# kelpdecline: an R package to detect giant kelp decline in the Californias

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kelpdecline is an R package that aims to detect regions with kelp forests in decline based on analysis of a time series of Landsat estimated biomass (Cavanaugh et al. 2011, Bell et al. 2017). Two functions are presented below to (1) detected regions in decline and (2) to estimate trends in habitat occupancy. The methods proposed provide a framework for a quick quantification of the kelp biomass time series in the context of a historical baseline and should be valuable for a variety of kelp forest conservation goals.

Our specific motivation for building this tool was to design an efficient sampling strategy for genetic monitoring studies (Klingbeil et al. 2022). Beyond this manual, further considerations can be found in the companion publication describing this package (Tennies & Alberto, in prep).

## Input data

The analysis starts by processing a NetCDF file containing a time series of kelp biomass curated by the Santa Barbara Coatal-Long Term Ecological Research (SBC-LTER) program. The data is available at https://sbclter.msi.ucsb.edu/data/catalog/package/?package=knb-lter-sbc.74. Make sure to read the license agreement before using this package. We quote below how SBC-LTER describes the file.

"This data file represents a time series of canopy area of giant kelp, *Macrocystis pyrifera*, and bull kelp, *Nereocystis luetkeana*, and canopy biomass of giant kelp derived from Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Landsat 8 Operational Land Imager (OLI), and Landsat 9 Operational Land Imager 2 satellite imagery, along with relevant metadata. The kelp canopy is composed of the portions of fronds and stipes floating on the surface of the water. Canopy area (m) data are given for individual 30 x 30 meter pixels for all coastal areas of Baja California, Mexico, California, Oregon, and the outer coast of Washington (including offshore islands). Biomass data (wet weight, kg) are given for individual 30 x 30 meter pixels in the coastal areas extending from near Ano Nuevo, CA through the southern range limit in Baja California (including offshore islands), representing the range where giant kelp is the dominant canopy forming species."

The kelpdecline package uses only the biomass (giant kelp) layer in the NetCDF file. The package does not come with the NetCDF data file; users need to download it from the link above to run the examples below. The most recent file is about 2.3 GB, and the file is updated annually.

## Example run

### Installing and loading the kelpdecline package

The first step is to install the R package directly from github.

```
library(devtools)
install_github("UWMAlberto-Lab/kelpdecline")
```

Next load the package to your R session.

```
library(kelpdecline)
```

### Converting the NetCDF file with *nc_convert*

The first function *nc_convert*, converts the NetCDF file into a data.frame used internally by kelpdecline. You need to provide the name of the NetCDF file. If your file is stored in the R session working directory, you don't need the "../../ before the file name. The file used here is the latest update at the time of publication (4th quarter of 2022).

```
# The conversion function has a single argument that takes the name of the NetCDF file
kelp.TS.DF<-nc_convert(nc_data_location="../../LandsatKelpBiomass_2022_Q4_withmetadata.nc")
```

### Estimating kelp decline with decline_finder

The resulting R object *kelp.TS.DF*, produced by *nc_convert*, is then the first argument (*data*) of the main function *decline_finder*. Im the example below, all other arguments to the function are set to the default values.

```
PropDeclineRaster <- decline_finder(data = kelp.TS.DF, baseline_threshold = 0.1,
    scarce_cutoff = 0.4, present_window = 16, hist_period = 100,
    window_lag = 0, lat_min = 27.01, lat_max = 37.5, lon_min = -123.5,
    lon_max = -114, table_name = "Output stats.txt")
```

The function saves a raster file to the global environment containing the proportions of pixels in decline (PPD) within larger areas of 0.25 x 0.25, lat x long decimal degrees, hereafter called regions. If a file name is supplied to the argument *table_name*, a tab-delimited text file is recorded to the working directory. The default to *table_name* is NULL, so make sure to supply a file name to get an output table written to the working directory.

### The output table

The output table produced by *decline_finder* is shown below for the full extent of the giant kelp biomass layer in the NetCDF file. To visualize or further manipulate this file, we read the file back into R using the read.delim function. For better visualization of the output file, it is best to use spreadsheet software like Excel.

The most critical outputs in this table are in the first two columns: the proportion of pixels in decline (PPD) and the total number of pixels for each region (row), discounting pixels with low frequency of kelp presence (see below). Users should know the bounding coordinates for regions of interest (last columns). Generally, regions with high proportion of pixels in decline and high pixel counts are more concerning. However, regions with low pixel counts, depending on their location, might be critical for stepping-stone connectivity. Therefore, the overall distribution of regions, number of pixels and their decline status should be considered together.

To better interpret the table below, we provide the following row indexes for regions with substantial declines: Monterey Peninsula (4th row); San Miguel Island (23rd row); Carlsbad (46th row); Primo Tapia (53rd row); and Islas de San Benito (69th row). Note that changing the value for argument *scarce_cutoff* (read below) will likely result in a different number of rows in the output value, so always check for the boundary geographic coordinates for regions of interest.

```
#read the output file back to R
Summary.Stats<-read.delim("Output stats.txt")
```

Table 1: The output table produced by running decline_finder with default values to its arguments. In this example, the table is stored in Summary.Stats object, in R memory, and in the Output stats.txt file, in the working directory

|    | PPD   | Pixels | AVG.biomass | kelp.area_km.sq | long_west | long_east | lat_south | lat_north |
|----|-------|--------|-------------|-----------------|-----------|-----------|-----------|-----------|
| 1  | 0.000 | 54     | 741.5       | 0.049           | -122.50   | -122.25   | 37.00     | 37.25     |
| 2  | 0.013 | 815    | 1107.5      | 0.733           | -122.25   | -122.00   | 36.75     | 37.00     |
| 3  | 0.008 | 626    | 940.1       | 0.563           | -122.00   | -121.75   | 36.75     | 37.00     |
| 4  | 0.432 | 2656   | 1150.1      | 2.390           | -122.00   | -121.75   | 36.50     | 36.75     |
| 5  | 0.104 | 5242   | 1467.2      | 4.718           | -122.00   | -121.75   | 36.25     | 36.50     |
| 6  | 0.009 | 846    | 1769.2      | 0.761           | -122.00   | -121.75   | 36.00     | 36.25     |
| 7  | 0.173 | 3040   | 1421.1      | 2.736           | -121.75   | -121.50   | 36.00     | 36.25     |
| 8  | 0.000 | 17     | 1150.4      | 0.015           | -121.75   | -121.50   | 35.75     | 36.00     |
| 9  | 0.094 | 2382   | 1355.9      | 2.144           | -121.50   | -121.25   | 35.75     | 36.00     |
| 10 | 0.007 | 458    | 1029.9      | 0.412           | -121.50   | -121.25   | 35.50     | 35.75     |
| 11 | 0.021 | 3333   | 1186.8      | 3.000           | -121.25   | -121.00   | 35.50     | 35.75     |
| 12 | 0.004 | 486    | 1023.5      | 0.437           | -121.25   | -121.00   | 35.25     | 35.50     |
| 13 | 0.081 | 1234   | 1261.0      | 1.111           | -121.00   | -120.75   | 35.25     | 35.50     |
| 14 | 0.185 | 211    | 1192.9      | 0.190           | -121.00   | -120.75   | 35.00     | 35.25     |
| 15 | 0.025 | 564    | 1106.9      | 0.508           | -120.75   | -120.50   | 35.00     | 35.25     |
| 16 | 0.006 | 783    | 1284.5      | 0.705           | -120.75   | -120.50   | 34.50     | 34.75     |
| 17 | 0.024 | 127    | 1364.3      | 0.114           | -120.75   | -120.50   | 34.25     | 34.50     |
| 18 | 0.108 | 2468   | 834.2       | 2.221           | -120.50   | -120.25   | 34.25     | 34.50     |
| 19 | 0.051 | 525    | 916.0       | 0.472           | -120.25   | -120.00   | 34.25     | 34.50     |
| 20 | 0.001 | 1820   | 932.1       | 1.638           | -120.00   | -119.75   | 34.25     | 34.50     |
| 21 | 0.000 | 98     | 855.7       | 0.088           | -119.75   | -119.50   | 34.25     | 34.50     |
| 22 | 0.020 | 50     | 846.3       | 0.045           | -119.50   | -119.25   | 34.25     | 34.50     |
| 23 | 0.800 | 2622   | 1227.9      | 2.360           | -120.50   | -120.25   | 34.00     | 34.25     |
| 24 | 0.756 | 41     | 747.2       | 0.037           | -120.25   | -120.00   | 34.00     | 34.25     |
| 25 | 0.317 | 104    | 799.6       | 0.094           | -120.00   | -119.75   | 34.00     | 34.25     |
| 26 | 0.000 | 14     | 341.2       | 0.013           | -119.75   | -119.50   | 34.00     | 34.25     |
| 27 | 0.000 | 70     | 450.2       | 0.063           | -119.50   | -119.25   | 34.00     | 34.25     |
| 28 | 0.193 | 984    | 872.9       | 0.886           | -119.00   | -118.75   | 34.00     | 34.25     |
| 29 | 0.424 | 33     | 813.4       | 0.030           | -118.75   | -118.50   | 34.00     | 34.25     |
| 30 | 1.000 | 5      | 1106.7      | 0.004           | -120.50   | -120.25   | 33.75     | 34.00     |
| 31 | 0.195 | 1765   | 904.3       | 1.588           | -120.25   | -120.00   | 33.75     | 34.00     |
| 32 | 0.013 | 792    | 722.8       | 0.713           | -120.00   | -119.75   | 33.75     | 34.00     |
| 33 | 0.008 | 244    | 466.3       | 0.220           | -119.75   | -119.50   | 33.75     | 34.00     |
| 34 | 0.000 | 524    | 537.7       | 0.472           | -118.50   | -118.25   | 33.75     | 34.00     |
| 35 | 0.000 | 291    | 605.1       | 0.262           | -118.50   | -118.25   | 33.50     | 33.75     |
| 36 | 0.000 | 482    | 853.7       | 0.434           | -119.75   | -119.50   | 33.25     | 33.50     |
| 37 | 0.000 | 6      | 719.3       | 0.005           | -119.50   | -119.25   | 33.25     | 33.50     |
| 38 | 0.143 | 7      | 365.6       | 0.006           | -119.25   | -119.00   | 33.25     | 33.50     |
| 39 | 0.000 | 149    | 563.9       | 0.134           | -118.75   | -118.50   | 33.25     | 33.50     |
| 40 | 0.020 | 251    | 710.0       | 0.226           | -118.50   | -118.25   | 33.25     | 33.50     |
| 41 | 0.739 | 23     | 690.5       | 0.021           | -117.75   | -117.50   | 33.25     | 33.50     |
| 42 | 0.000 | 18     | 741.8       | 0.016           | -117.50   | -117.25   | 33.25     | 33.50     |
| 43 | 0.000 | 686    | 990.1       | 0.617           | -119.75   | -119.50   | 33.00     | 33.25     |
| 44 | 0.020 | 450    | 849.9       | 0.405           | -119.50   | -119.25   | 33.00     | 33.25     |
| 45 | 0.012 | 1027   | 713.0       | 0.924           | -118.75   | -118.50   | 33.00     | 33.25     |
| 46 | 0.955 | 22     | 698.0       | 0.020           | -117.50   | -117.25   | 33.00     | 33.25     |
| 47 | 0.000 | 2799   | 763.8       | 2.519           | -118.75   | -118.50   | 32.75     | 33.00     |

| | PPD | Pixels | AVG.biomass | kelp.area_km.sq | long_west | long_east | lat_south | lat_north |
|---|---|---|---|---|---|---|---|---|
| 48 | 0.006 | 1443 | 744.9 | 1.299 | -118.50 | -118.25 | 32.75 | 33.00 |
| 49 | 0.060 | 811 | 607.1 | 0.730 | -117.50 | -117.25 | 32.75 | 33.00 |
| 50 | 0.099 | 1511 | 660.9 | 1.360 | -117.50 | -117.25 | 32.50 | 32.75 |
| 51 | 0.234 | 64 | 803.9 | 0.058 | -117.25 | -117.00 | 32.25 | 32.50 |
| 52 | 1.000 | 1 | 64.5 | 0.001 | -117.00 | -116.75 | 32.25 | 32.50 |
| 53 | 0.577 | 758 | 893.1 | 0.682 | -117.00 | -116.75 | 32.00 | 32.25 |
| 54 | 0.056 | 54 | 771.1 | 0.049 | -117.00 | -116.75 | 31.75 | 32.00 |
| 55 | 0.000 | 4 | 827.8 | 0.004 | -116.75 | -116.50 | 31.75 | 32.00 |
| 56 | 0.248 | 4122 | 1292.8 | 3.710 | -116.75 | -116.50 | 31.50 | 31.75 |
| 57 | 0.000 | 573 | 1032.0 | 0.516 | -116.75 | -116.50 | 31.25 | 31.50 |
| 58 | 0.332 | 190 | 1137.8 | 0.171 | -116.50 | -116.25 | 31.25 | 31.50 |
| 59 | 0.917 | 12 | 105.9 | 0.011 | -116.50 | -116.25 | 31.00 | 31.25 |
| 60 | 0.000 | 30 | 639.7 | 0.027 | -116.50 | -116.25 | 30.75 | 31.00 |
| 61 | 0.831 | 703 | 1247.0 | 0.633 | -116.25 | -116.00 | 30.25 | 30.50 |
| 62 | 0.885 | 61 | 862.3 | 0.055 | -116.00 | -115.75 | 30.25 | 30.50 |
| 63 | 0.000 | 136 | 1004.4 | 0.122 | -116.00 | -115.75 | 30.00 | 30.25 |
| 64 | 0.696 | 1131 | 1037.5 | 1.018 | -116.00 | -115.75 | 29.75 | 30.00 |
| 65 | 0.069 | 58 | 167.8 | 0.052 | -115.75 | -115.50 | 29.75 | 30.00 |
| 66 | 0.877 | 440 | 996.3 | 0.396 | -116.00 | -115.75 | 29.50 | 29.75 |
| 67 | 0.326 | 279 | 1202.2 | 0.251 | -115.75 | -115.50 | 29.50 | 29.75 |
| 68 | 0.143 | 14 | 1235.9 | 0.013 | -115.25 | -115.00 | 29.25 | 29.50 |
| 69 | 0.966 | 910 | 1014.1 | 0.819 | -115.75 | -115.50 | 28.25 | 28.50 |
| 70 | 0.341 | 1205 | 1759.0 | 1.084 | -115.50 | -115.25 | 28.25 | 28.50 |
| 71 | 0.600 | 1451 | 1546.3 | 1.306 | -115.25 | -115.00 | 28.25 | 28.50 |
| 72 | 0.145 | 2939 | 1386.8 | 2.645 | -115.50 | -115.25 | 28.00 | 28.25 |
| 73 | 0.843 | 83 | 1353.4 | 0.075 | -115.25 | -115.00 | 28.00 | 28.25 |
| 74 | 0.013 | 6515 | 1406.6 | 5.864 | -115.25 | -115.00 | 27.75 | 28.00 |
| 75 | 0.000 | 380 | 1216.1 | 0.342 | -115.25 | -115.00 | 27.50 | 27.75 |
| 76 | 0.007 | 4844 | 1570.6 | 4.360 | -115.00 | -114.75 | 27.50 | 27.75 |
| 77 | 0.217 | 115 | 984.8 | 0.104 | -114.75 | -114.50 | 27.50 | 27.75 |

## Other important arguments in the *decline_finder* function

The remaining arguments in the function control how we compare a present period of kelp biomass to a historical baseline. Using the approach detailed below, we first classify kelp biomass decline at the Landsat pixel scale (30 x30 m) as a binomial variable (i.e., *in decline* or *not in decline*). Then, the proportion of Landsat pixels flagged as *in decline* is counted within regions of 0.25 x 0.25 degrees, lat x long.

A pixel is classified as *in decline* if the biomass recorded for that pixel in ALL the most recent quarters (argument *present_window* sets the length in quarters) is below a proportion (argument *baseline_threshold* sets the threshold proportion) of historical average biomass. The number of quarters used to calculate the historical average biomass per pixel is defined by the argument *hist_period*. These quarters are counted backwards from when the present period starts. This flexibility allows using different temporal baselines in specific comparisons. Likewise, it is possible to slide the focus "present" window to the past by a certain lag number of quarters (argument: *window_lag*), allowing us to estimate how kelp decline statistics varied in time.

Landsat pixels where biomass was rarely recorded throughout the time series affect the calculation of historical averages. Given the effect these pixels have, and their poor indicator status for the overall trend of a kelp forest, we removed from the analysis pixels that thad biomass through the *hist_period* in less than a given proportion (argument: *scarce_cutoff*) of all quarters in the series.

Geographic boundaries for the study extent are available with the arguments *lat_min*, *lat_max*, *long_min*,

and *long_max*. These default to the full extent of the biomass layer in the NetCDF file.

**Plotting proportions of pixels in decline by region**

Once the *decline_finder* function runs, users can quickly plot the produced raster file containing the proportions of decline by 0.25 x 0.25 degree region. In the plot below, we added a shapefile to visualize the coastline. Note that the shapefile used in the code below is not included in the package; users must obtain their own if they want to print the coastline (https://www.ngdc.noaa.gov/mgg/shorelines/).

```
# loading the shapefile
coast = raster::shapefile("../../GSHHS_l_L1.shp")
raster::crs(coast) = raster::crs(PropDeclineRaster)

# plotting the raster with a better color scale
raster::plot(PropDeclineRaster, col = rev(topo.colors(30, alpha = 1)),
    main = "Giant kelp proportion of pixels in decline (PPD)",
    xlab = "long", ylab = "lat")

# adding coastal lines
raster::lines(coast)
```



Giant kelp proportion of pixels in decline (PPD)
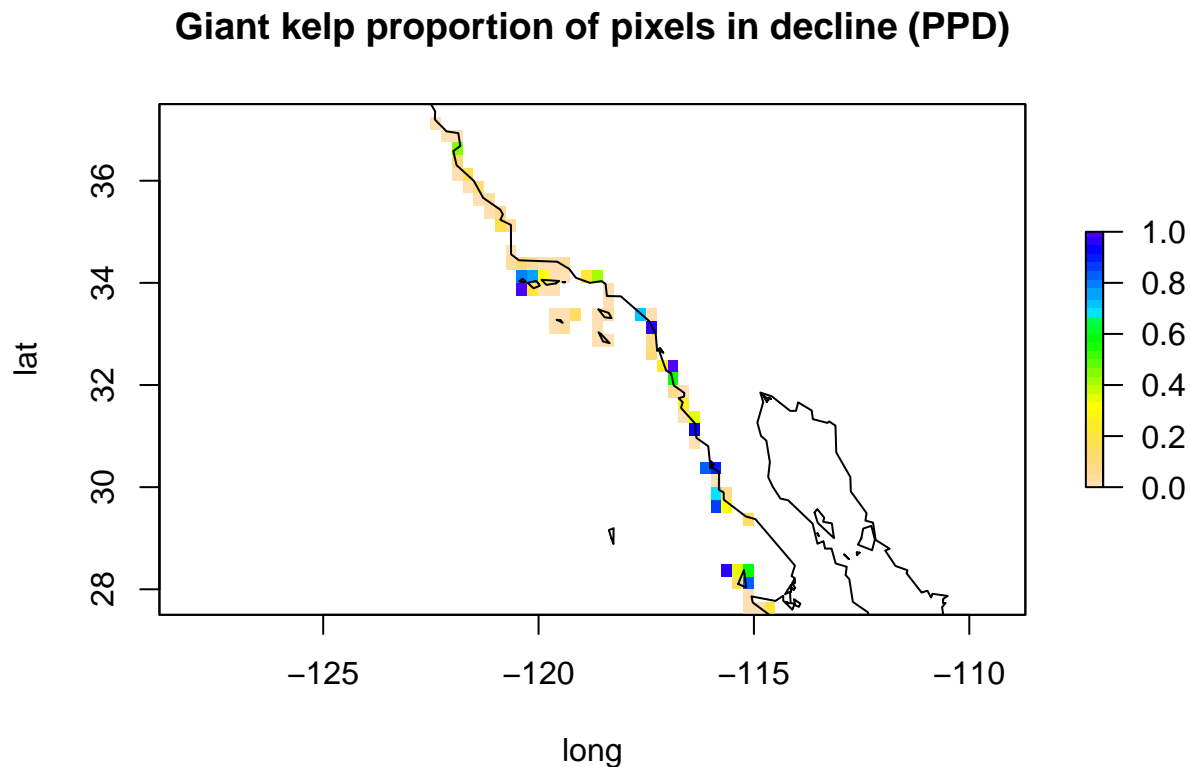
**Decline_finder parameter variation**

The function's default values should not be interpreted as the best practices to compare a present period with a historical baseline, and only reflect our opinion on reasonable initial values. The tool was built to provide a flexible method to explore the effects of parameter variation. Higher confidence about the proposed classification of kelp decline can be obtained for regions where inferred decline is independent of function

parametrization. Below we explore this method for four regions of concern, initially identified with the default values. We chose to show here, as an example, four regions with different levels of decline: Monterey Bay (Central California), San Miguel Island (Southern California), Primo Tapia (Baja California), and Islas de San Benito (Baja California). We also show Point Loma (Southern California) as a region with stable biomass. As an example of a sensitivity analysis, we explored the effect of orthogonal combinations of *present_window* and *hist_threshold* in these five regions.

Be warned that the code below will take its time to run; about one hour on our laptop. Once the output files are produced the remaining code is fast.

```r
# create vectors of parameter space over the two arguments

# baseline threshold from 0.1 to 1 in increments of 0.1
baseline_thresholdV <- seq(0.1, 1, 0.1)
# present_window from 8 to 24 quarters in increments of 2
# quarters
present_windowV <- seq(8, 24, 2)

# looping decline_finder over different combinations the
# arguments above
for (bt in baseline_thresholdV) {
    for (pw in present_windowV) {

        decline_finder(data = kelp.TS.DF, baseline_threshold = bt,
            scarce_cutoff = 0.4, present_window = pw, hist_period = 100,
            window_lag = 0, table_name = paste0("Stats.", bt,
                ".", pw, ".txt"))

        print(paste("pw: ", pw))  # helps to see where we are while waiting
    }
    print(paste("bt: ", bt))
}
```

The code above creates one output file for each combination of argument values in *baseline_threshold* (0.1 to 1, in increments of 0.1) and *present_window* (8 to 24 quarters in increments of 2). The output files will be saved in the working directory and named "Stats.*bt.pw*.txt", with *bt* and *pw* the values of *baseline_threshold* and *present_window* for a specific combination of values in the two arguments.

Next, we will read the output files back to R, using two nested *for* loops, and produce a perspective plot to visualize how the proportion of pixels in decline is affected by the combination of *baseline_threshold* and *present_window* values.

```r
# baseline threshold from 0.1 to 1 in increments of 0.1
baseline_thresholdV <- seq(0.1, 1, 0.1)
# present_window from 8 to 24 quarters in increments of 2
# quarters
present_windowV <- seq(8, 24, 2)

# matrices to store the proportion in decline values for
# different argument combinations
Cell.Matrix.Monterey <- matrix(nrow = length(baseline_thresholdV),
    ncol = length(present_windowV))
Cell.Matrix.SanMiguel <- matrix(nrow = length(baseline_thresholdV),
    ncol = length(present_windowV))
Cell.Matrix.PrimoTapia <- matrix(nrow = length(baseline_thresholdV),
    ncol = length(present_windowV))
```

```r
Cell.Matrix.SanBenito <- matrix(nrow = length(baseline_thresholdV),
    ncol = length(present_windowV))
Cell.Matrix.PointLoma <- matrix(nrow = length(baseline_thresholdV),
    ncol = length(present_windowV))

for (bt in 1:length(baseline_thresholdV)) {
    for (pw in 1:length(present_windowV)) {

        DFtemp <- utils::read.delim(paste0("Stats.", baseline_thresholdV[bt],
            ".", present_windowV[pw], ".txt"))

        # filter output for the specific coordinates for
        # different regions
        regionMonterey <- (DFtemp$long_west == -122 & DFtemp$long_east ==
            -121.75 & DFtemp$lat_south == 36.5 & DFtemp$lat_north ==
            36.75)
        regionSanMiguel <- (DFtemp$long_west == -120.5 & DFtemp$long_east ==
            -120.25 & DFtemp$lat_south == 34 & DFtemp$lat_north ==
            34.25)
        regionPrimoTapia <- (DFtemp$long_west == -117 & DFtemp$long_east ==
            -116.75 & DFtemp$lat_south == 32 & DFtemp$lat_north ==
            32.25)
        regionSanBenitos <- (DFtemp$long_west == -115.75 & DFtemp$long_east ==
            -115.5 & DFtemp$lat_south == 28.25 & DFtemp$lat_north ==
            28.5)
        regionPointLoma <- (DFtemp$long_west == -117.5 & DFtemp$long_east ==
            -117.25 & DFtemp$lat_south == 32.5 & DFtemp$lat_north ==
            32.75)

        Cell.Matrix.Monterey[bt, pw] <- DFtemp$decline_proportion[regionMonterey]
        Cell.Matrix.SanMiguel[bt, pw] <- DFtemp$decline_proportion[regionSanMiguel]
        Cell.Matrix.PrimoTapia[bt, pw] <- DFtemp$decline_proportion[regionPrimoTapia]
        Cell.Matrix.SanBenito[bt, pw] <- DFtemp$decline_proportion[regionSanBenitos]
        Cell.Matrix.PointLoma[bt, pw] <- DFtemp$decline_proportion[regionPointLoma]

    }
}
```

Finally, we can create perspective plots using the information in the Cell.Matrix objects for the different regions.

```
# For Monterey Peninsula
par(cex = 0.7)
persp(baseline_thresholdV, present_windowV, Cell.Matrix.Monterey,
    theta = 140, phi = 10, zlim = c(0, 1), zlab = "proportion in decline",
    xlab = "baseline threshold", ylab = "present window", main = "Monterey Peninsula",
    border = "grey65", col = "grey95", ticktype = "detailed")
```
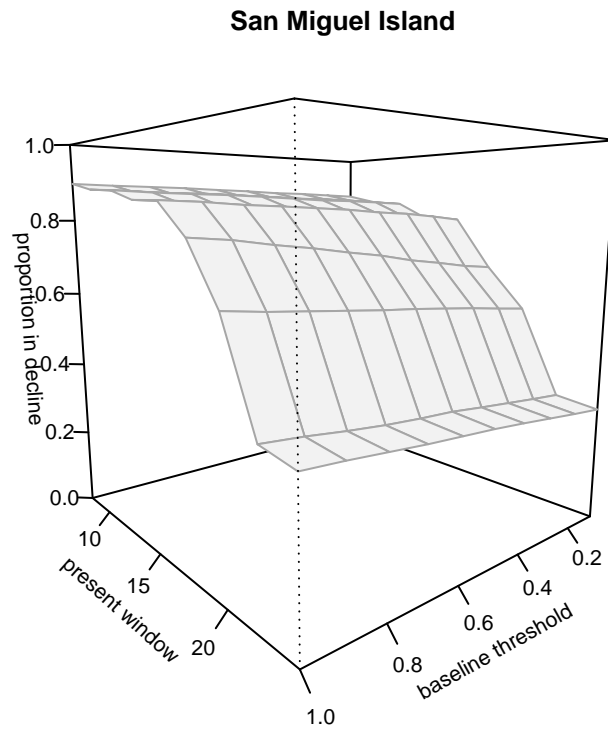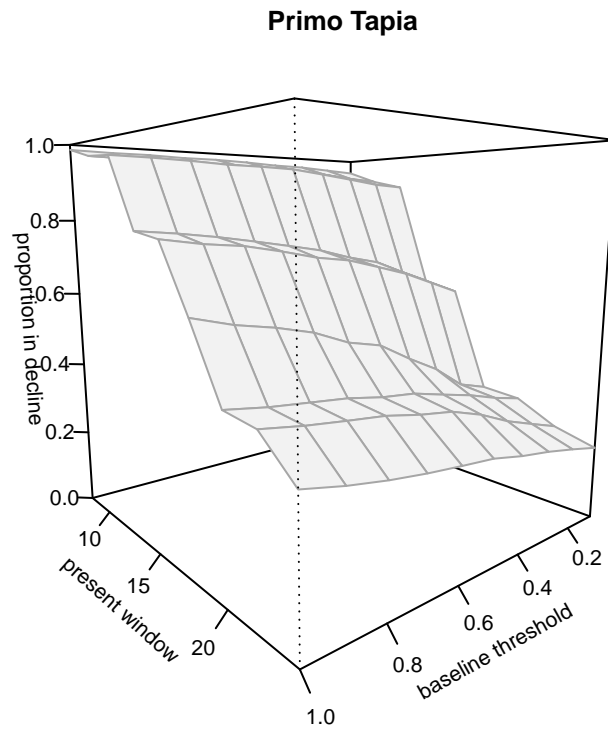
**Monterey Peninsula**
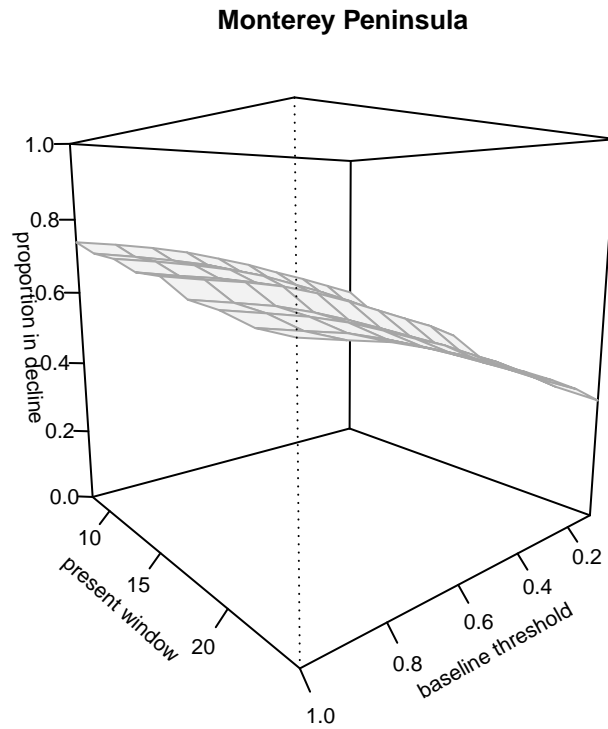
```r
# For San Miguel Island
par(cex = 0.7)
persp(baseline_thresholdV, present_windowV, Cell.Matrix.SanMiguel,
    theta = 140, phi = 10, zlim = c(0, 1), zlab = "proportion in decline",
    xlab = "baseline threshold", ylab = "present window", main = "San Miguel Island",
    border = "grey65", col = "grey95", ticktype = "detailed")
```
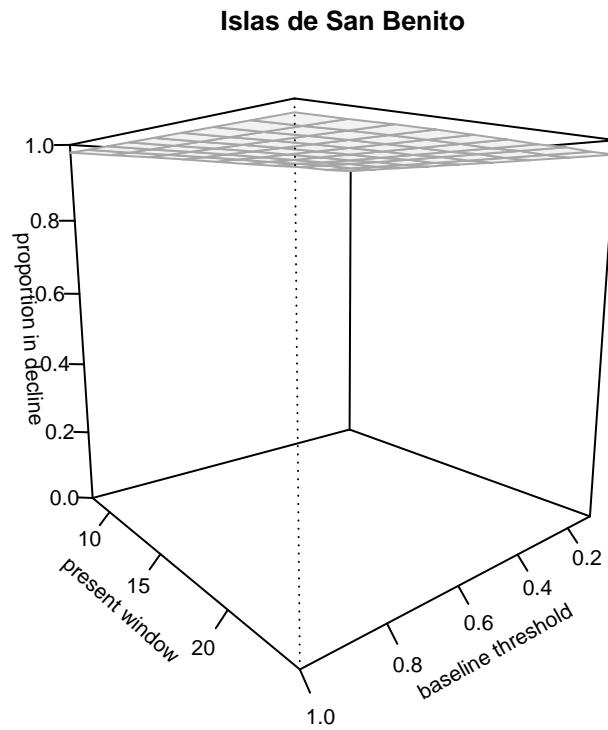


**San Miguel Island**

```
# For Primo Tapia
par(cex = 0.7)
persp(baseline_thresholdV, present_windowV, Cell.Matrix.PrimoTapia,
    theta = 140, phi = 10, zlim = c(0, 1), zlab = "proportion in decline",
    xlab = "baseline threshold", ylab = "present window", main = "Primo Tapia",
    border = "grey65", col = "grey95", ticktype = "detailed")
```

**Primo Tapia**

```
# For Islas de San Benito
par(cex = 0.7)
persp(baseline_thresholdV, present_windowV, Cell.Matrix.SanBenito,
    theta = 140, phi = 10, zlim = c(0, 1), zlab = "proportion in decline",
    xlab = "baseline threshold", ylab = "present window", main = "Islas de San Benito",
    border = "grey65", col = "grey95", ticktype = "detailed")
```

**Islas de San Benito**

```
# For Point Loma
par(cex = 0.7)
persp(baseline_thresholdV, present_windowV, Cell.Matrix.PointLoma,
    theta = 140, phi = 10, zlim = c(0, 1), zlab = "proportion in decline",
    xlab = "baseline threshold", ylab = "present window", main = "Point Loma",
    border = "grey65", col = "grey95", ticktype = "detailed")
```
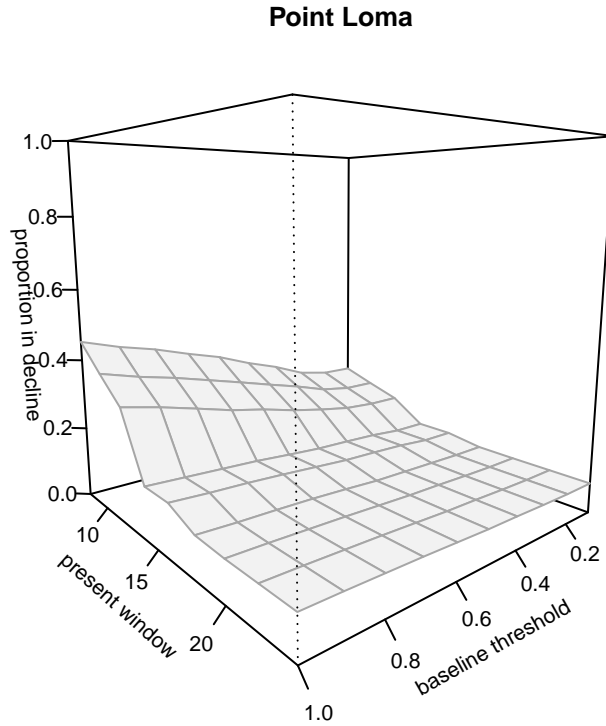


## Interpreting the results

The effect of *present_window* on the proportion of pixels in decline is more prominent than *baseline_threshold*, for the range of parameters tested, except for Monterey Peninsula and Isla de San Benito (the latter has no variation from both arguments variation). Remember the parameter *present_window* defines the length in quarters of the present period and for a pixel to be classified in decline, it must be below a threshold proportion of the historical biomass average for that pixel throughout all quarters in *present_window*. Therefore, the longer the period, the higher the chances that some quarters have higher biomass than the threshold. This means that the effect of *present_window* in the proportion of pixels in decline is monotonically decreasing.

How fast the curve decreases over an axis of variable *present_window* periods is informative of how long a certain proportion of decline is present. For example, in the San Miguel and Primo Tapia regions, the proportion of pixels in decline falls fast from 8 to 16 quarters (2 to 4 years). In contrast, in Monterey and Islas de San Benito, we observe a flatter surface from 8 to 24 quarters (2-6 years). The conclusion is that the decrease in kelp biomass has been more permanent in these two regions. Islas de San Benito looks very close to a case of local extinction (i.e., flat surface near 1.0 proportion of decline).

In Monterey, an effect of *baseline_threshold* in the response variable was observed. This will occur if the biomass in pixels classified as in decline is close to the proportions of the historical average biomass used in the sensitivity analysis. In all other cases shown here, the small effect observed from variable *baseline_threshold*

results from most pixels in decline having biomass below all the tested proportions of the historical average. A quick guide for interpreting *baseline_threshold* is that observing a flat response is the worst scenario (overall lower biomass) than observing an increase in the response variable with increasing *baseline_threshold* values.

Thus, the interpretation of the effects of these two function arguments is that *present_window* is informative of how long a certain proportion of pixels in decline has been present, while *baseline_threshold* on the standing biomass levels.

Another consequence of this algorithm is that a single (new) quarter with a large proportion of the pixels recovering above the threshold is sufficient to produce a flat surface at much lower levels of the response variable. This makes sense because the method should capture full recovery whenever it occurs in a future quarter.

## Detecting annual trends in pixel occupancy

The proportions of kelp in decline estimated by *decline_finder* are not well suited to detect recovery of kelp biomass. To tackle this, we developed an additional method based on annual pixel occupancy. The approach is implemented with function *occupancy_trend*.

### Rationale

Kelp pixel occupancy is first converted to an annual, binomial series of pixel occupancy at the Landsat pixel scale (30 x 30 m). If at least one quarter in a given year has non-zero biomass, the pixel is considered occupied during the year. Next, we calculate the long-term probability of annual pixel occupancy (*LTPAPO*) and subtract it from the reference year pixel occupancy *RYPO* (1 or 0), i.e., *RYPO-LTPAPO*. This trend statistic, which ranges from -1 to 1, provides a weighted measure of how the present occupancy diverges from long-term occupancy probability when averaging across all pixels in a region. For example, an occupied pixel (*RYPO* of 1) with a *LTPAPO* of 0.8 produces a 0.2 trend, whereas if *LTPAPO* is only 0.1, the trend is 0.9. Pixel trends are averaged for all pixels within a 0.25 x 0.25 degrees scale to produce a single trend value for each region. A significance test is available, where randomized *RYPO* values are sampled with *LTPAPO* chances. The procedure is repeated npermuts times to generate a randomized distribution for the trend, in each region, under the null hypothesis that pixel occupancy follows *LTPAPO*. The test does not integrate the autoregressive nature of kelp occupancy (the effect of the previous year's occupancy) and should be improved in the future.

The main argument in the function *occupancy_trend* is the data frame produce above by *nc_convert*

```
TrendRaster <- occupancy_trend(data = kelp.TS.DF, present_year = 2022,
    outFile = "Out.DF.txt", test = F, npermuts = 1000)
#> [1] "allocating pixels to 0.25 x 0.25 degree regions"
#> [1] "Estimating present occupancy"
#> [1] "Estimating the Long term annual probability of pixel occupancy"
```

The function outputs a raster file with trends summarized per 0.25 x 0.25 decimal degrees region. Users can change the argument *present_year*, defining the reference year for which the trend is estimated. The function doesn't allow values of reference year before 2000 to allow for a long enough time series to estimate LTPAPO. A tab-delimited text file containing summary statistics per region is written to the working directory with default name "Out.DF.txt". We will open it here below. The argument *test*, is a logical switch to run the significance test, the default is FALSE. Finally, the number of permutations used by the test can be controlled with *npermuts*, set to 1000 by default.

Below we read the output file back into R and print it.

```
Occupancy.OUT <- read.delim("Out.DF.txt")
```

Table 2: The output table produced by running occupancy_trend for reference year 2022 without a significance test. Each row is for a region of 0.25º x0.25º degree side from Central to Baja California. The southeast corner of each region is given in Lat and Long columns. Other columns are the number of Landsat pixels (30 x 30 meter) per region, counted as areas that had kelp present in at least one quarter in the time-series; the average annual giant kelp biomass per region; the average reference year pixel occupancy (RYPO), the average long-term probability of annual pixel occurrence (LTPAPO), the pixel occupancy trend (POT); the lower and upper quartiles of the randomized distribution at alpha = 0.01, and the direction in the regional POT.

|    | Lat   | Long    | N.Pixel | AVG.Biomass | RYPO   | LTPAPO | POT     | Direction |
|----|-------|---------|---------|-------------|--------|--------|---------|-----------|
| 1  | 37.00 | -122.50 | 1029    | 677188      | 0.3003 | 0.1580 | 0.1423  | UP        |
| 2  | 37.00 | -122.25 | 295     | 609         | 0.0034 | 0.0841 | -0.0807 | DOWN      |
| 3  | 36.75 | -122.25 | 3443    | 6750159     | 0.6346 | 0.4801 | 0.1545  | UP        |
| 4  | 36.75 | -122.00 | 1927    | 2786895     | 0.6352 | 0.4953 | 0.1399  | UP        |
| 5  | 36.50 | -122.00 | 8834    | 2574103     | 0.2319 | 0.5308 | -0.2989 | DOWN      |
| 6  | 36.25 | -122.00 | 13432   | 25462310    | 0.4933 | 0.6160 | -0.1227 | DOWN      |
| 7  | 36.00 | -122.00 | 1658    | 5136116     | 0.7069 | 0.6574 | 0.0495  | UP        |
| 8  | 36.00 | -121.75 | 8666    | 8584547     | 0.3921 | 0.5807 | -0.1886 | DOWN      |
| 9  | 35.75 | -121.75 | 131     | 83981       | 0.5649 | 0.4015 | 0.1634  | UP        |
| 10 | 35.75 | -121.50 | 8468    | 19402439    | 0.5777 | 0.4948 | 0.0829  | UP        |
| 11 | 35.50 | -121.50 | 4519    | 5427143     | 0.4970 | 0.3793 | 0.1177  | UP        |
| 12 | 35.50 | -121.25 | 15174   | 23328307    | 0.4885 | 0.5049 | -0.0164 | DOWN      |
| 13 | 35.25 | -121.25 | 5362    | 11028372    | 0.5649 | 0.4287 | 0.1362  | UP        |
| 14 | 35.25 | -121.00 | 5915    | 7364182     | 0.5107 | 0.4027 | 0.1080  | UP        |
| 15 | 35.00 | -121.00 | 4623    | 2018343     | 0.3238 | 0.2429 | 0.0809  | UP        |
| 16 | 35.00 | -120.75 | 2643    | 2140876     | 0.3674 | 0.4428 | -0.0754 | DOWN      |
| 17 | 34.50 | -120.75 | 4342    | 6382749     | 0.4701 | 0.3649 | 0.1052  | UP        |
| 18 | 34.25 | -120.75 | 845     | 522692      | 0.2201 | 0.4587 | -0.2386 | DOWN      |
| 19 | 34.25 | -120.50 | 13137   | 8789444     | 0.3043 | 0.4068 | -0.1025 | DOWN      |
| 20 | 34.25 | -120.25 | 1941    | 1212235     | 0.2880 | 0.4356 | -0.1477 | DOWN      |
| 21 | 34.25 | -120.00 | 6718    | 6882619     | 0.4470 | 0.3977 | 0.0493  | UP        |
| 22 | 34.25 | -119.75 | 2833    | 723949      | 0.1804 | 0.2641 | -0.0837 | DOWN      |
| 23 | 34.25 | -119.50 | 1019    | 18310       | 0.0648 | 0.2247 | -0.1599 | DOWN      |
| 24 | 34.00 | -120.75 | 1       | 0           | 0.0000 | 0.2564 | -0.2564 | DOWN      |
| 25 | 34.00 | -120.50 | 19554   | 2101287     | 0.0365 | 0.3614 | -0.3249 | DOWN      |
| 26 | 34.00 | -120.25 | 20150   | 1520839     | 0.0327 | 0.2177 | -0.1850 | DOWN      |
| 27 | 34.00 | -120.00 | 2408    | 164940      | 0.0473 | 0.2618 | -0.2144 | DOWN      |
| 28 | 34.00 | -119.75 | 917     | 210933      | 0.2181 | 0.2297 | -0.0115 | DOWN      |
| 29 | 34.00 | -119.50 | 1260    | 449560      | 0.2952 | 0.3126 | -0.0174 | DOWN      |
| 30 | 34.00 | -119.25 | 2       | 0           | 0.0000 | 0.0897 | -0.0897 | DOWN      |
| 31 | 34.00 | -119.00 | 5674    | 1332914     | 0.1625 | 0.3803 | -0.2178 | DOWN      |
| 32 | 34.00 | -118.75 | 898     | 31528       | 0.0234 | 0.2349 | -0.2115 | DOWN      |
| 33 | 33.75 | -120.50 | 686     | 0           | 0.0000 | 0.2509 | -0.2509 | DOWN      |
| 34 | 33.75 | -120.25 | 22288   | 6576754     | 0.1441 | 0.3657 | -0.2216 | DOWN      |
| 35 | 33.75 | -120.00 | 4848    | 3151095     | 0.3672 | 0.3908 | -0.0237 | DOWN      |
| 36 | 33.75 | -119.75 | 5684    | 952588      | 0.1946 | 0.3137 | -0.1191 | DOWN      |
| 37 | 33.75 | -119.50 | 10      | 0           | 0.0000 | 0.1538 | -0.1538 | DOWN      |
| 38 | 33.75 | -119.00 | 17      | 0           | 0.0000 | 0.1719 | -0.1719 | DOWN      |
| 39 | 33.75 | -118.50 | 3141    | 1780880     | 0.2693 | 0.3692 | -0.0999 | DOWN      |

|    | Lat   | Long    | N.Pixel | AVG.Biomass | RYPO   | LTPAPO | POT     | Direction |
|----|-------|---------|---------|-------------|--------|--------|---------|-----------|
| 40 | 33.50 | -118.50 | 3824    | 1784531     | 0.2746 | 0.3351 | -0.0605 | DOWN      |
| 41 | 33.50 | -118.25 | 7       | 0           | 0.0000 | 0.1698 | -0.1698 | DOWN      |
| 42 | 33.50 | -118.00 | 893     | 77899       | 0.0817 | 0.1713 | -0.0896 | DOWN      |
| 43 | 33.25 | -119.75 | 22053   | 8108590     | 0.1861 | 0.2464 | -0.0603 | DOWN      |
| 44 | 33.25 | -119.50 | 4317    | 434169      | 0.0903 | 0.2442 | -0.1538 | DOWN      |
| 45 | 33.25 | -119.25 | 2442    | 1415152     | 0.4128 | 0.2143 | 0.1985  | UP        |
| 46 | 33.25 | -118.75 | 628     | 444398      | 0.5494 | 0.3846 | 0.1647  | UP        |
| 47 | 33.25 | -118.50 | 1138    | 686548      | 0.4095 | 0.3391 | 0.0704  | UP        |
| 48 | 33.25 | -117.75 | 4901    | 13125       | 0.0057 | 0.1819 | -0.1762 | DOWN      |
| 49 | 33.25 | -117.50 | 1058    | 11174       | 0.0274 | 0.2278 | -0.2004 | DOWN      |
| 50 | 33.00 | -119.75 | 1970    | 2653205     | 0.6096 | 0.5005 | 0.1092  | UP        |
| 51 | 33.00 | -119.50 | 2103    | 3939849     | 0.6947 | 0.4615 | 0.2332  | UP        |
| 52 | 33.00 | -118.75 | 5668    | 2954480     | 0.5173 | 0.4082 | 0.1091  | UP        |
| 53 | 33.00 | -117.50 | 2998    | 592         | 0.0007 | 0.2335 | -0.2329 | DOWN      |
| 54 | 32.75 | -118.75 | 9897    | 7906432     | 0.5457 | 0.4512 | 0.0946  | UP        |
| 55 | 32.75 | -118.50 | 6304    | 4191238     | 0.5103 | 0.4282 | 0.0821  | UP        |
| 56 | 32.75 | -117.50 | 9334    | 955890      | 0.1023 | 0.3033 | -0.2010 | DOWN      |
| 57 | 32.50 | -117.50 | 12727   | 2625947     | 0.1803 | 0.3252 | -0.1449 | DOWN      |
| 58 | 32.50 | -117.25 | 5862    | 1011        | 0.0003 | 0.1055 | -0.1051 | DOWN      |
| 59 | 32.25 | -119.25 | 454     | 2268        | 0.0044 | 0.1727 | -0.1683 | DOWN      |
| 60 | 32.25 | -117.50 | 25      | 0           | 0.0000 | 0.0472 | -0.0472 | DOWN      |
| 61 | 32.25 | -117.25 | 2861    | 36253       | 0.0196 | 0.2239 | -0.2044 | DOWN      |
| 62 | 32.25 | -117.00 | 812     | 0           | 0.0000 | 0.1900 | -0.1900 | DOWN      |
| 63 | 32.00 | -117.00 | 7424    | 2562        | 0.0012 | 0.3097 | -0.3085 | DOWN      |
| 64 | 31.75 | -117.00 | 5149    | 154817      | 0.0216 | 0.2304 | -0.2088 | DOWN      |
| 65 | 31.75 | -116.75 | 2083    | 5145        | 0.0029 | 0.1339 | -0.1310 | DOWN      |
| 66 | 31.50 | -117.00 | 15      | 0           | 0.0000 | 0.1350 | -0.1350 | DOWN      |
| 67 | 31.50 | -116.75 | 15008   | 11463424    | 0.2041 | 0.4003 | -0.1962 | DOWN      |
| 68 | 31.25 | -116.75 | 9881    | 3286881     | 0.1937 | 0.2426 | -0.0489 | DOWN      |
| 69 | 31.25 | -116.50 | 8365    | 447986      | 0.0306 | 0.2001 | -0.1695 | DOWN      |
| 70 | 31.00 | -116.50 | 1121    | 0           | 0.0000 | 0.1087 | -0.1087 | DOWN      |
| 71 | 30.75 | -116.50 | 2455    | 404282      | 0.1222 | 0.1357 | -0.0135 | DOWN      |
| 72 | 30.75 | -116.25 | 20723   | 1184284     | 0.0279 | 0.1218 | -0.0939 | DOWN      |
| 73 | 30.50 | -116.25 | 2       | 0           | 0.0000 | 0.0270 | -0.0270 | DOWN      |
| 74 | 30.25 | -116.25 | 1684    | 158208      | 0.0475 | 0.3868 | -0.3393 | DOWN      |
| 75 | 30.25 | -116.00 | 1172    | 19628       | 0.0171 | 0.2098 | -0.1927 | DOWN      |
| 76 | 30.00 | -116.00 | 3920    | 8532077     | 0.5202 | 0.2358 | 0.2843  | UP        |
| 77 | 29.75 | -116.00 | 24760   | 1136054     | 0.0209 | 0.2052 | -0.1843 | DOWN      |
| 78 | 29.75 | -115.75 | 2486    | 1189920     | 0.1372 | 0.1653 | -0.0282 | DOWN      |
| 79 | 29.50 | -116.00 | 7343    | 16586       | 0.0045 | 0.3396 | -0.3352 | DOWN      |
| 80 | 29.50 | -115.75 | 5258    | 2235086     | 0.2529 | 0.2192 | 0.0337  | UP        |
| 81 | 29.50 | -115.50 | 38      | 266         | 0.0526 | 0.1209 | -0.0683 | DOWN      |
| 82 | 29.25 | -115.25 | 617     | 393590      | 0.1929 | 0.2174 | -0.0245 | DOWN      |
| 83 | 29.25 | -115.00 | 763     | 25107       | 0.0183 | 0.1340 | -0.1156 | DOWN      |
| 84 | 29.00 | -114.75 | 21      | 0           | 0.0000 | 0.1002 | -0.1002 | DOWN      |
| 85 | 28.25 | -115.75 | 6081    | 150335      | 0.0176 | 0.3374 | -0.3198 | DOWN      |
| 86 | 28.25 | -115.50 | 3621    | 3396337     | 0.2693 | 0.4515 | -0.1822 | DOWN      |
| 87 | 28.25 | -115.25 | 3864    | 2186376     | 0.1866 | 0.4385 | -0.2519 | DOWN      |
| 88 | 28.00 | -115.50 | 16087   | 20626117    | 0.3241 | 0.3439 | -0.0199 | DOWN      |
| 89 | 28.00 | -115.25 | 2480    | 17911       | 0.0145 | 0.2096 | -0.1951 | DOWN      |
| 90 | 27.75 | -115.25 | 28090   | 34082183    | 0.3670 | 0.3964 | -0.0294 | DOWN      |
| 91 | 27.50 | -115.25 | 1705    | 898259      | 0.3161 | 0.3455 | -0.0294 | DOWN      |

|    | Lat   | Long    | N.Pixel | AVG.Biomass | RYPO   | LTPAPO | POT     | Direction |
|----|-------|---------|---------|-------------|--------|--------|---------|-----------|
| 92 | 27.50 | -115.00 | 9752    | 14855881    | 0.5225 | 0.5055 | 0.0170  | UP        |
| 93 | 27.50 | -114.75 | 827     | 146603      | 0.1403 | 0.3430 | -0.2027 | DOWN      |
| 94 | 27.25 | -114.75 | 904     | 2389        | 0.0066 | 0.2207 | -0.2140 | DOWN      |
| 95 | 27.25 | -114.50 | 32      | 0           | 0.0000 | 0.1948 | -0.1948 | DOWN      |
| 96 | 27.00 | -114.50 | 4129    | 3196        | 0.0024 | 0.2657 | -0.2633 | DOWN      |
| 97 | 27.00 | -114.25 | 29      | 0           | 0.0000 | 0.0878 | -0.0878 | DOWN      |

You may note that this table is longer than the one produced by *decline_finder*. This is because all pixels are used when analyzing pixel occupancy resulting in a larger number of regions.

**Plotting the trends in pixel occupancy by region**

```
raster::plot(TrendRaster, col = topo.colors(30, alpha = 1), axes = T,
    main = "Giant kelp pixel occupancy trend (POT) in 2022",
    xlab = "long", ylab = "lat")
# adding coastal lines
raster::lines(coast)
```
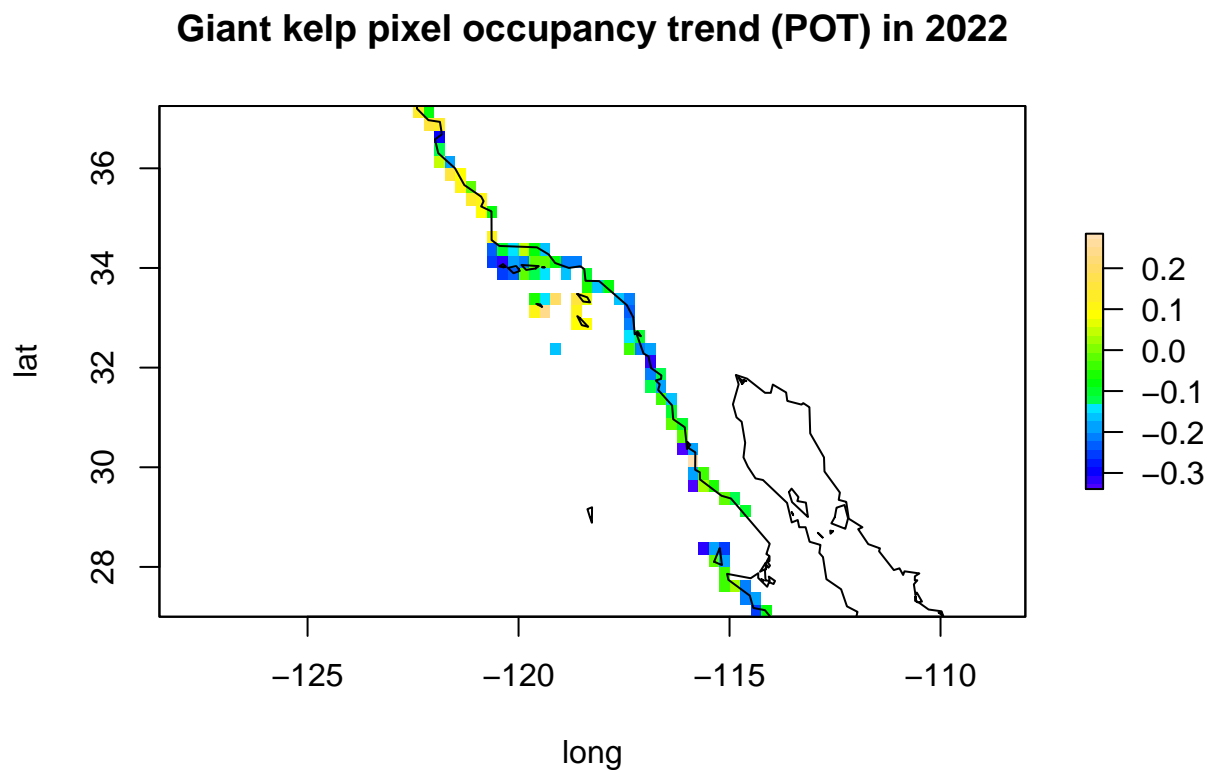


**Comparing the results from the two functions**

Below we compare the two statistics, *proportions of pixels in decline* and *trends in pixel annual occupancy*.

```
# Summary.Stats is the output of decline_finder
# (Table 1) Occupancy.OUT is the output of
```

```
# occupancy_trend (Table 2)

# First we merge the two outputs to match rows
# (Regions)
Summary.Stats$Merge <- paste0(Summary.Stats$long_west,
    ":", Summary.Stats$lat_south)
Occupancy.OUT$Merge <- paste0(Occupancy.OUT$Long, ":",
    Occupancy.OUT$Lat)

Merged <- merge(x = Summary.Stats, y = Occupancy.OUT,
    by = "Merge")

# Plotting the relationship, and scaling points
# by number of pixels in cells
plot(Merged$POT, Merged$PPD, cex = sqrt(Merged$Pixel)/15,
    xlab = "Annual pixel occupancy trend (POT)", ylab = "Proportion of pixels in decline (PPD)")
lines(smooth.spline(Merged$POT, Merged$PPD, nknots = 10),
    lwd = "2", col = "grey70")
```
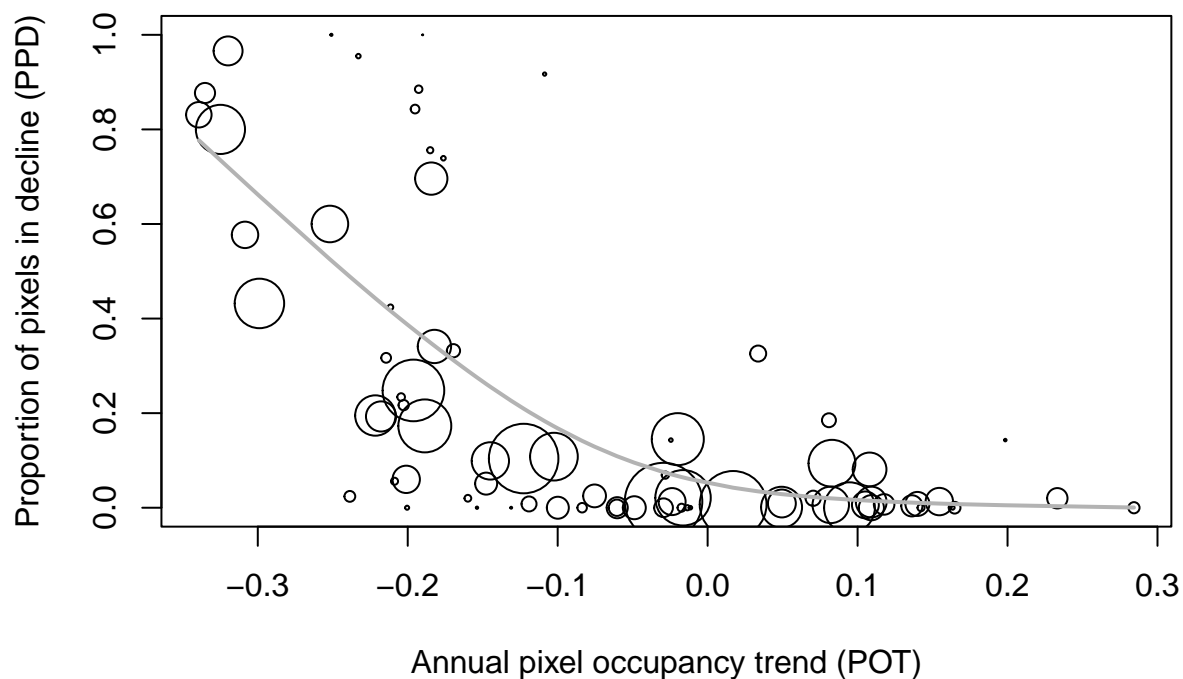


The relationship between the two statistics is tight for regions with a negative pixel occupancy trend. The proportion of pixels in decline is not well suited to interpret kelp recovery, thus it makes sense that the relationship is only good for the range of negative trends (declines) in annual pixel occupancy. The highest values for negative trends ($>$ -0.3, Table 3.) were all for regions with high proportion of pixels in decline and high pixel numbers (Table 3, upper left corner of the figure above).

Table 3: Proportion of pixels in decline (PPD) and annual pixel occupancy trend (POT) for regions of concern. Both statistics correlate well for regions with negative POT and large numbers of pixels

| Lat | Long | PPD | POT | N.Pixel | Region |
|---|---|---|---|---|---|
| 36.50 | -122.00 | 0.432 | -0.299 | 8834 | Monterey Peninsula |
| 34.00 | -120.50 | 0.800 | -0.349 | 19554 | San Miguel Isl. |
| 32.00 | -117.00 | 0.577 | -0.308 | 2562 | Primo Tapia |
| 30.25 | -116.25 | 0.831 | -0.339 | 158208 | San Martin |
| 29.50 | -116.00 | 0.877 | -0.335 | 16586 | Punta Baja |
| 28.25 | -115.75 | 0.966 | -0.320 | 150335 | Islas de San Benito |

## Acknowledgments and license

## References

Bell, T., Cavanaugh, K.C., Saccomanno, V.R., Cavanaugh, K.C., Houskeeper, H.F., Eddy, N., Schuetzenmeister, F., Rindlaub, N. & Gleason, M. (2022) Kelpwatch: A new visualization and analysis tool to explore kelp canopy dynamics reveals variable resistance and resilience to marine heat waves. bioRxiv, pp.2022-07.

Bell, T., Cavanaugh, K.C., & Siegel., D. (2023) SBC LTER: Time series of quarterly NetCDF files of kelp biomass in the canopy from Landsat 5, 7 and 8, since 1984 (ongoing) ver 19. Environmental Data Initiative. https://doi.org/10.6073/pasta/630565d6a8bf54c7cbce6802284dd431. Accessed 2023-02-22.

Cavanaugh, K.C., Siegel, D. A., Reed, D. C., & Dennison, P. E. (2011). Environmental controls of giant-kelp biomass in the Santa Barbara Channel, California. *Marine Ecology Progress Series*, 429, 1-17.

Klingbeil, W., Montecinos, G., & Alberto, F. (2022) Giant kelp genetic monitoring before and after disturbance reveals stable genetic diversity in Southern California. Frontiers in Marine Science. 9:947393.doi: 10.3389/fmars.2022.947393

Tennies, N. & Alberto, F. (in prep) A tool for detecting giant kelp canopy biomass decline in the Californias. *Journal of Phycology*

Wessel, P., & Smith, W.H.F. (1996) A global, self-consistent, hierarchical, high-resolution shoreline database. *Journal of Geophysical Research*, 101(B4), 8741–8743, doi:10.1029/96JB00104.