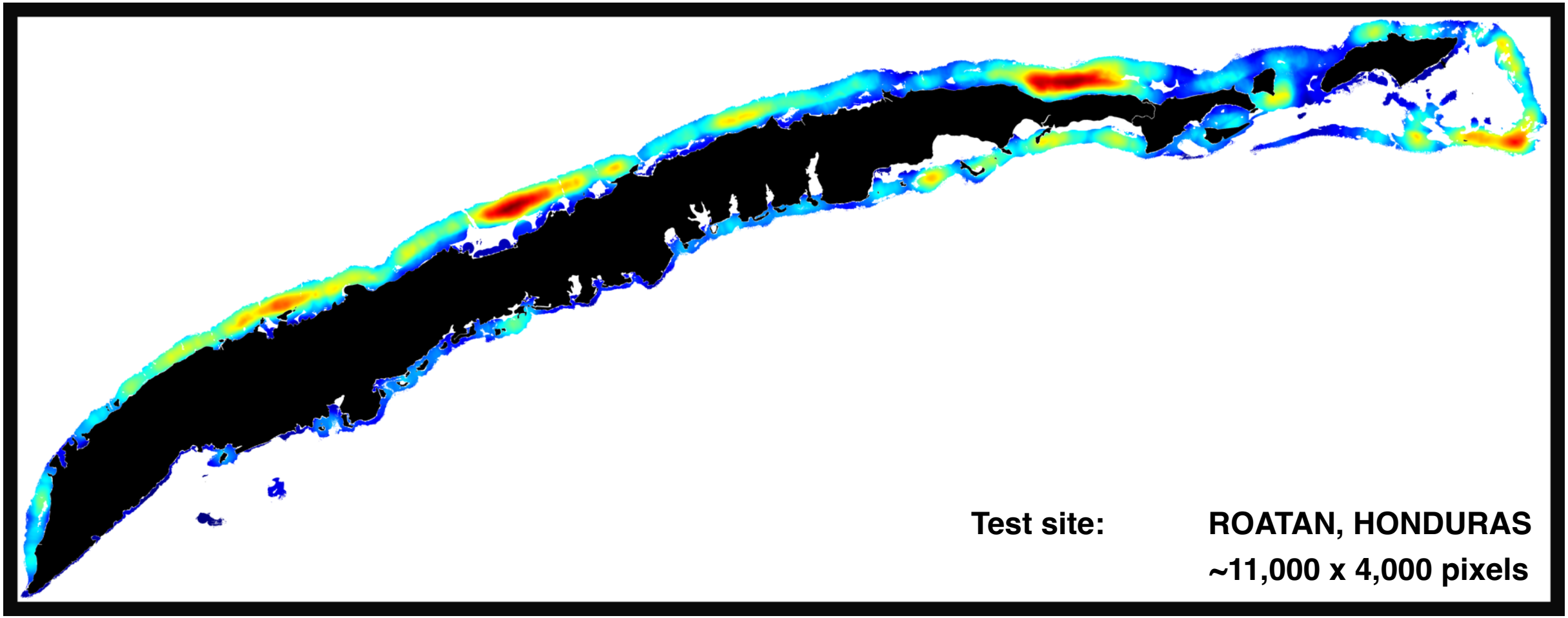
P_i - fraction of points consisting of habitat *i*

Coral Reef Biodiversity (image analysis)

Performance

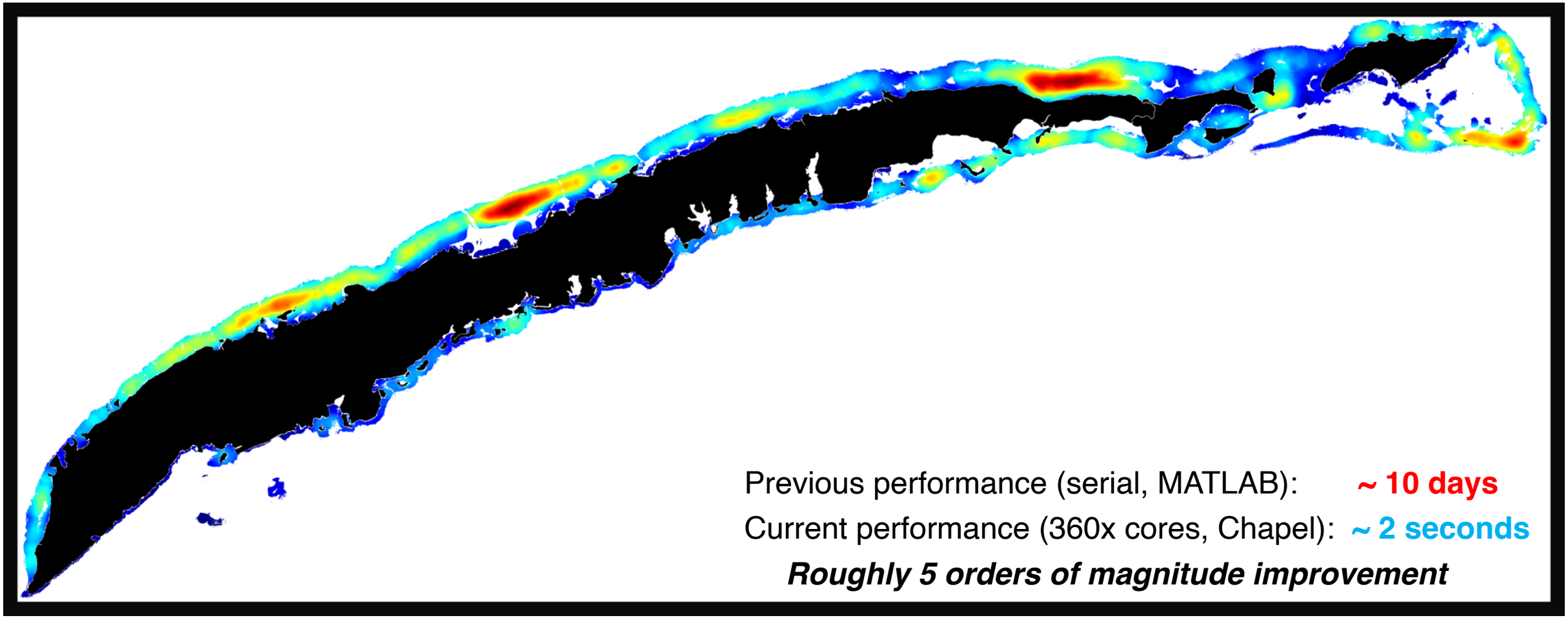
Coral Reef Biodiversity (image analysis)

Performance



Coral Reef Biodiversity (image analysis)

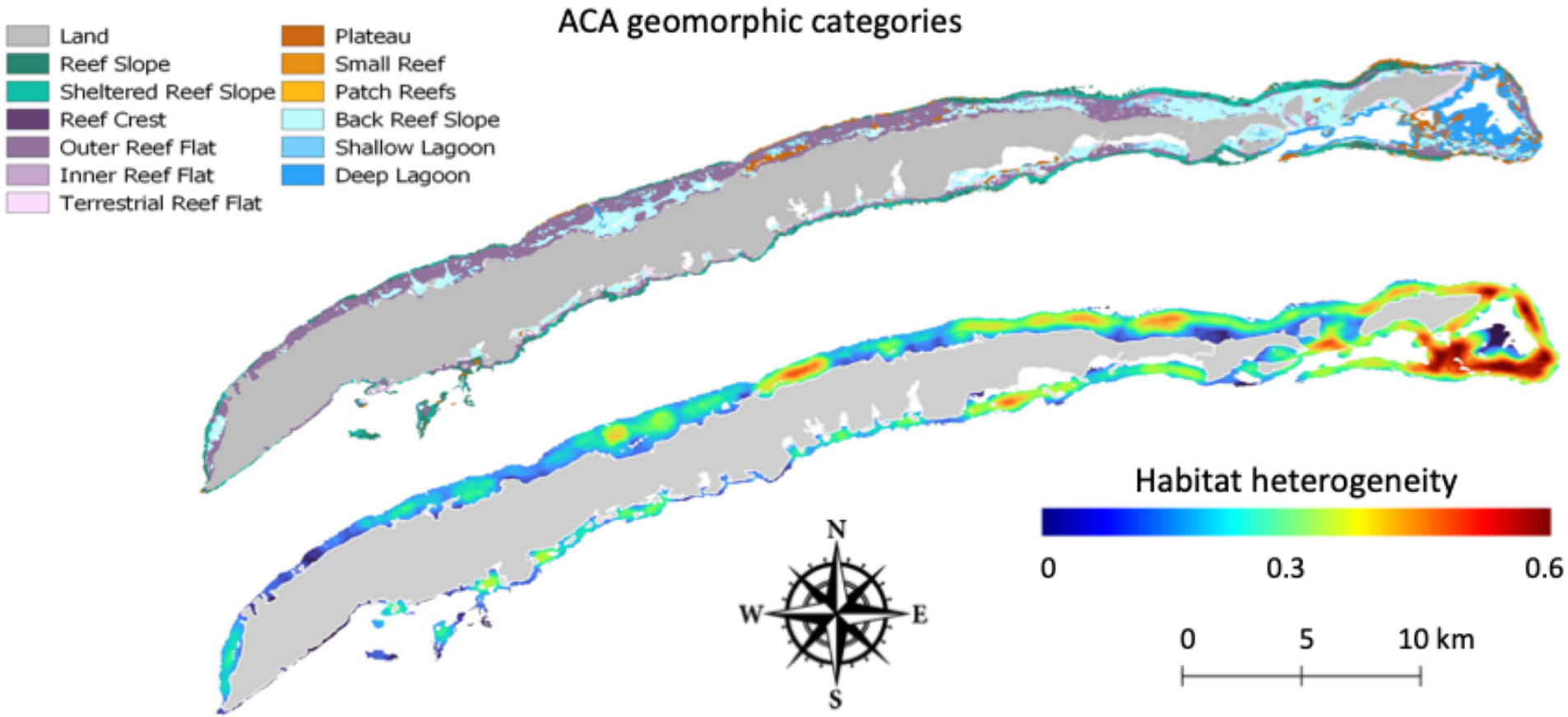
Performance



- Collaborations/discussions w/ U. Miami, Coral Reef Alliance, U. Leeds (UK), U. Hawaii
- Unexpected shoutout here(!): https://www.youtube.com/watch?v=tlp2_DI6NaI

Coral Reef Biodiversity (image analysis)

Performance



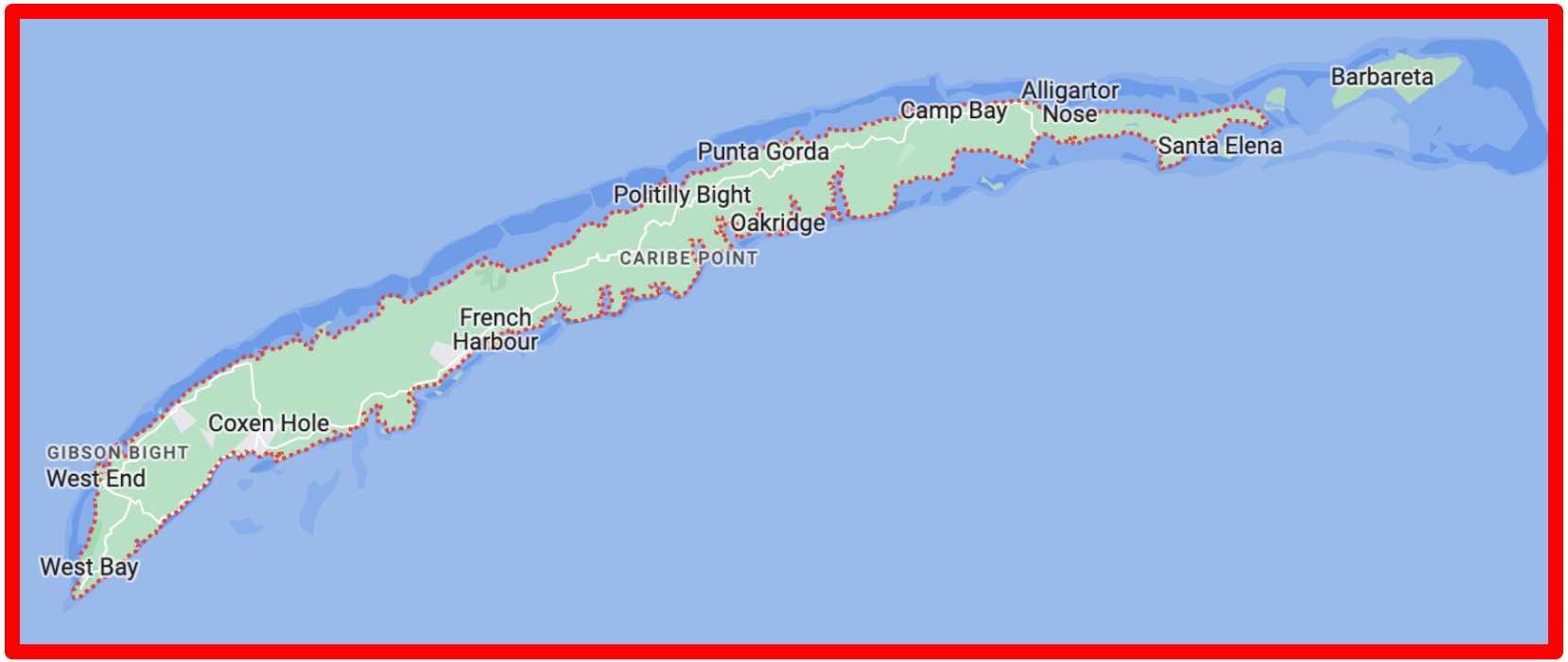
Previous performance (serial, MATLAB): **~ Multiple days**

Current performance (360x cores, Chapel): **~ 2 seconds**

Roughly 5 orders of magnitude improvement

Coral Reef Biodiversity (image analysis)

Scaling Up

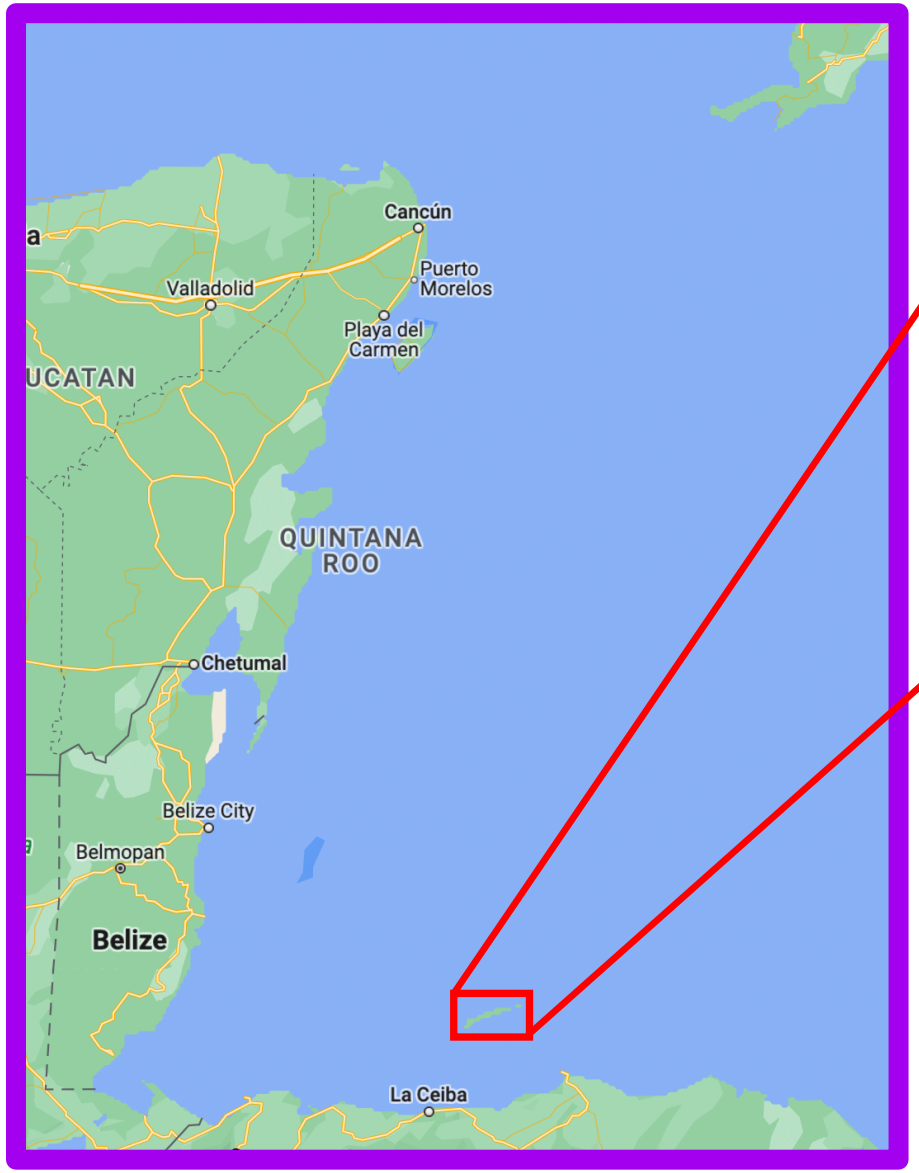


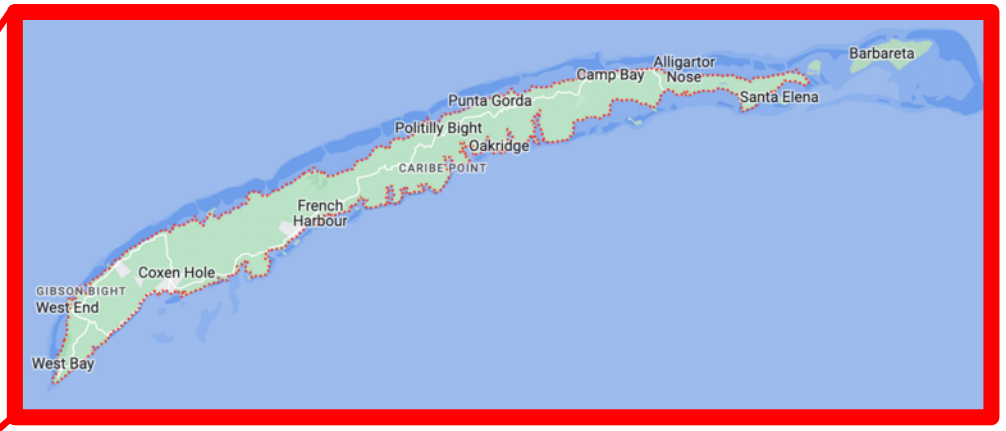
Can we try bigger regions?

Coral Reef Biodiversity (image analysis)

Scaling Up

21.7 GB





49 MB

Coral Reef Biodiversity (image analysis)

Scaling Up

```
coforall loc in Locales do on loc {

  const loc_d_size = d_size;
  const loc_Mask_Size = Mask_Size;

  var locD = D.localSubdomain();
  var locD_plus = locD.expand(offset);
  var locImage : [locD_plus] int(8);

  // Read in array
  var f = open(in_array, iomode.r);
  var first_point = locD_plus.first[0]*locD_plus.shape[1] + locD_plus.first[1];
  var r = f.reader(kind=ionative, region=first_point..);

  for i in locD_plus.first[0]..locD_plus.last[0] {
    for j in locD_plus.first[1]..locD_plus.last[1] {
      var tmp : int(8);
      r.readBinary(tmp);
      locImage[i,j] = tmp;
    }
  }
  r.close();
```

Distributed read of the input image

Coral Reef Biodiversity (image analysis)

Scaling Up

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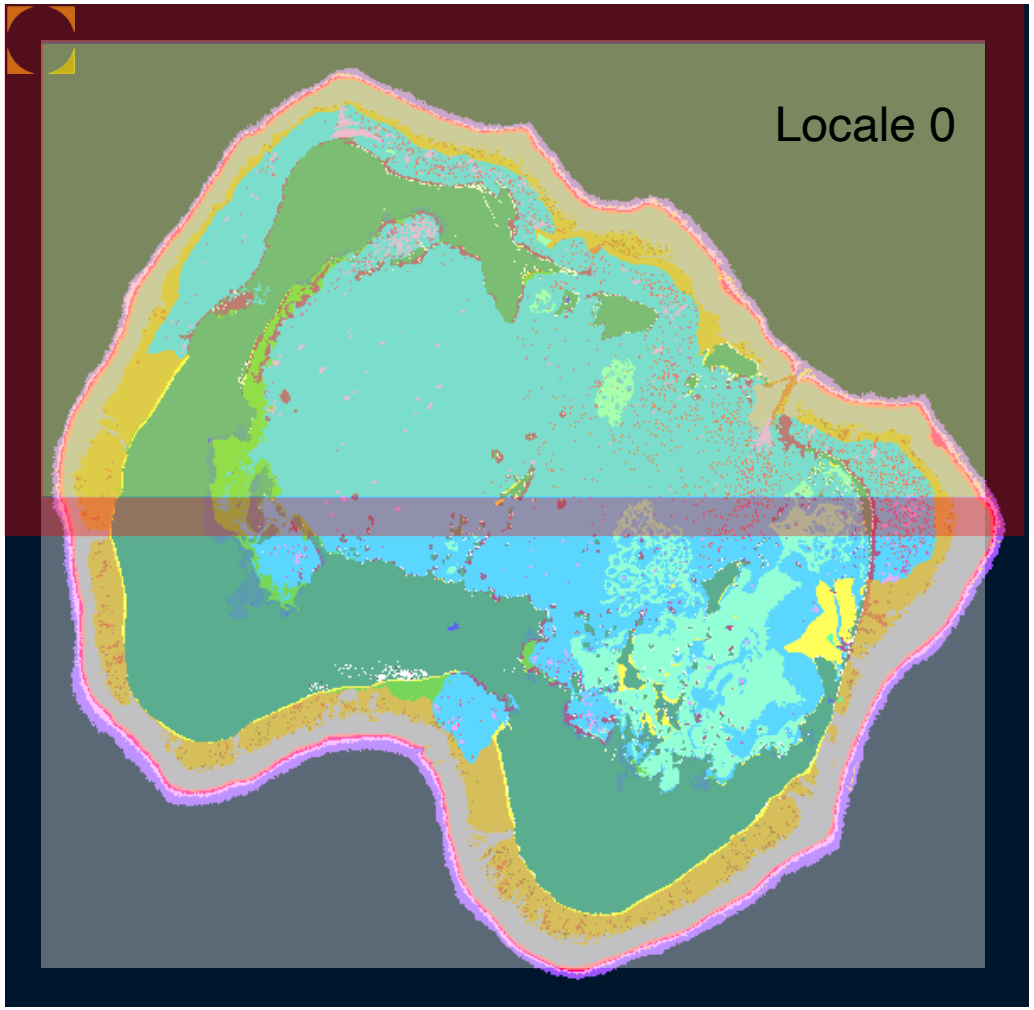
  for i in locD_plus.first[0]..locD_plus.last[0] {
    for j in locD_plus.first[1]..locD_plus.last[1] {
      var tmp : int(8);
      r.readBinary(tmp);
      locImage[i,j] = tmp;
    }
  }
  r.close();
```

Passes the local Subdomain + a halo equal to half the mask width



Coral Reef Biodiversity (image analysis)

Scaling Up

Distributed write of the output image (using C-interoperability)

```
proc WriteOutput(filename : string, ref arr_out: [?D] real(32), ImageSpace : ?, varid
_in : int, offset : int) {


coforall loc in Locales do on loc {

  var ncid : c_int;
  var varid = varid_in : c_int;

  extern proc nc_open(path : c_string, mode : c_int, ncidp : c_ptr(c_int)) : c_int;
  nc_open( filename.c_str() , NC_WRITE, c_ptrTo(ncid));

  /* Determine where to start reading file, and how many elements to read */
  // Start specifies a hyperslab.  It expects an array of dimension sizes
    var start = tuplify(D.localSubdomain().first);
  // Count specifies a hyperslab.  It expects an array of dimension sizes
    var count = tuplify(D.localSubdomain().shape);

    var start_c : [0..#start.size] c_size_t;
    var count_c : [0..#count.size] c_size_t;

    for i in 0..<count.size {
      start_c[i] = start[i] : c_size_t;
      count_c[i] = count[i] : c_size_t;
    }

    extern proc nc_put_vara_float(ncid : c_int, varid : c_int, startp : c_ptr(c_size_
t), countp : c_ptr(c_size_t), op : c_ptr(c_float)) : c_int;
    nc_put_vara_float(ncid, varid, c_ptrTo(start_c), c_ptrTo(count_c), c_ptrTo(arr_ou
t[start]));

    nc_close(ncid);

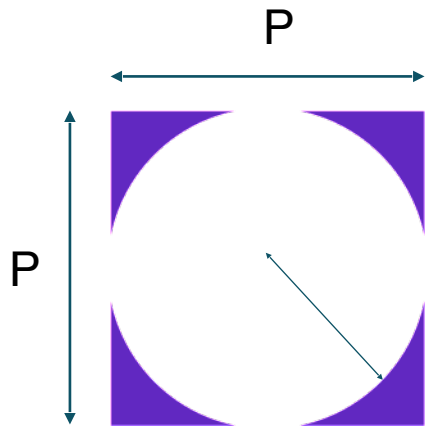
  }
}
```

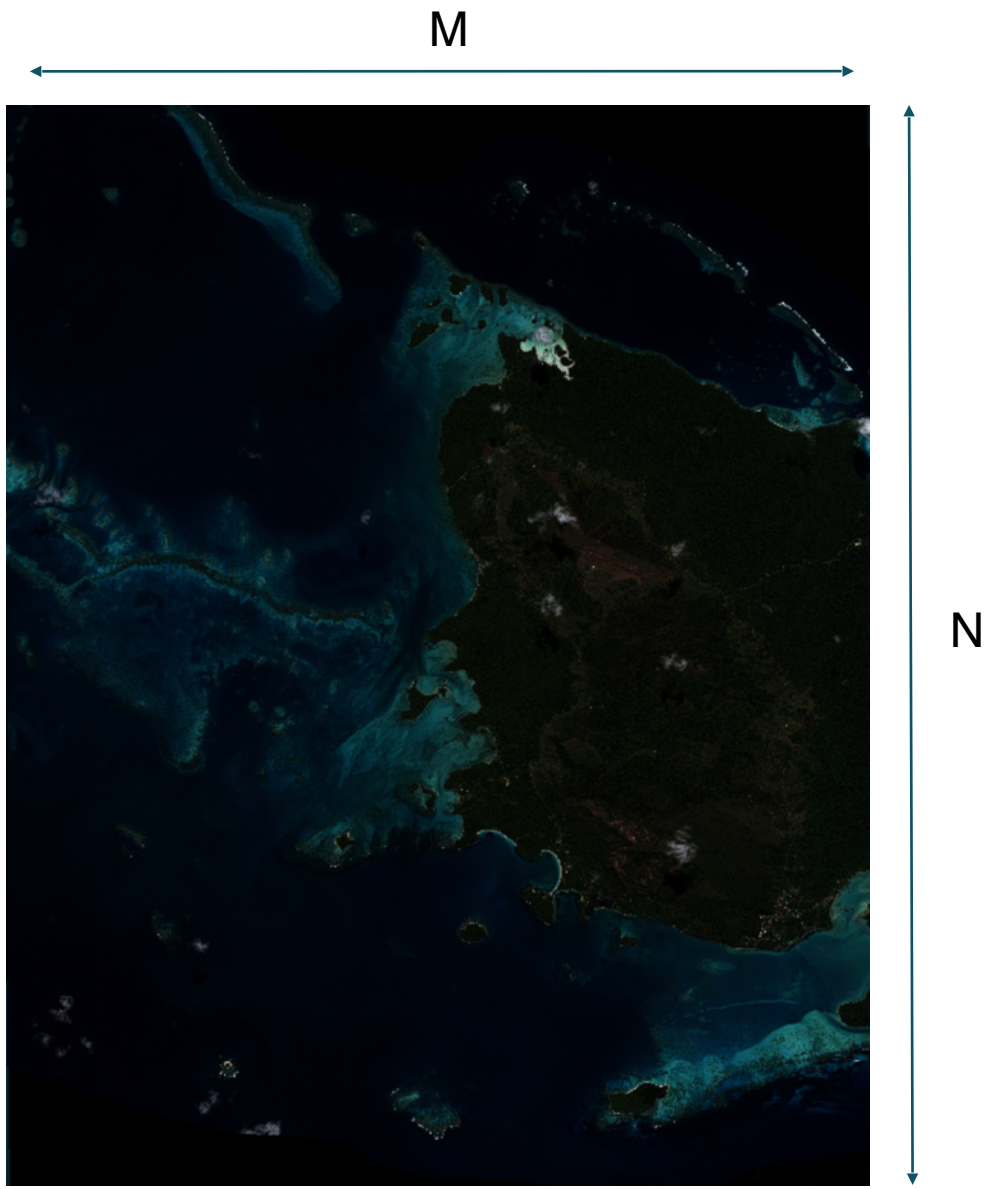
Coral Reef Biodiversity (image analysis)

Variant algorithms

Spectral diversity

”How much variation in the visible spectrum exists within a neighborhood?”





Habitat diversity: Count the number of points of each type

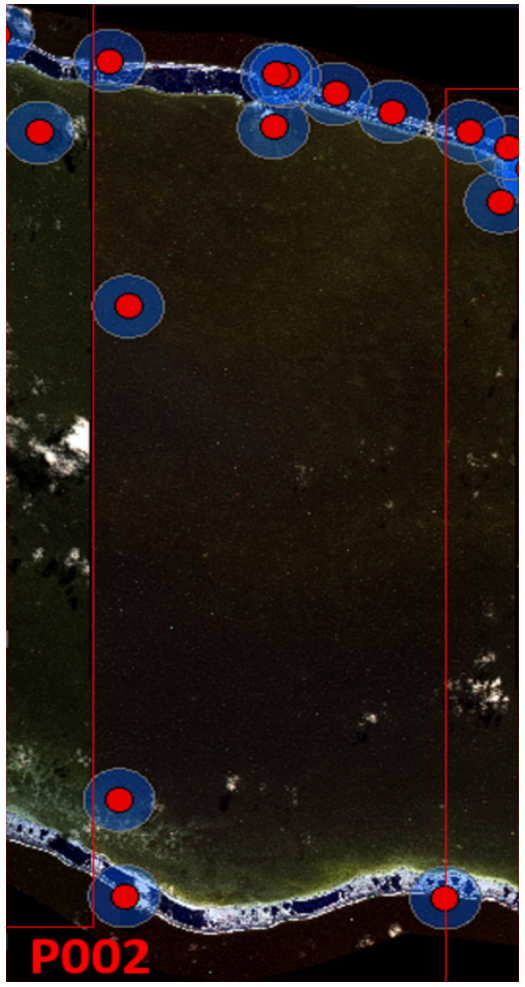
Spectral diversity: For each point, compare spectrum *against every other point*

Habitat diversity: $O(MNP)$

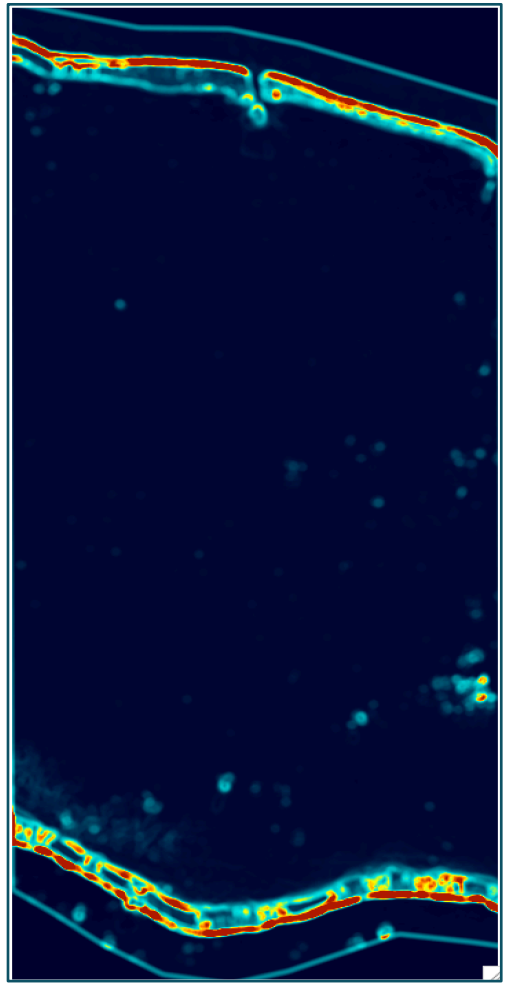
Spectral diversity: $O(MNP^3)$

Coral Reef Biodiversity (image analysis)

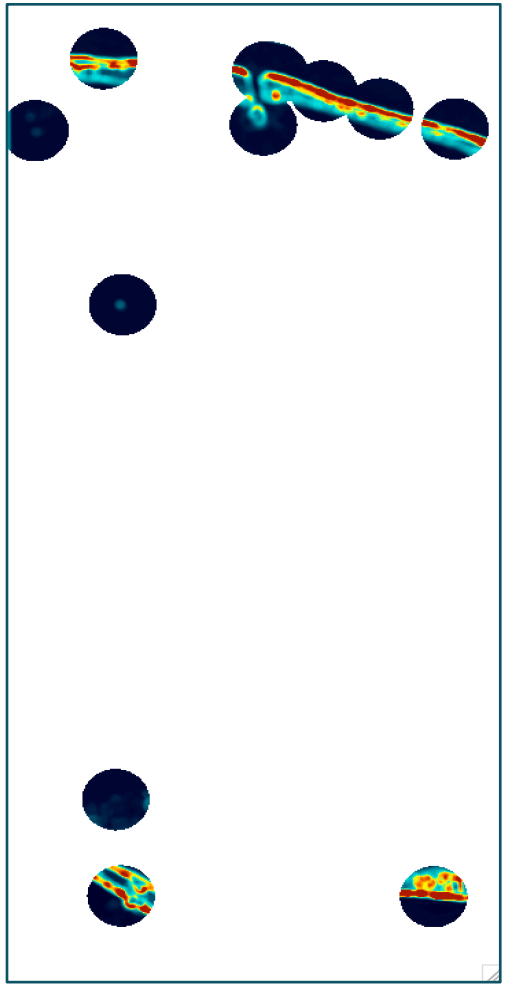
Variant algorithms



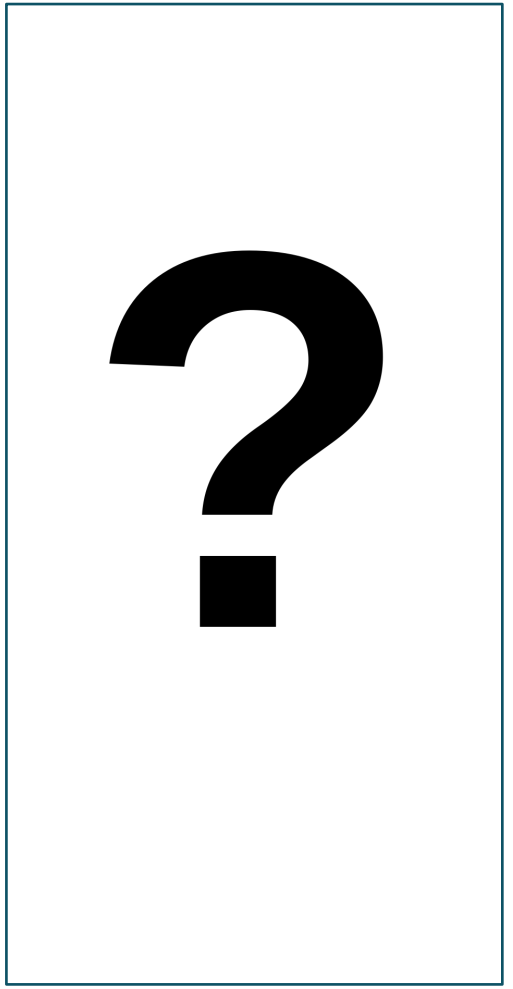
Rangiroa, French Polynesia
19,639 x 9,015 (8 color bands)



Full map
12 hours on 432 cores



Dive sites only
1.5 hours on 432 cores



GPU version
?

Coral Reef Biodiversity (image analysis)

Variant algorithms

Spectral diversity ***on GPU***

```
foreach i in centerPoints.dim(0) {
//for i in centerPoints.dim(0) {
  assertOnGpu();

  var tmpLL : real = 0;
  var tmpLC : real = 0;
  var tmpLR : real = 0;
  var tmpCC : real = 0;
  var tmpCR : real = 0;
  var tmpRR : real = 0;

  calc_distance(Array, Masker.left(), Masker.left(), tmpLL, bs, be, i, first_point);
  calc_distance(Array, Masker.left(), Masker.center(), tmpLC, bs, be, i, first_point);
  calc_distance(Array, Masker.left(), Masker.right(), tmpLR, bs, be, i, first_point);
  calc_distance(Array, Masker.center(), Masker.center(), tmpCC, bs, be, i, first_point);
  calc_distance(Array, Masker.center(), Masker.right(), tmpCR, bs, be, i, first_point);
  calc_distance(Array, Masker.right(), Masker.right(), tmpRR, bs, be, i, first_point);
```

```
Distance circle has a radius of 5 points.
Elapsed time at start of coforall loop: 6e-05 seconds.
Starting coforall loop.
Distance circle has a radius of 5 points.
Made masker on 0
Starting convolution at 18.5078.
Before gpu 6..15236
6
10066
0 (gpu 0): main_GPU_iter2.chpl:38: kernel launch (block size: 512x1x1)
Took 0.005122 seconds to complete convolve.
Elapsed time to finish coforall loop: 18.6655 seconds.
```

Coral Reef Biodiversity (image analysis)

Applications and Projects

- Assessing whether habitat heterogeneity metrics may be linked to thermal variability and genetic diversity of reefs.

Methods:

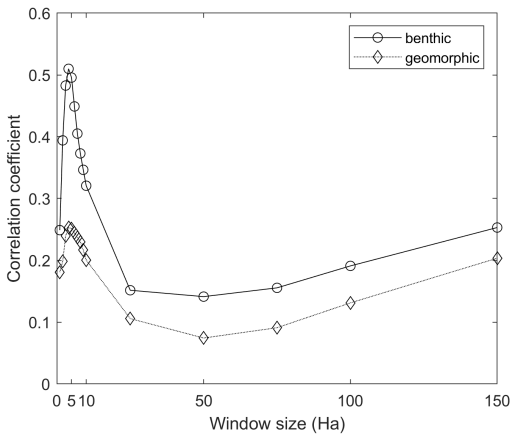
- Publicly available maps of coral reef benthic and geomorphic zonation from **Allen Coral Atlas** used in **RapidQ.**

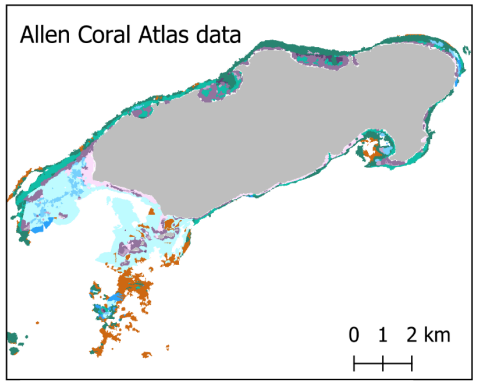
- 40 temperature loggers deployed for 24 months, genetic samples from coral species taken.

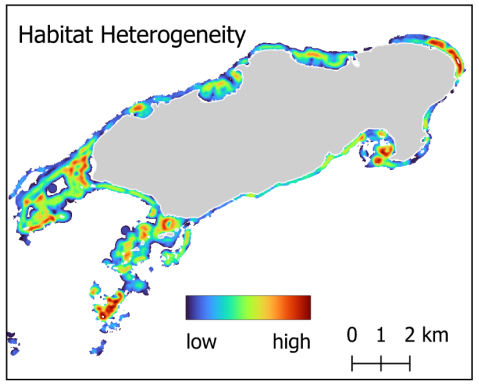
Initial Results:

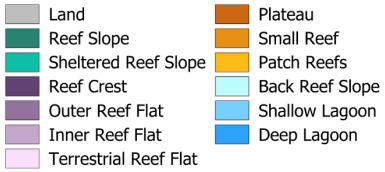
- Daily temperature range at coral sampling sites correlated to habitat heterogeneity at window sizes of 4 and 5 Ha.

- Higher correlations in benthic habitat maps.









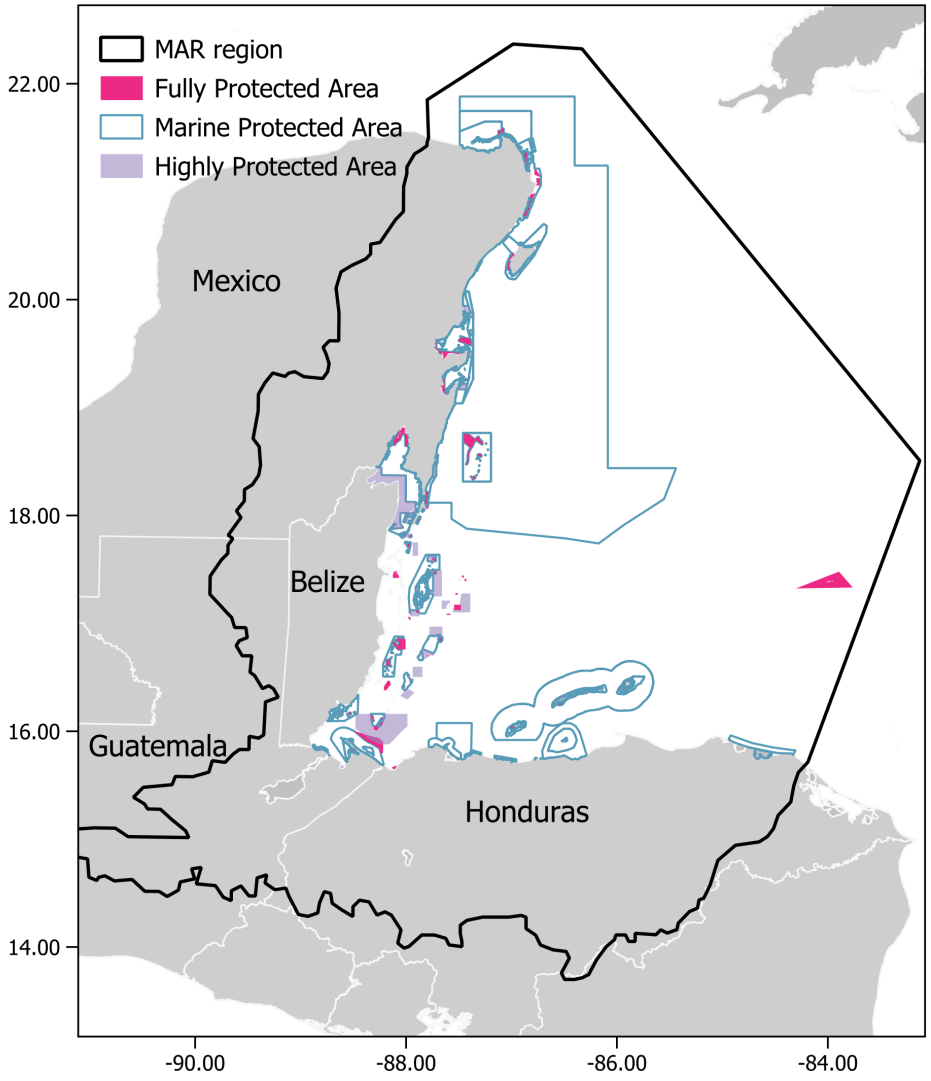
Coral Reef Biodiversity (image analysis)

Applications and Projects

- Largest barrier reef system in the Western Hemisphere, stretching for >1000km along the coasts of Honduras, Guatemala, Belize and Mexico.
- Habitat heterogeneity layers created for entire reef system, currently evaluating against Marine Protected Area (MPA) status.
- End goal: deliver a product derived from satellite remote sending that can be used in effective global marine conservation planning.

Photo credit Antonio Busiello

Mesoamerican Reef Marine Protected Area boundaries

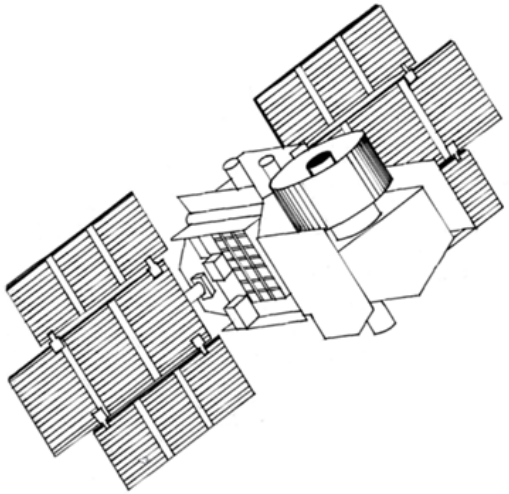


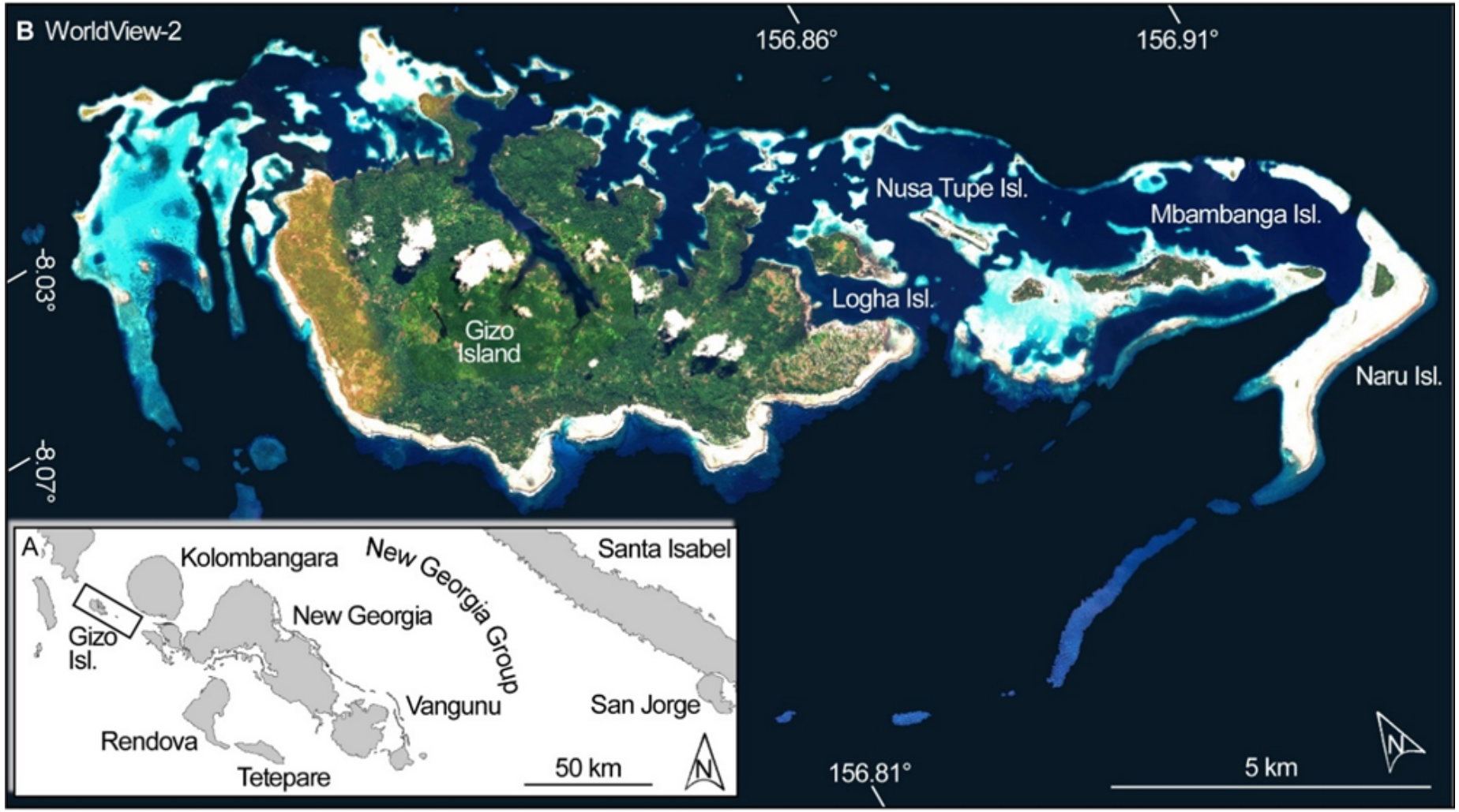
Coral Reef Biodiversity (image analysis)

Measuring Diversity (in situ)

Coral Reef Biodiversity (image analysis)

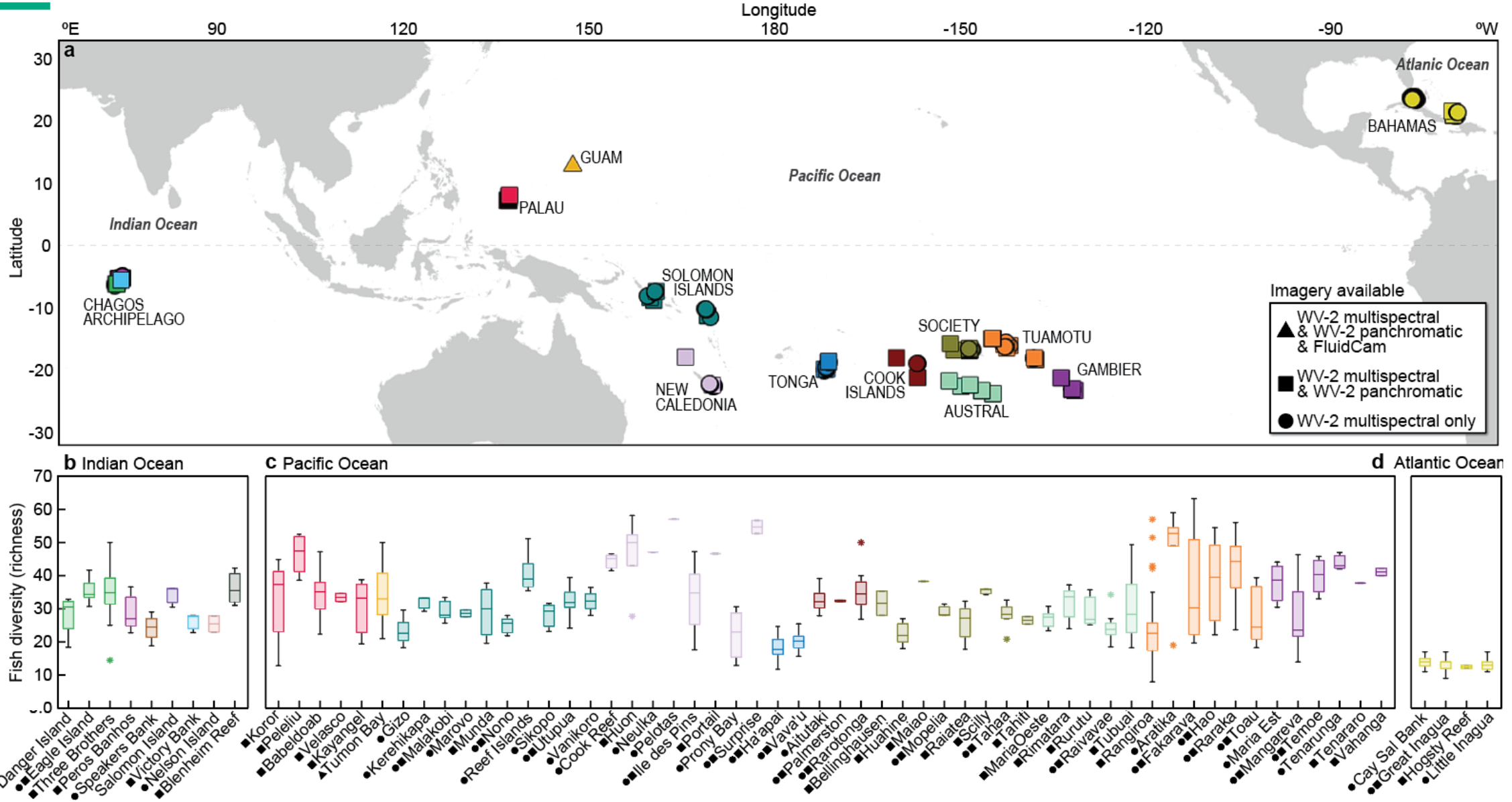
Measuring Diversity (remote)





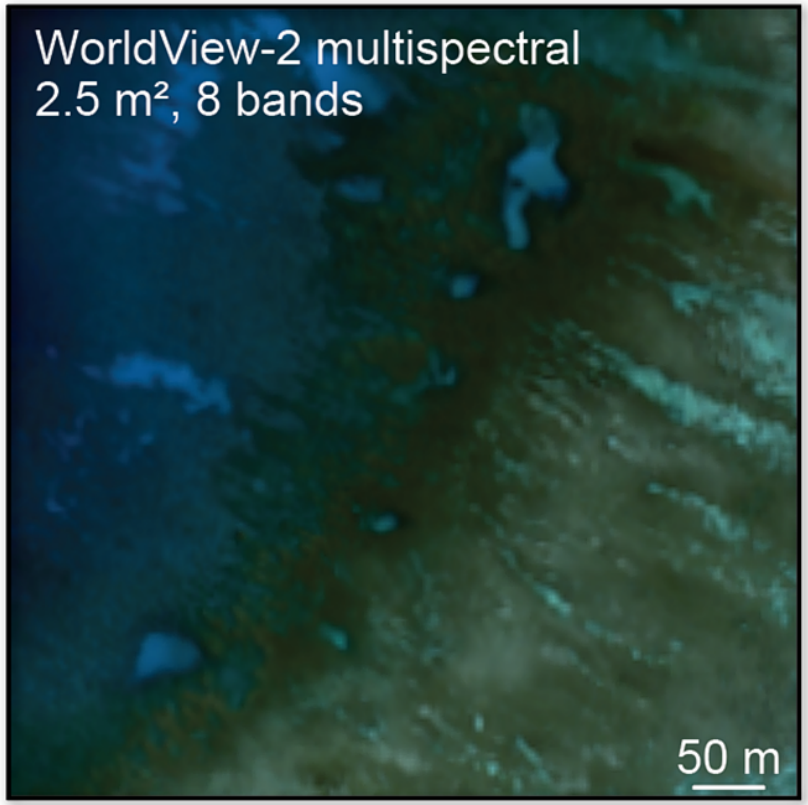
Coral Reef Biodiversity (image analysis)

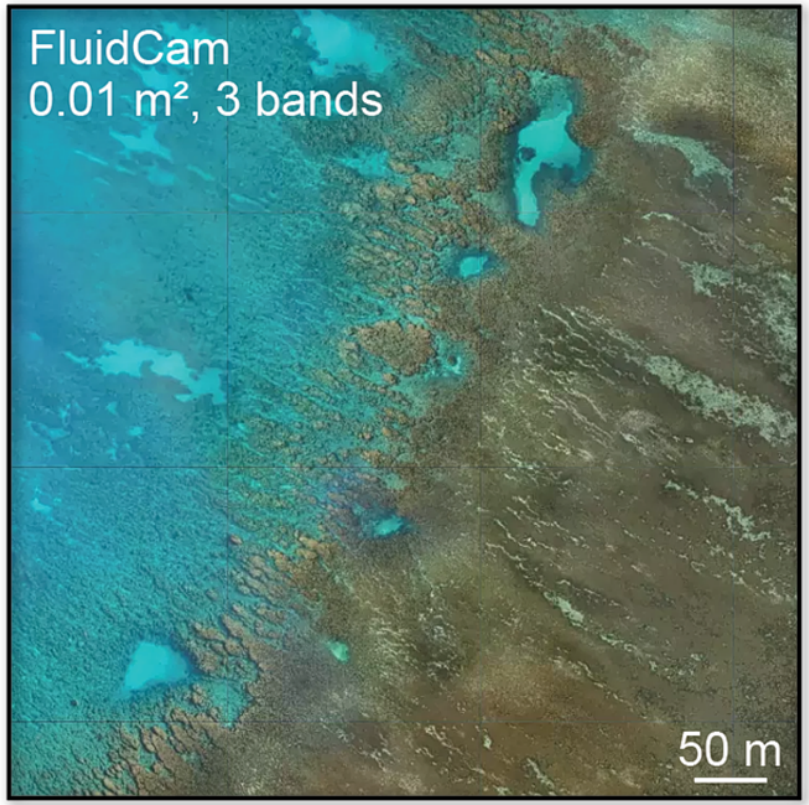
Applications and Projects



Coral Reef Biodiversity (image analysis)

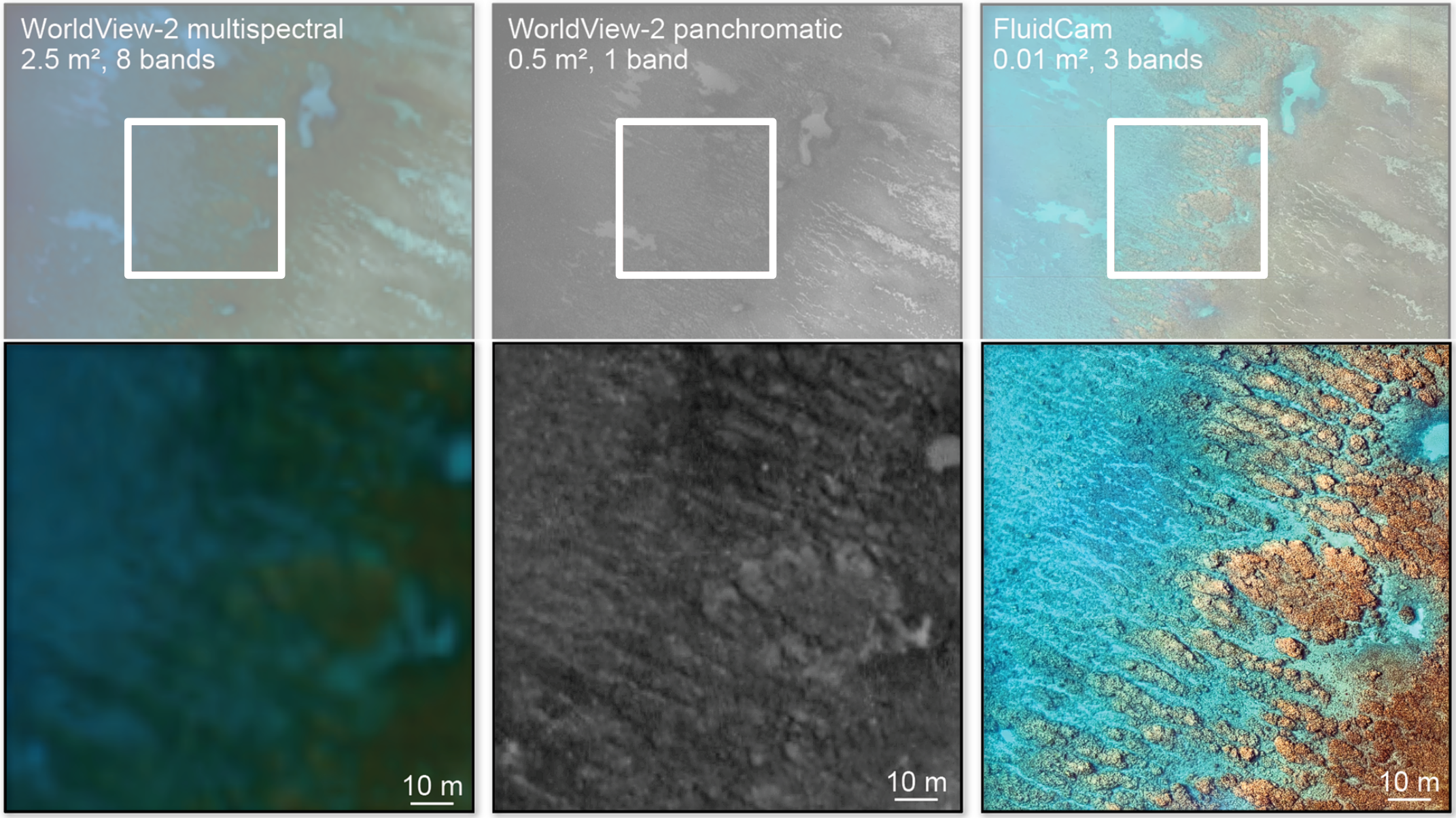
Applications and Projects





Coral Reef Biodiversity (image analysis)

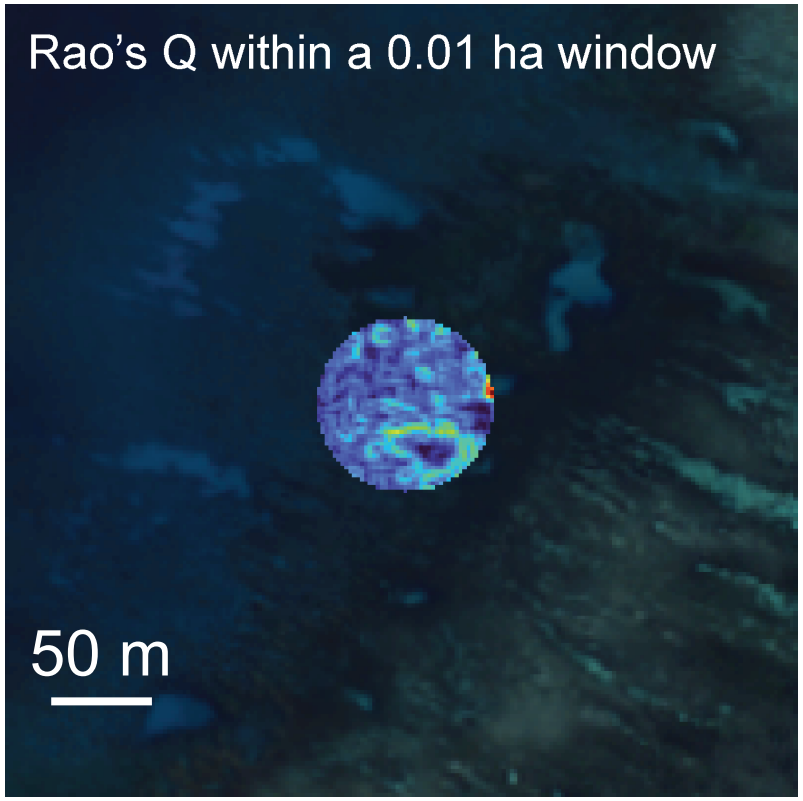
Applications and Projects



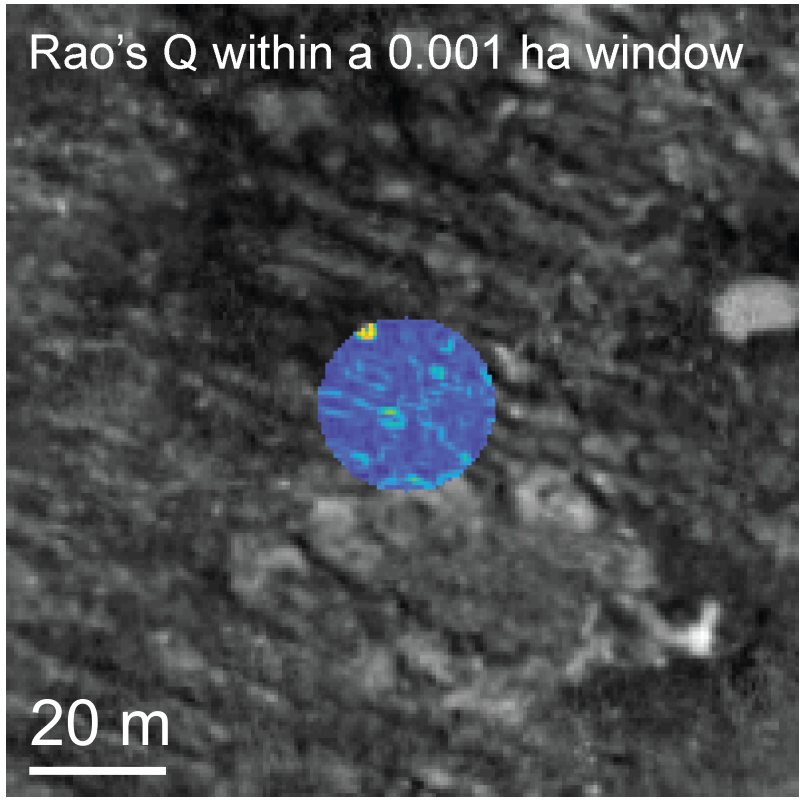
Coral Reef Biodiversity (image analysis)

Applications and Projects

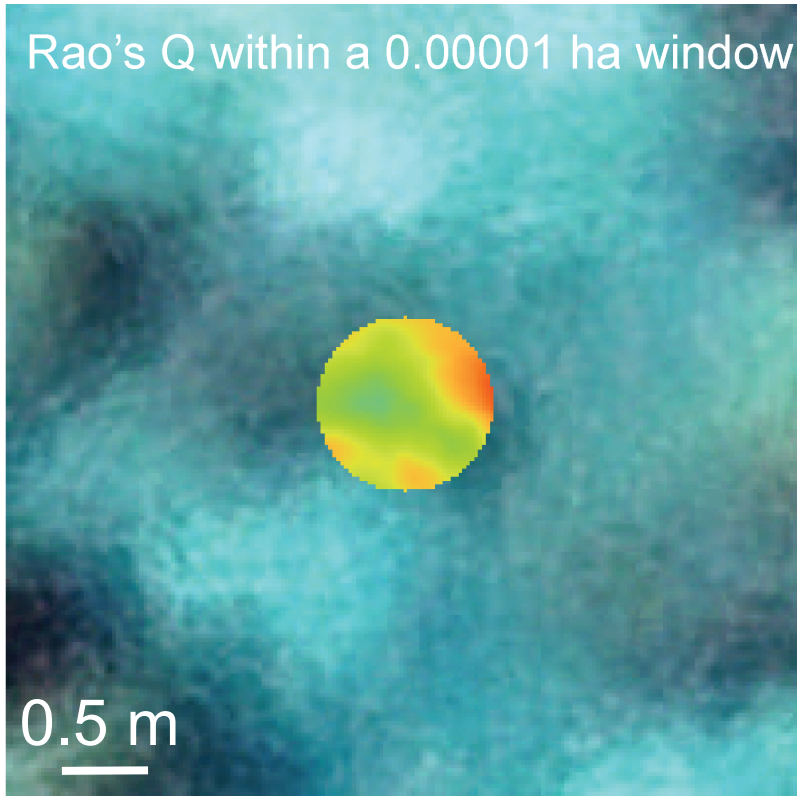
WV-2 multispectral



WV-2 panchromatic



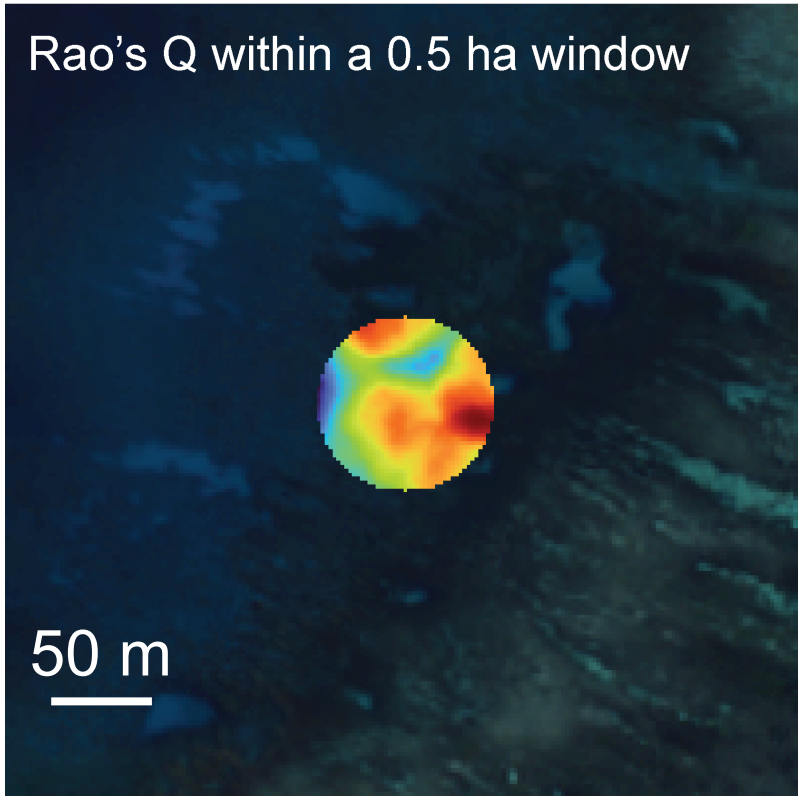
FluidCam



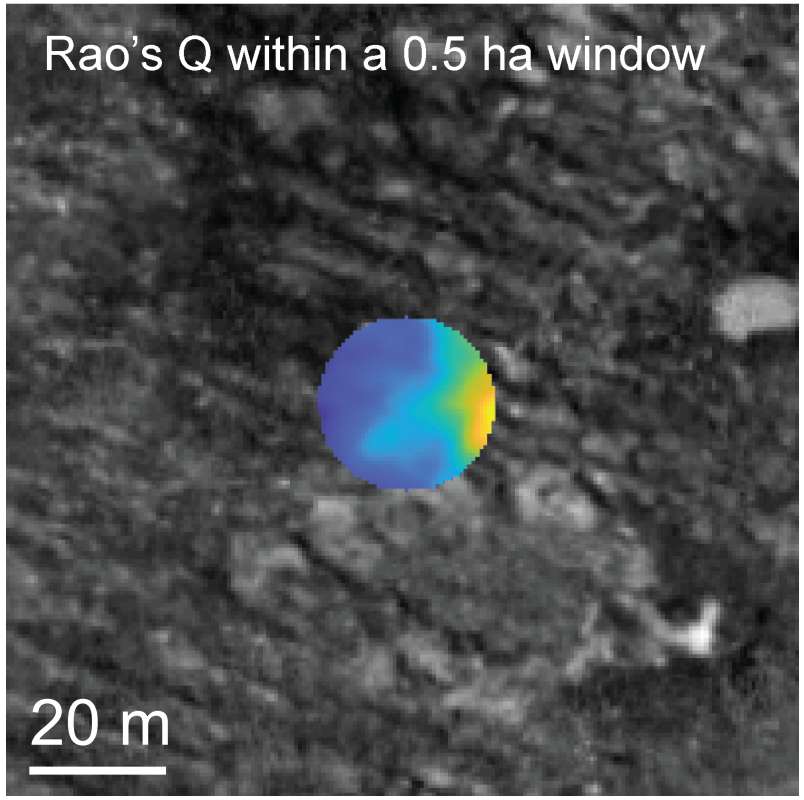
Coral Reef Biodiversity (image analysis)

Applications and Projects

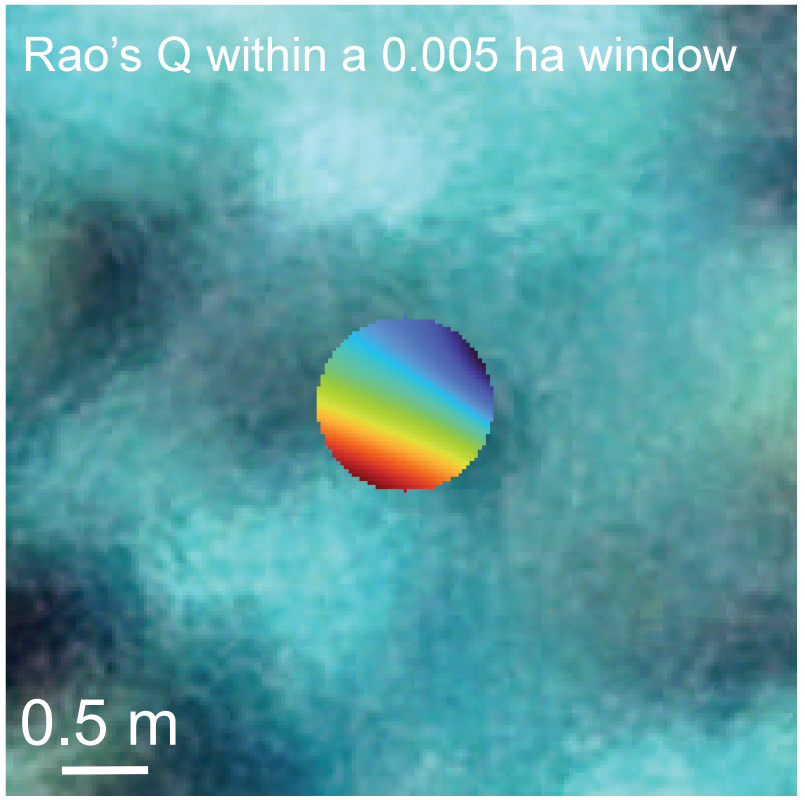
WV-2 multispectral



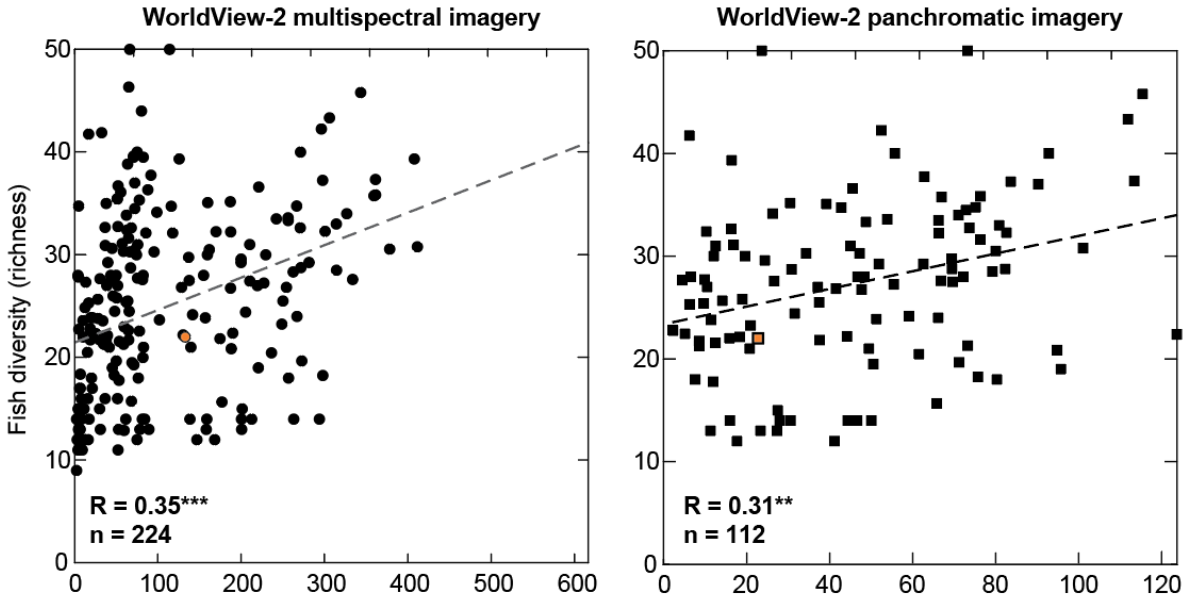
WV-2 panchromatic

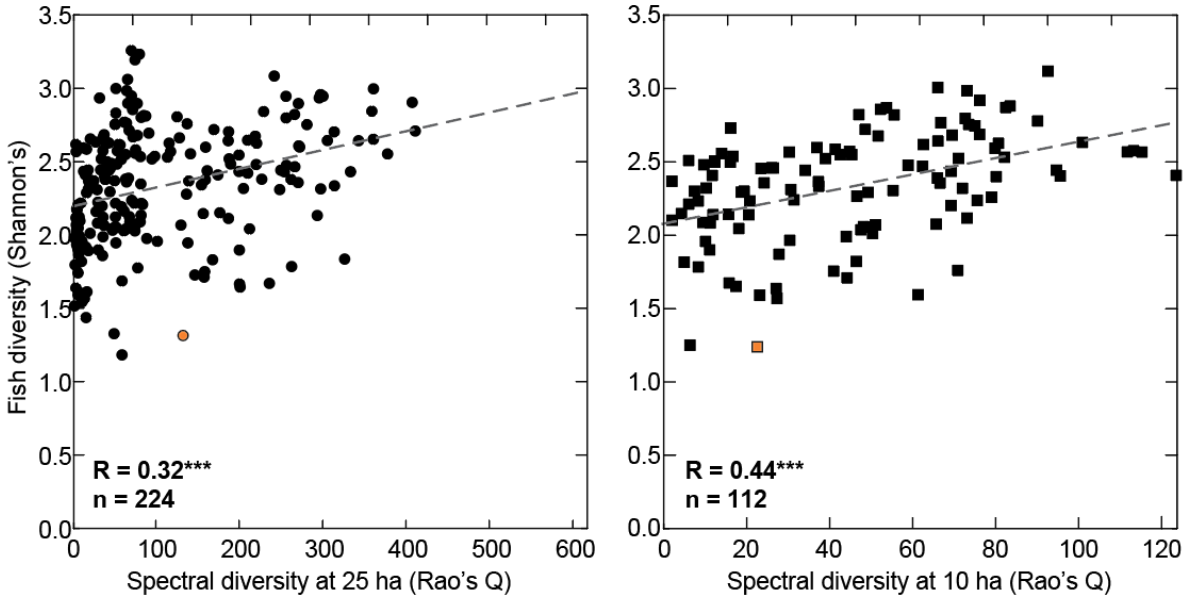


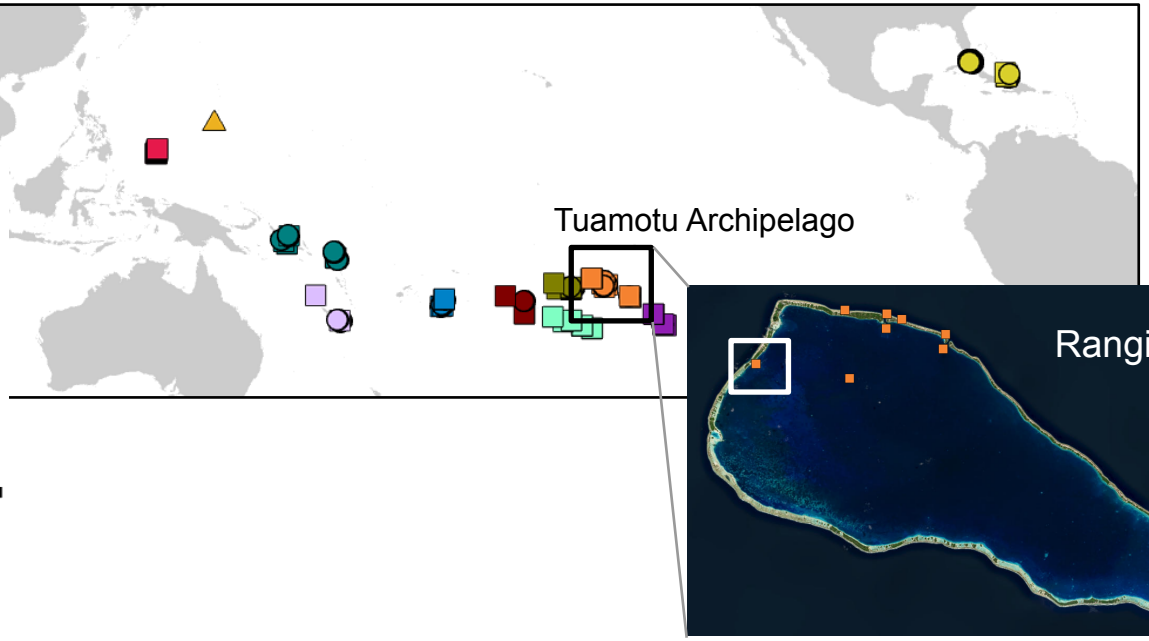
FluidCam



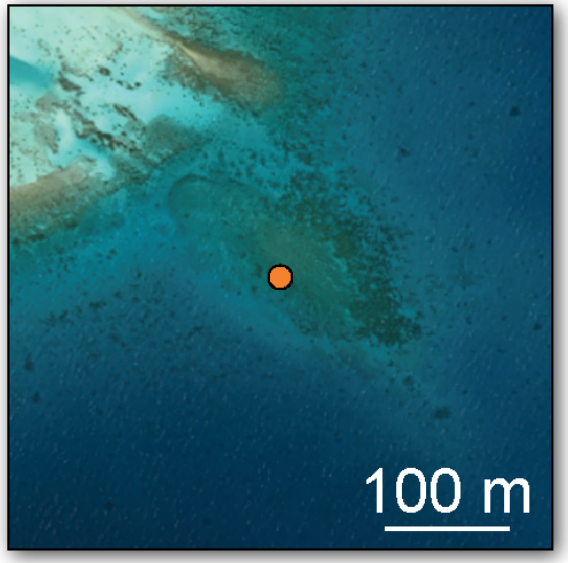
GLOBAL SITES



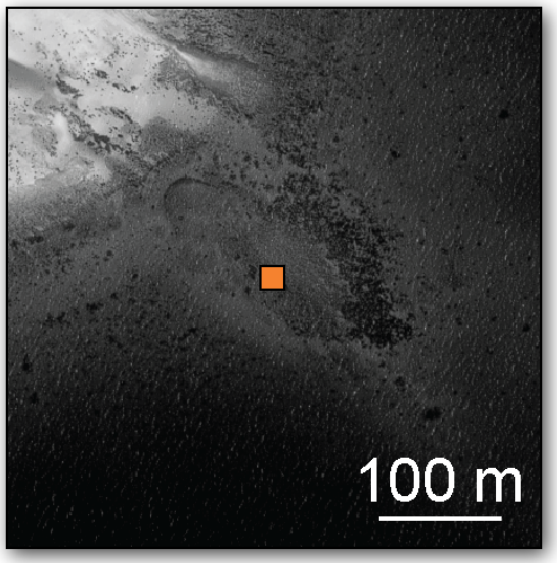




WV-2 multispectral



WV-2 panchromatic



Coral Reef Biodiversity (image analysis)

Summary

- Chapel program to estimate reef biodiversity using satellite imagery
  - Embarrassingly parallel and scalable
  - Multiple orders faster than incumbent MATLAB program
  - *Very* exciting for my colleagues in the conservation world!
- Takeaway? Lots of applications out there (not necessarily complicated) that could benefit from what Chapel provides