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

Nathaniel Tennies & Filipe Alberto

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 = 0.6, 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 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 and the total number of pixels for each region (row). 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

	decline_proportion	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

	decline_proportion	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. The 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.

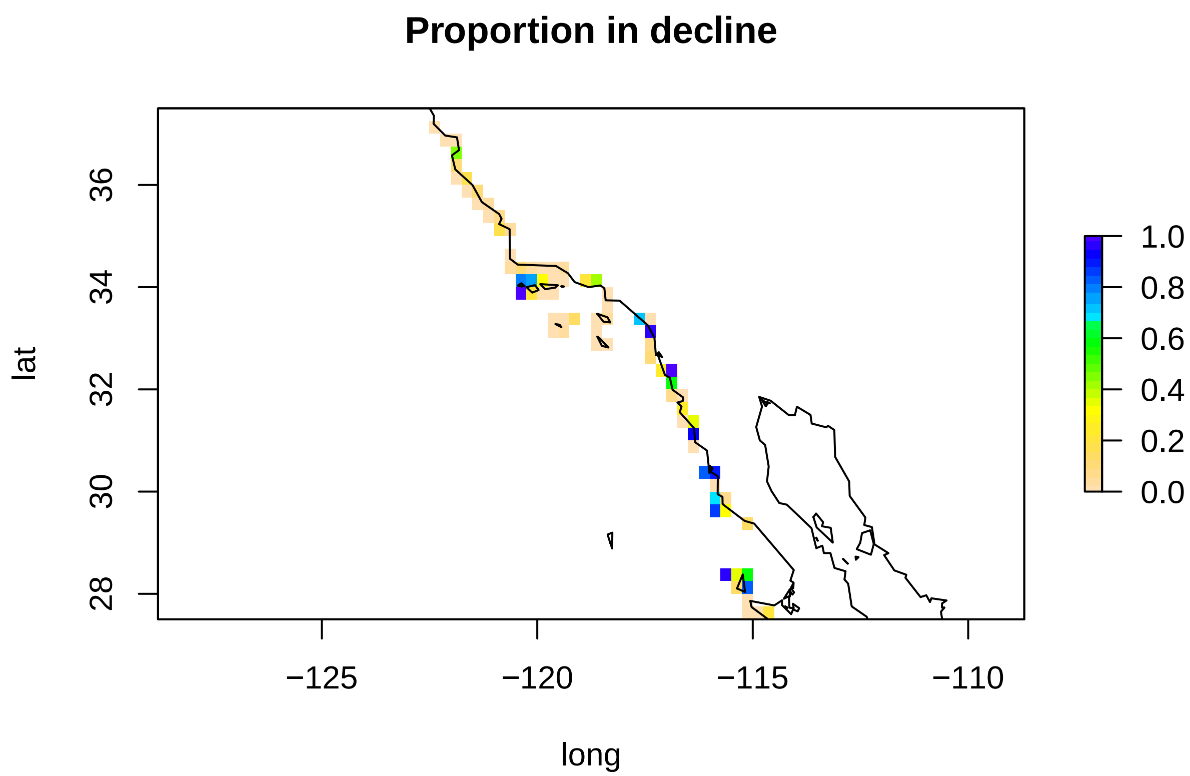
Landsat pixels where biomass was rarely recorded throughout the time series affect the calculation of historical averages. Given the effect these pixels have, and their poor indicator status for the overall trend of a kelp forest, we removed from the analysis pixels tha thad zero biomass through the *hist_period* in more 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 shapefiles to visualize the coastline. Note that the shapefiles used in the code below are not part of the package. Users must obtain their own if they want to print the coastline (https://www.ngdc.noaa.gov/mgg/shorelines/).

```
# loading shapefiles.
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 = "Proportion in decline", xlab = "long", ylab = "lat")

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



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 parameterization. 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.

```
# 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 = 0.6, 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.

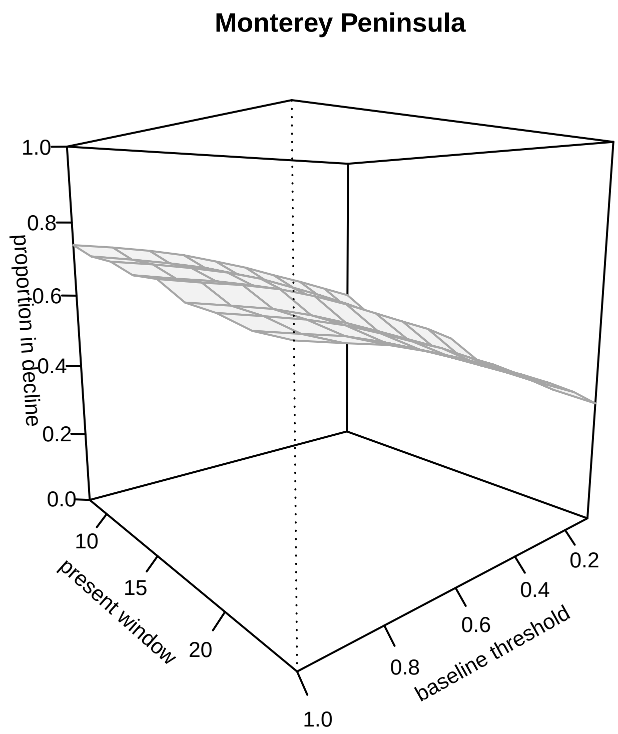
Next, we will read the output files back to R, using two nested *for* loops, and produce a perspective plot to visualize how the proportion of pixels in decline is affected by the combination of *baseline_threshold* and *present_window* values.

```
# 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))
Cell.Matrix.SanBenito <- matrix(nrow = length(baseline_thresholdV),
```

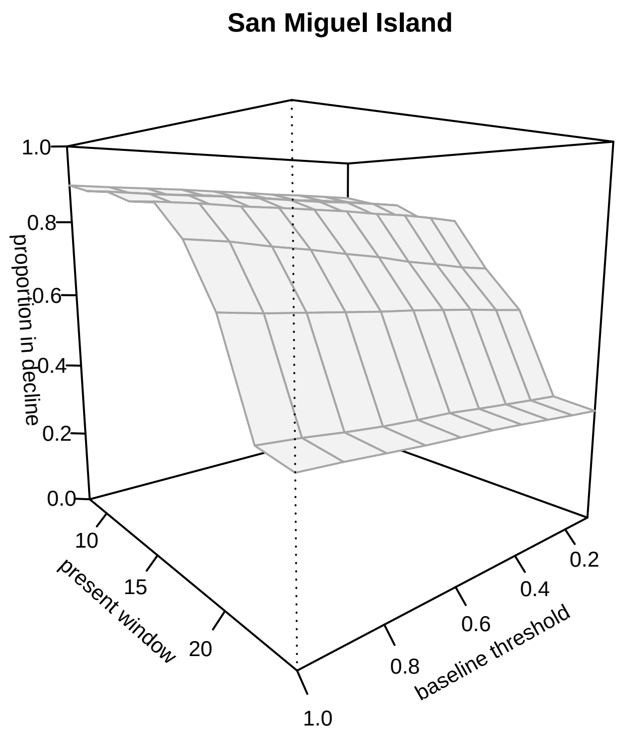
```
    ncol = length(present_windowV))
Cell.Matrix.PointLoma <- matrix(nrow = length(baseline_thresholdV),
    ncol = length(present_windowV))

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.

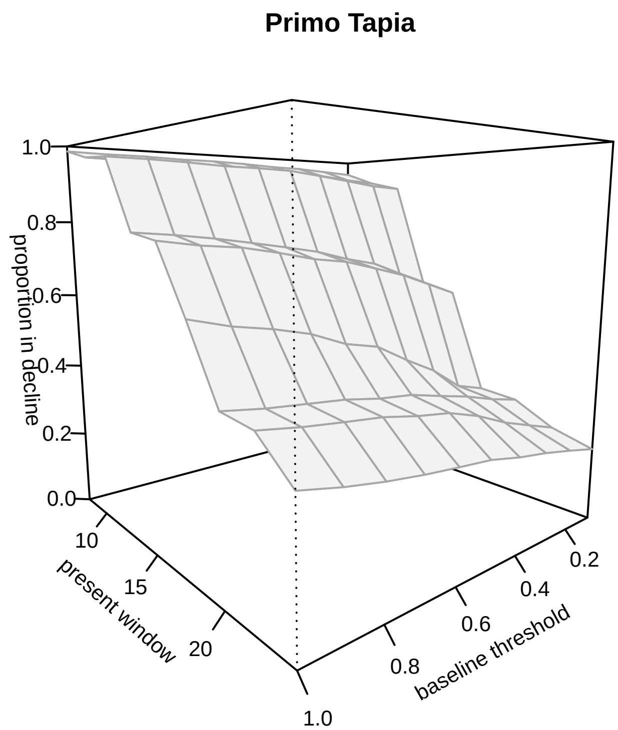
```
# For Monterey Peninsula
par(cex = 0.7)
persp(baseline_thresholdV, present_windowV, Cell.Matrix.Monterey,
    theta = 140, phi = 10, zlim = c(0, 1), zlab = "proportion in decline",
    xlab = "baseline threshold", ylab = "present window", main = "Monterey Peninsula",
    border = "grey65", col =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



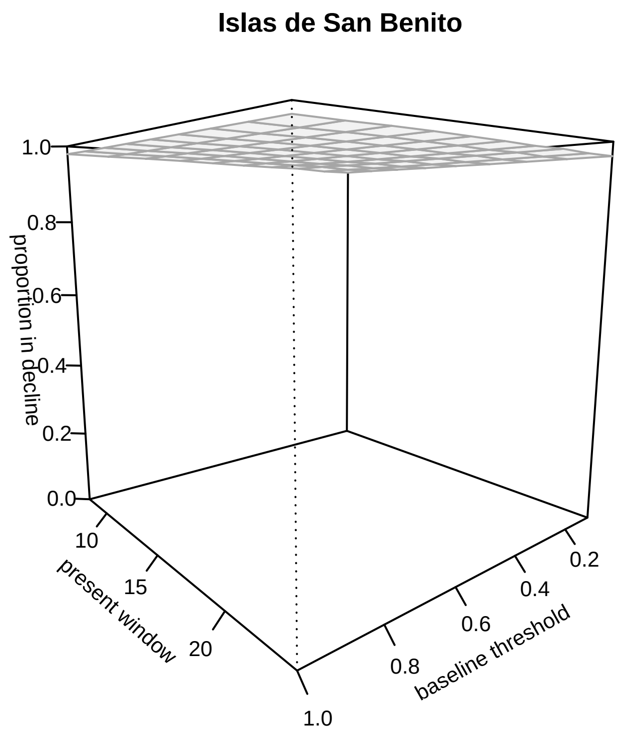

```r
# For San Miguel Island
par(cex = 0.7)
persp(baseline_thresholdV, present_windowV, Cell.Matrix.SanMiguel,
    theta = 140, phi = 10, zlim = c(0, 1), zlab = "proportion in decline",
    xlab = "baseline threshold", ylab = "present window", main = "San Miguel Island",
    border = "grey65", col =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



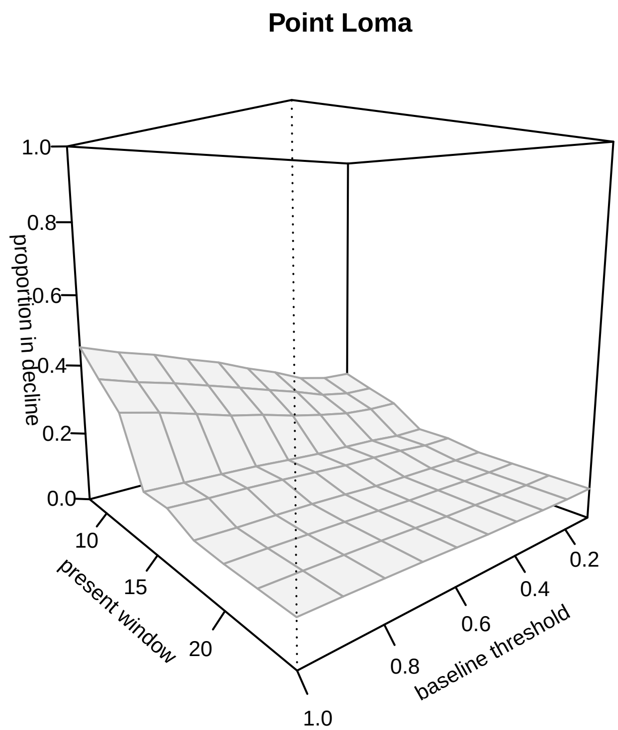

```
# For Primo Tapia
par(cex = 0.7)
persp(baseline_thresholdV, present_windowV, Cell.Matrix.PrimoTapia,
    theta = 140, phi = 10, zlim = c(0, 1), zlab = "proportion in decline",
    xlab = "baseline threshold", ylab = "present window", main = "Primo Tapia",
    border = "grey65", col = "grey95", ticktype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




```
# 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")
```




```
# 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 window. 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 2020 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.

	Lat	Long	N.Pixel	AVG.Biomass	Trend	RYPO	LTPAPO	Direction
1	37.00	-122.50	1029	677188	0.1423	0.3003	0.1580	UP
2	37.00	-122.25	295	609	-0.0807	0.0034	0.0841	DOWN
3	36.75	-122.25	3443	6750159	0.1545	0.6346	0.4801	UP
4	36.75	-122.00	1927	2786895	0.1399	0.6352	0.4953	UP
5	36.50	-122.00	8834	2574103	-0.2989	0.2319	0.5308	DOWN

	Lat	Long	N.Pixel	AVG.Biomass	Trend	RYPO	LTPAPO	Direction
6	36.25	-122.00	13432	25462310	-0.1227	0.4933	0.6160	DOWN
7	36.00	-122.00	1658	5136116	0.0495	0.7069	0.6574	UP
8	36.00	-121.75	8666	8584547	-0.1886	0.3921	0.5807	DOWN
9	35.75	-121.75	131	83981	0.1634	0.5649	0.4015	UP
10	35.75	-121.50	8468	19402439	0.0829	0.5777	0.4948	UP
11	35.50	-121.50	4519	5427143	0.1177	0.4970	0.3793	UP
12	35.50	-121.25	15174	23328307	-0.0164	0.4885	0.5049	DOWN
13	35.25	-121.25	5362	11028372	0.1362	0.5649	0.4287	UP
14	35.25	-121.00	5915	7364182	0.1080	0.5107	0.4027	UP
15	35.00	-121.00	4623	2018343	0.0809	0.3238	0.2429	UP
16	35.00	-120.75	2643	2140876	-0.0754	0.3674	0.4428	DOWN
17	34.50	-120.75	4342	6382749	0.1052	0.4701	0.3649	UP
18	34.25	-120.75	845	522692	-0.2386	0.2201	0.4587	DOWN
19	34.25	-120.50	13137	8789444	-0.1025	0.3043	0.4068	DOWN
20	34.25	-120.25	1941	1212235	-0.1477	0.2880	0.4356	DOWN
21	34.25	-120.00	6718	6882619	0.0493	0.4470	0.3977	UP
22	34.25	-119.75	2833	723949	-0.0837	0.1804	0.2641	DOWN
23	34.25	-119.50	1019	18310	-0.1599	0.0648	0.2247	DOWN
24	34.00	-120.75	1	0	-0.2564	0.0000	0.2564	DOWN
25	34.00	-120.50	19554	2101287	-0.3249	0.0365	0.3614	DOWN
26	34.00	-120.25	20150	1520839	-0.1850	0.0327	0.2177	DOWN
27	34.00	-120.00	2408	164940	-0.2144	0.0473	0.2618	DOWN
28	34.00	-119.75	917	210933	-0.0115	0.2181	0.2297	DOWN
29	34.00	-119.50	1260	449560	-0.0174	0.2952	0.3126	DOWN
30	34.00	-119.25	2	0	-0.0897	0.0000	0.0897	DOWN
31	34.00	-119.00	5674	1332914	-0.2178	0.1625	0.3803	DOWN
32	34.00	-118.75	898	31528	-0.2115	0.0234	0.2349	DOWN
33	33.75	-120.50	686	0	-0.2509	0.0000	0.2509	DOWN
34	33.75	-120.25	22288	6576754	-0.2216	0.1441	0.3657	DOWN
35	33.75	-120.00	4848	3151095	-0.0237	0.3672	0.3908	DOWN
36	33.75	-119.75	5684	952588	-0.1191	0.1946	0.3137	DOWN
37	33.75	-119.50	10	0	-0.1538	0.0000	0.1538	DOWN
38	33.75	-119.00	17	0	-0.1719	0.0000	0.1719	DOWN
39	33.75	-118.50	3141	1780880	-0.0999	0.2693	0.3692	DOWN
40	33.50	-118.50	3824	1784531	-0.0605	0.2746	0.3351	DOWN
41	33.50	-118.25	7	0	-0.1698	0.0000	0.1698	DOWN
42	33.50	-118.00	893	77899	-0.0896	0.0817	0.1713	DOWN
43	33.25	-119.75	22053	8108590	-0.0603	0.1861	0.2464	DOWN
44	33.25	-119.50	4317	434169	-0.1538	0.0903	0.2442	DOWN
45	33.25	-119.25	2442	1415152	0.1985	0.4128	0.2143	UP
46	33.25	-118.75	628	444398	0.1647	0.5494	0.3846	UP
47	33.25	-118.50	1138	686548	0.0704	0.4095	0.3391	UP
48	33.25	-117.75	4901	13125	-0.1762	0.0057	0.1819	DOWN
49	33.25	-117.50	1058	11174	-0.2004	0.0274	0.2278	DOWN
50	33.00	-119.75	1970	2653205	0.1092	0.6096	0.5005	UP
51	33.00	-119.50	2103	3939849	0.2332	0.6947	0.4615	UP
52	33.00	-118.75	5668	2954480	0.1091	0.5173	0.4082	UP
53	33.00	-117.50	2998	592	-0.2329	0.0007	0.2335	DOWN
54	32.75	-118.75	9897	7906432	0.0946	0.5457	0.4512	UP
55	32.75	-118.50	6304	4191238	0.0821	0.5103	0.4282	UP
56	32.75	-117.50	9334	955890	-0.2010	0.1023	0.3033	DOWN
57	32.50	-117.50	12727	2625947	-0.1449	0.1803	0.3252	DOWN

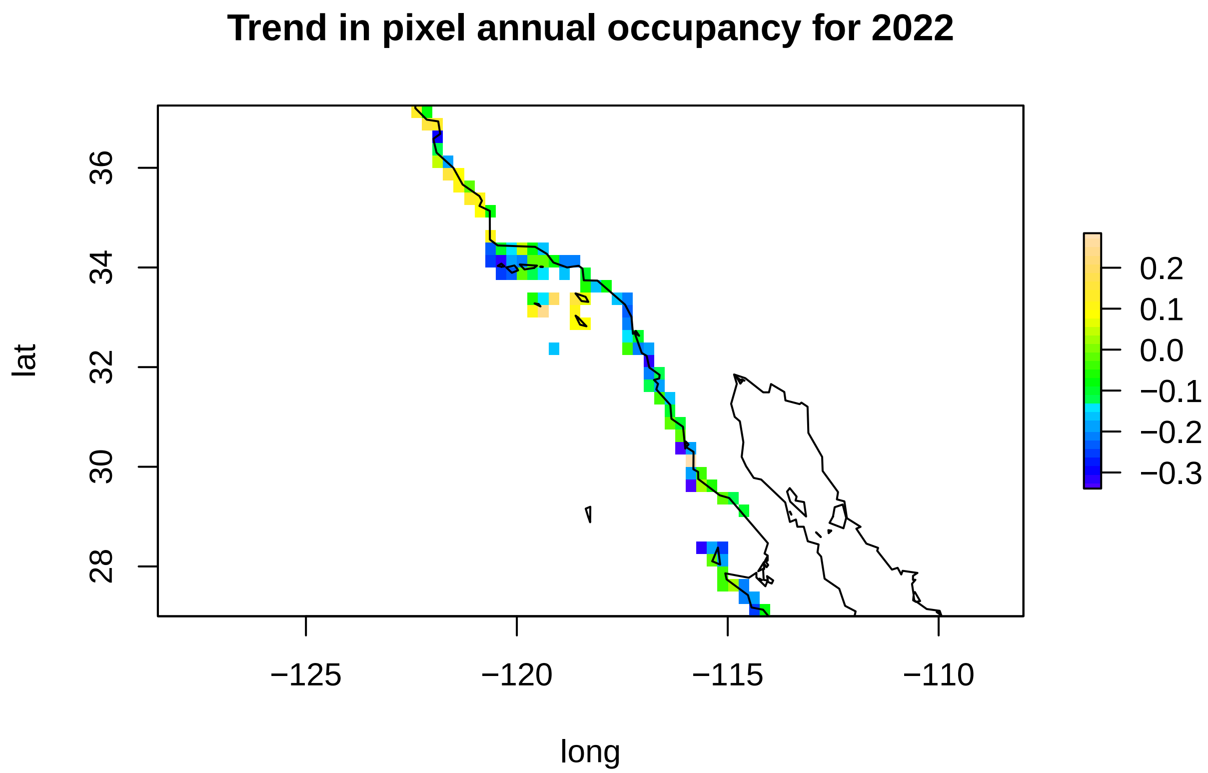
	Lat	Long	N.Pixel	AVG.Biomass	Trend	RYPO	LTPAPO	Direction
58	32.50	-117.25	5862	1011	-0.1051	0.0003	0.1055	DOWN
59	32.25	-119.25	454	2268	-0.1683	0.0044	0.1727	DOWN
60	32.25	-117.50	25	0	-0.0472	0.0000	0.0472	DOWN
61	32.25	-117.25	2861	36253	-0.2044	0.0196	0.2239	DOWN
62	32.25	-117.00	812	0	-0.1900	0.0000	0.1900	DOWN
63	32.00	-117.00	7424	2562	-0.3085	0.0012	0.3097	DOWN
64	31.75	-117.00	5149	154817	-0.2088	0.0216	0.2304	DOWN
65	31.75	-116.75	2083	5145	-0.1310	0.0029	0.1339	DOWN
66	31.50	-117.00	15	0	-0.1350	0.0000	0.1350	DOWN
67	31.50	-116.75	15008	11463424	-0.1962	0.2041	0.4003	DOWN
68	31.25	-116.75	9881	3286881	-0.0489	0.1937	0.2426	DOWN
69	31.25	-116.50	8365	447986	-0.1695	0.0306	0.2001	DOWN
70	31.00	-116.50	1121	0	-0.1087	0.0000	0.1087	DOWN
71	30.75	-116.50	2455	404282	-0.0135	0.1222	0.1357	DOWN
72	30.75	-116.25	20723	1184284	-0.0939	0.0279	0.1218	DOWN
73	30.50	-116.25	2	0	-0.0270	0.0000	0.0270	DOWN
74	30.25	-116.25	1684	158208	-0.3393	0.0475	0.3868	DOWN
75	30.25	-116.00	1172	19628	-0.1927	0.0171	0.2098	DOWN
76	30.00	-116.00	3920	8532077	0.2843	0.5202	0.2358	UP
77	29.75	-116.00	24760	1136054	-0.1843	0.0209	0.2052	DOWN
78	29.75	-115.75	2486	1189920	-0.0282	0.1372	0.1653	DOWN
79	29.50	-116.00	7343	16586	-0.3352	0.0045	0.3396	DOWN
80	29.50	-115.75	5258	2235086	0.0337	0.2529	0.2192	UP
81	29.50	-115.50	38	266	-0.0683	0.0526	0.1209	DOWN
82	29.25	-115.25	617	393590	-0.0245	0.1929	0.2174	DOWN
83	29.25	-115.00	763	25107	-0.1156	0.0183	0.1340	DOWN
84	29.00	-114.75	21	0	-0.1002	0.0000	0.1002	DOWN
85	28.25	-115.75	6081	150335	-0.3198	0.0176	0.3374	DOWN
86	28.25	-115.50	3621	3396337	-0.1822	0.2693	0.4515	DOWN
87	28.25	-115.25	3864	2186376	-0.2519	0.1866	0.4385	DOWN
88	28.00	-115.50	16087	20626117	-0.0199	0.3241	0.3439	DOWN
89	28.00	-115.25	2480	17911	-0.1951	0.0145	0.2096	DOWN
90	27.75	-115.25	28090	34082183	-0.0294	0.3670	0.3964	DOWN
91	27.50	-115.25	1705	898259	-0.0294	0.3161	0.3455	DOWN
92	27.50	-115.00	9752	14855881	0.0170	0.5225	0.5055	UP
93	27.50	-114.75	827	146603	-0.2027	0.1403	0.3430	DOWN
94	27.25	-114.75	904	2389	-0.2140	0.0066	0.2207	DOWN
95	27.25	-114.50	32	0	-0.1948	0.0000	0.1948	DOWN
96	27.00	-114.50	4129	3196	-0.2633	0.0024	0.2657	DOWN
97	27.00	-114.25	29	0	-0.0878	0.0000	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. The table outputs the following statistics per region: total number of pixels, average biomass, the average reference year pixel occupancy (RYPO), average long-term probability of annual pixel occupancy (LTPAPO), trend (i.e.,RYPO-LTPAPO), and a trend direction (UP, DOWN or NS, if a test was made, otherwise just UP or DOWN).

Plotting the trends in pixel occupancy by region

```
raster::plot(TrendRaster, col = topo.colors(30, alpha = 1), axes = T,
    main = "Trend in pixel annual occupancy for 2022", xlab = "long",
```

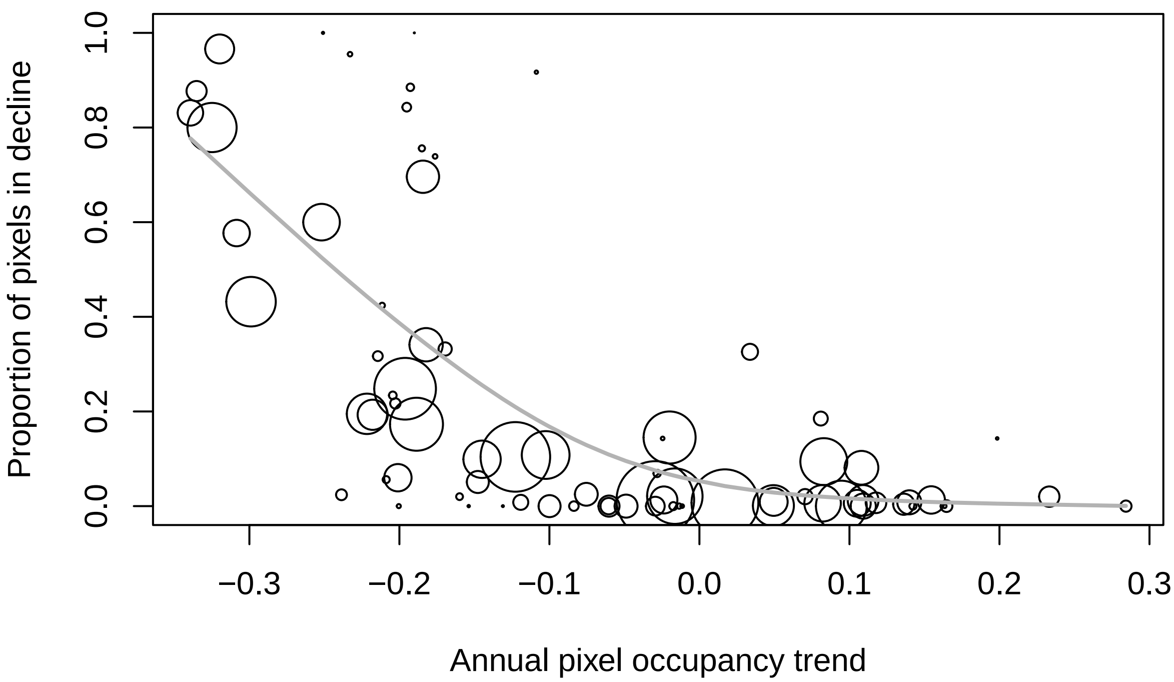
```
    ylab = "lat")
# adding coastal lines
raster::lines(coast)
```



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$Trend, Merged$decline_proportion, cex = sqrt(Merged$Pixel)/15,
    xlab = "Annual pixel occupancy trend", ylab = "Proportion of pixels in decline")
lines(smooth.spline(Merged$Trend, Merged$decline_proportion,
    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.) where 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 and trend in annual pixel occupancy for regions of concerned. Both statistics correlate well for regions with large numbers of pixels

Lat	Long	Prop.Decline	Occu.Trend	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

 We do not redistribute the NetCDF data file here; all summary statistics produced from it are the authors' responsibility. To the best of our knowledge, the method proposed here does not duplicate efforts by others. Another tool to run similar work is the webpage https://kelpwatch.org which provides an excellent tool for the temporal and spatial visualization of the kelp biomass time series. Analyses based on kelpwatch.org were aimed at larger areas and used other methods (Bell et al. 2022 preprint).

We thank the great work of the SBC-LTER team for curating and producing this data set. Among many others, we are thankful to K. Cavanaugh, T. Bell, D. Siegel, and D. Reed.

We thank UWM's office of undergraduate research, and their SURF program, for funding to N Tennies.

References

Bell, T., Cavanaugh, K.C., Saccomanno, V.R., Cavanaugh, K.C., Houskeeper, H.F., Eddy, N., Schuetzenmeister, F., Rindlaub, N. and 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, K. Cavanaugh, D. Siegel. (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., and W. H. F. Smith (1996) A global, self-consistent, hierarchical, high-resolution shoreline database. *Journal of Geophysical Research*, 101(B4), 8741–8743, doi:10.1029/96JB00104.