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Article

Developing a Status and Trends Assessment for Floating Kelp Canopies across Large Geographic Areas

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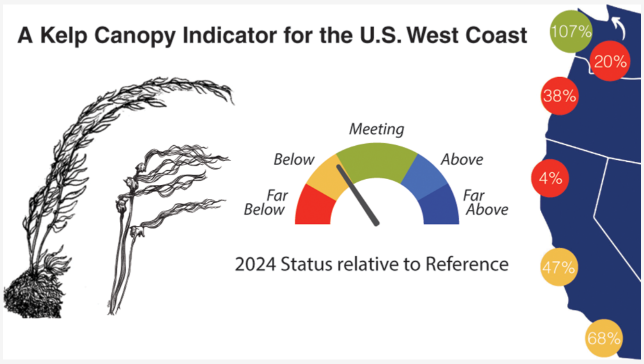

ABSTRACT: Effective kelp forest stewardship and management requires understanding of status and trends, but most kelp monitoring data streams on the U.S. West Coast are focused on subregional scales with outputs targeted toward a scientific audience. Here, we developed an index of kelp status and trend that integrates across thousands of kilometers and is presented as a simple, informative gauge that can be easily communicated to multiple audiences, including high-level policymakers. The indicator has three main features: (1) it is based on floating kelps as they create canopies, and managers indicated their interest in whether the quantity of kelp surface canopy had changed relative to historical levels. (2) Kelp canopy is assessed within segments along the coastline, rather than as a single coast-wide, cumulative amount. This approach retains local-level information allowing the indicator to be calculated at multiple scales, which accommodates the multigovernance landscape of the U.S. West Coast. (3) Status of kelp is expressed as a comparison to a reference period, established using all data prior to a marine heat wave in 2014 that led to substantial kelp losses. When applied to data from recent years, we found that the kelp canopies continue to be below their historical baseline. Since 2014, there has been no coast-wide recovery to reference levels. Still, despite 2023 being among the worst years on record, there was substantial improvement in kelp canopies in 2024 and recent downward trends have stalled. This Kelp Indicator provides a tool to inform resource management, improve policy, and prioritize scientific research, recovery efforts, and monitoring.

KEYWORDS: *giant kelp, bull kelp, kelp canopy, California Current System, indicators, report card*

1. INTRODUCTION

Kelp forests are undergoing considerable pressure.[1] Rising ocean temperatures, marine heat waves, and anthropogenic activities threaten kelp forests and the ecosystem services they provide.[1−5] Resource management agencies, conservation groups, and environmental stewards are engaged in protection and restoration initiatives to augment kelp forest resilience and identify the enabling conditions to mitigate kelp loss.[1] Effective initiatives can benefit from a shared understanding about the extent and reasons for which changes in kelp are operating from small-to-broad scales that can span biogeographic or geopolitical boundaries.

Along the U.S. West Coast, the canopy-forming species are giant kelp, *Macrocystis pyrifera*, and bull kelp, *Nereocystis luetkeana*, both of which grow on rocky subtidal reefs. In this region, there are existing programs that recurrently assess kelp canopy amounts with remote imagery. For example, in Washington, the Floating Kelp Indicator is part of the Puget Sound Vital Signs that reports on measures of ecosystem health and progress toward recovery goals, specifically geared toward managers and decision makers at the state level.[6] The Washington Floating Kelp Indicator has informed decisions about where to designate new areas for protection, such as the Elwha Kelp and Eelgrass Priority Area and the Squaxin Island Kelp Protection Zone, designated by the Washington Department of Natural Resources, and in the latter case, in partnership with the Squaxin Island Tribe. Kelpwatch is another program that annually assesses kelp using canopy extent data available for the entire U.S. West Coast and is

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geared toward kelp-specific audiences, including environmental stewards and managers. Kelpwatch is an open-access platform that is being increasingly incorporated into decision-making frameworks for kelp restoration prioritization.[7] The current limitation of these kelp assessments is that high-level managers and legislators have requested something that spans broad geographies, like Kelpwatch does, and that also reports in a similar format across a range of ocean health indicators, like Puget Sound Vital Signs does.

The West Coast Ocean Alliance (WCOA), a regional ocean partnership of state, tribal, and federal government members for the U.S. West Coast, is responding to this request by developing such an environmental report card of ocean health indicators. The WCOA report card, currently in development, intends to use a gauge to report on status for individual indicators, kelp or otherwise (Figure 1). In parallel, California's Ocean Protection Council is developing a state-level coast and ocean report card to report on status for individual indicators. Both report cards will include more than a dozen ocean-related metrics, of which floating kelp is one.

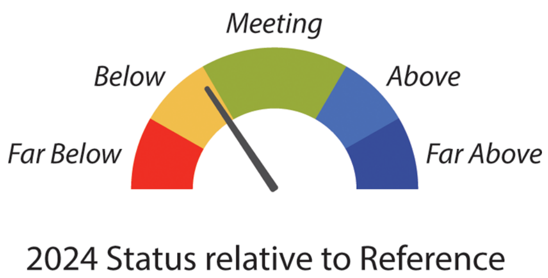

Figure 1. U.S. West Coast-wide status for kelp canopy for 2024. The needle indicates the single coast-wide score and categorization.

Here, we present a methodology to translate spatially and temporally dense kelp data into such a report card framework, with status reported on the gauge as a single value and supported by an assessment of trends. We (1) evaluate which data sets are best suited for the application, (2) determine the appropriate scale at which to spatially segment kelp along the coastline for assessment, (3) identify which kelp status and trend metrics are robust yet sensitive from year-to-year, and (4) provide a routine for integrating segments into single values, one for status and one for trend. The geographic extent for this demonstration is California's mainland and Channel Islands, Oregon's coastline, and Washington's outer coast and western Strait of Juan de Fuca. Since there is multilevel governance across the U.S. West Coast, the methodology presented here can be performed across any number of segments. We discuss the key decisions that went into populating the Kelp Indicator and compare this approach to other kelp assessment programs.

2. METHODS

The metrics to develop the Kelp Indicator are based on two remote surveys (satellite and aerial) that measure the extent of emergent kelp canopy on the ocean surface, so it captures giant kelp and bull kelp. Subcanopy, intertidal, and understory kelp species are not assessed. From the U.S.-Mexico border northward through Oregon, we relied on the Santa Barbara Coastal Long-term Ecological Research (SBC LTER) project's kelp canopy dynamics data set derived from Landsat imagery.[8] This data set provides quarterly (3 month) estimates of kelp canopy area from 30 m resolution Landsat imagery from 1984 to present. Pixels containing kelp canopy are identified using a random forest classifier from band-normalized, atmospherically corrected imagery, with intertidal pixels masked, from Landsat 5 Thematic Mapper, Landsat 7 Enhanced Thematic Mapper +, Landsat 8 Operational Land Imager, and Landsat 9 Operational Land Imager 2.[9] The second remote survey we relied on was Washington's aerial overflights.[10] Aerial imagery was collected from a fixed-wing plane annually between 1989 and 2024 during the climatological peak kelp canopy (between August and October). Surveys were conducted during the first available survey window with optimal weather, tide, and sun-angle conditions and always before the first Fall storms. Survey photographs were collected during an initial flight at 7500′ MSL. Additional low-altitude observation flights (2000′ MSL) were conducted for identification and documentation of individual kelp canopy species composition.[11] Baseline maps were used for kelp canopy area mapping, kelp species determination, and kelp bed area mapping (for more information on mapping methods, see ref 11).

The spatial units of assessment for kelp canopy coverage were semiregularly spaced coastal segments approximately 10 km in length. Coastlines included California's mainland and Channel Islands, Oregon's mainland, Washington's Olympic coast, and Washington's western Strait of Juan de Fuca. Coastal segments were adopted from pre-existing coastal polygons developed for canopy kelp monitoring (Washington; see ref 10) or de novo for this assessment. For all segments, boundaries began at the coastline and encompassed state waters, which also encompass kelp habitat. Most coastal segments were 10 km in length along the coastline, but with minor manual adjustments made to alongshore boundaries based on coastal geomorphology or to ensure the cores of kelp forests were not split among segments (full range in segment length was 4 and 20 km). A supporting web map visualizes the overlay of the coastal segments with kelp canopy (https://bit.ly/KelpIndicatorMap).

Coastal segments were categorized as either "No Historical Kelp", "Ephemeral Kelp", or "Contains Kelp". Segments with less than 10 pixels detected across the full data set, or <0.02% of its area, with kelp-containing pixels were categorized as having "No Historical Kelp". These also included areas known to be devoid of kelp, e.g., sandy beaches. Segments with either <0.15% of its area with kelp-containing pixels or where kelp is inconsistently present (specifically, canopy present in less than half the years of available observations) were categorized as having "Ephemeral Kelp"; otherwise, the segment was categorized as "Contains Kelp".

For the quarterly Landsat data set, we take the sum of kelp-containing pixels within each segment and convert to total canopy area by multiplying this sum by the size of an individual pixel (900 m^2). Because giant kelp and bull kelp vary in timing and magnitude of seasonality, we then take the maximum quarter of coverage for each year for each segment. The result is an annual time series of kelp canopy area since 1984 per coastal segment (see term C in eq 1). For the Washington aerial overflight data, we use the annual observations of the kelp canopy area that are captured during the climatological peak in late Summer. The segment-level time series spans 1989 to present (except for 1993). Both data sets expressed total kelp canopy coverage within each applicable coastal segment in km^2.

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2.1. Status Calculation. Kelp status was assessed by evaluating the most recent year of kelp canopy coverage relative to the reference period. The calculation was made in one of two ways for comparison. The first evaluated the current year's coverage as a percentile of the distribution of canopy coverage from a reference period (values range from 0−100). The second calculated the current year's coverage as a percentage of the median coverage from a reference period, where values less than 100% are when kelp canopy coverage is less than the reference coverage and values greater than 100% are more than the reference coverage (eq 1).

$$S_{i,T} = \frac{C_{i,T}}{\text{med}(C_{i,T\text{ref}})} \times 100 \quad (1)$$

Status, S, of segment i in year T was assessed as the annual canopy coverage, C, for that segment relative to reference coverage (eq 1). Reference coverage, $C_{i,T\text{ref}}$, was the canopy coverage for all years for which data were available prior to 2014, which demarcated the onset of the 2014−2015 marine heat wave. The median, med, was used given that many of the segment-level time series are non-normally distributed.

To obtain a single coast-wide value of status, we applied a segment-level scoring rubric. Each segment received an integer score between −2 and 2 based on $C_{i,T}$ relative to $C_{i,T\text{ref}}$ (as shown in Figure 2). The coast-wide status was calculated as the average of all of the segment-level scores and assigned a gauge position and category based on the translation in Table 1. This scoring rubric was developed by the broader report card framework to be used across multiple indicators so that gauge outcomes could be compared. However, we also evaluated other possibilities to translate the $S_{i,T}$ data to the gauge framework to test the sensitivity of the outcome to the coast-wide integration methodology. These were primarily statistical metrics and included (1) the percentage of coast-wide kelp segments above their reference coverage, (2) median status, S, of all kelp-containing segments, and (3) the gamma distribution shape parameter from eCDF curves using maximum likelihood estimation. We found that this last metric, the shape parameter, captured the extent of segments with very low S scores among years. Further description of these metrics and other metrics considered are provided in the Supporting Information. For these statistical metrics, the current year was compared to the reference period and was used to determine the position of the needle on the gauge. Each metric was standardized by transforming from its underlying distribution to a 0 to 100 scale, assuming normality. The five categories of the gauge were overlaid on this distribution based on the first and second standard deviations of the metric data. Meeting Expectation fell within the first standard deviation, Above and Below Expectation were between the first and second deviation, and Far Above and Far Below Expectation were beyond the second deviation of the metric data. This translation for each metric is shown in Figure 3C,D.

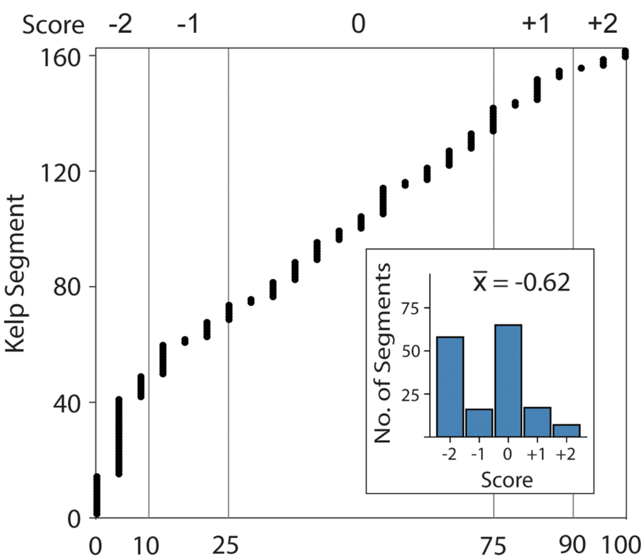

Figure 2. Segment-level kelp canopy coverage as a percentile of the distribution of the reference canopy coverage. Black points represent individual kelp-containing segments that have been numerically sorted. Inset shows the total number of kelp segments that fall within each percentile range and the corresponding score applied to that segment. The coast-wide score ($\bar{x}$) is calculated as the mean of all scores.

Table 1. Translation of the Coast-Wide Score to the Gauge Categories

average score	grade
less than −1.5	far below
between −1.5 and −0.5	below
between −0.5 and +0.5	meeting
between +0.5 and +1.5	above
greater than +1.5	far above

We also looked at the status of the kelp canopy area over the recent five years compared to the reference period. Recent 5 year status was calculated on a segment-level as the median kelp canopy area from the recent 5 years relative to the reference period defined in eq 1. A nonparametric median test was employed to test if the medians from these two time periods were different ($\alpha = 0.05$). This metric was not used in the construction of the status gauge, as the status is meant to reflect the most recent year of available data. This metric was used to support interpretation for how the current year status compares with recent years.

2.2. Trend Calculation. We evaluated recent changes in kelp canopy coverage, focusing on changes over the most recent five year period. We did not employ linear-model fitting or model fitting more generally, given shortcomings of limited sample size. Rather, we evaluated whether the cumulative year-on-year changes were positive or negative. To do this, we calculated the cumulative annual change in absolute coverage over the last five years and normalized that to the cumulative canopy coverage over the same period (eq 2).

$$\delta_i = \frac{\sum_{t=T-5}^{T} (C_{i,t} - C_{i,t-1})}{\sum_{s=T-5}^{T} C_{i,t}} \quad (2)$$

where T is the latest year and $C_{i,t}$ is the absolute canopy coverage at year t for segment i. δ_i is then the segment-level five year cumulative change normalized to the cumulative canopy area over those five years. To derive a coast-wide estimate of 5 year changes, we took the weighted average from the segment-level values, using the 5 year cumulative canopy coverages per segment as weights. We then derived a 95% confidence interval

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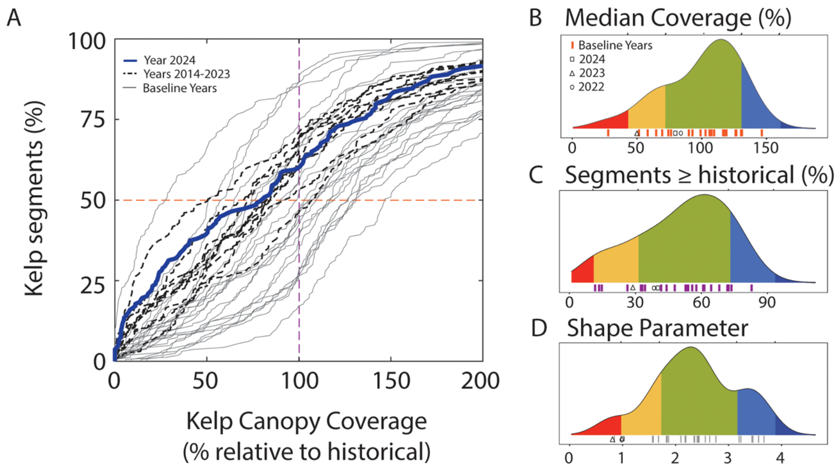

Figure 3. (A) Empirical cumulative distribution function of kelp canopy coverage for all kelp-containing segments. All years in the reference period shown in light gray; 2024 shown as a bold blue line and other recent years shown as black dashed lines. The horizontal reference line (orange) indicates the median kelp canopy coverage; the vertical reference line (purple) indicates the percentage of kelp-containing segments that are at, or below, their median historical coverage. (B−D) Kernel density estimation of three metrics derived from eCDFs during the reference period. Data from the baseline years shown just above the *x*-axes, values for 2022, 2023, and 2024 also indicated. The kernel density is colored according to the gauge categories: Far Below (red), Below (yellow), Meeting (green), Above (blue), and Far Above (dark blue) Expectation. Median coverage (% relative to historical) corresponds to the orange reference line in (a). Percent of kelp-containing segments above their historical coverage corresponds to the purple reference line in (a). The shape parameter is estimated from the gamma distribution of the eCDF.

around the coast-wide estimate through bootstrap resampling. If the distribution of all δ_i was not different from zero, i.e., zero was contained in the confidence interval, then the recent change was categorized as no trend. Otherwise, if the average coast-wide value was positive, or negative, it was categorized as increasing or decreasing, respectively. Cumulative 5 year changes were also calculated with eq 2 across the full time series of the segment-level data sets to confirm the typical range of coast-wide changes over the decades.

We also calculated long-term trends using the full extent of the data sets for each coastal segment by applying a linear fit to the annual time series of status, S (eq 1). Linear trends were assessed as significant if the slope was significantly different than zero (alpha level is 0.05). Segments with positive or negative slopes were categorized as undergoing long-term increase or decrease, respectively. We also tested the sensitivity of the trend outcome when using a simple linear regression model versus using an autoregressive integrated moving average statistical model to account for temporal autocorrelation (Supporting Information). Outcomes between the two were consistent, and results for the simple linear regression model are shown here.

To integrate all segment-level trends in the canopy area to a coast-wide estimate, the average coast-wide long-term linear regression slope of all kelp-containing segments was estimated with a 95% confidence interval using the following equations.

$$\overline{\beta} = \frac{1}{\sum_{j=1}^{n} m_j} \sum_{i=1}^{n} \beta_i m_i \tag{3}$$

$$\sigma^2 = \frac{1}{(\sum_{j=1}^{n} m_j)^2} \sum_{i=1}^{n} \text{s. e. } (\beta_i)^2 m_i^2 \tag{4}$$

where n is the number of kelp-containing segments, m_i is each segment's historical median canopy area, and β_i and s.e. (β_i) are the calculated slope values and their associated standard errors for each kelp-containing segment, respectively. $\overline{\beta}$ is then the point estimate for our coast-wide trend, and a 95% confidence interval around $\overline{\beta}$ was generated. When the confidence interval contained zero, we concluded there was not enough evidence to distinguish $\overline{\beta}$ from zero and consequently no long-term trend in the coast-wide kelp area. The long-term trend was not used in the construction of the trends assessment but was used to provide a greater historical context for the interpretation of recent changes.

Analytical methods to reproduce the Kelp Indicator are available as open-source code at https://github.com/SCCWRP/KelpAreaIndicator. Despite the demonstration of this indicator to floating kelps along the U.S. West Coast, the code can be modified to rely on other data sources along with a user-provided shapefile of coastal segments. A web map showing segment-level time series along with status and trends metrics is available through the West Coast Ocean Data Portal at https://bit.ly/KelpIndicatorMap.

3. RESULTS

The coastline segmentation procedure produced a total of 311 segments that were assessed for the presence of the canopy. In total, 163 of those were identified as containing kelp, 15 as having ephemeral kelp, and 114 as having no kelp. Table 2 shows the number of segments by geographic region that fall within these three categories.

3.1. Status. Coast-wide kelp canopy status for the year 2024 was assessed as below the reference condition (Figure 1). The coast-wide score was calculated as −0.62 (Figure 2), and the position of the needle was in the below expectation category following the scheme in Table 1. This outcome was primarily driven by the relatively large percentage of kelp-containing segments, 35%, with kelp canopy coverage at 10% or less of its reference distribution (Figure 2). Overall, 2024 was an improvement from 2023, which was among the worst years on record since 1989 (outcome for 2023 was −0.82).

The coast-wide statistical metrics of kelp canopy coverage for 2024 also assessed kelp canopy coverage as less than the reference period (Figure 3). The three metrics evaluated were (1) the coast-wide median of S, which was 80%; (2) the

Table 2. Number of Coastal Segments That Contain Kelp, Have Ephemeral Kelp, or Have No Historical Kelp by Region

	contains kelp	ephemeral kelp	no historical kelp
Washington[a]	40	0	24
Oregon	10	6	35
Northern California	15	4	30
Central California	30	1	14
Southern California	26	0	12
Channel Islands	42	3	1
total	163	15	114

[a]The Washington region includes the Olympic coast and Western Strait of Juan de Fuca, excluding greater Puget Sound.

percent of kelp segments above their historical median, which was 40%; (3) and the shape parameter, which was 0.98. When translated to the gauge using the 0 to 100 scaling, these metrics were 37, 39, and 17, respectively, resulting in a categorization of meeting expectation for the first two and below expectation for the latter two (Figure S6).

While the overall coast-wide status of 2024 kelp was below the historical baseline, there was a broad range of kelp canopy coverage; values ranged from 0−791% relative to reference baseline, and broad geographic patterns were apparent (Figure 4). Kelp canopy cover along Washington's Olympic coast and western Strait of Juan de Fuca was on par with the reference baseline, at 107%, while kelp canopies along the rest of the U.S. West Coast were less than their reference baselines. In Oregon, kelp canopies were at 38% of their reference baseline. Northern, central, and southern California were at 4%, 47%, and 36%, respectively. Likewise, the Channel Islands off southern California were at 84%. Across the coast, there were 22 segments with essentially no kelp canopy cover, which we considered as less than 5% relative to the reference.

Average coast-wide kelp canopy coverage in 2024 (80%; coverage relative to the historical median) was slightly better than the recent 5 year coast-wide median (66%; Figure 4). The 5 year medians for 31% of the 163 segments were significantly less than the median of their historical period. And of those, 13 had less than 5% of historical. Most of these kelp-containing segments that had essentially no remaining kelp canopy were in northern California.

3.2. Trends. The coast-wide recent 5 year cumulative change was −1% but was not significantly different from zero (95% CI; [−3% 2%]; Figure 5). On the other hand, the coast-wide historical linear trend was decreasing (−0.27 ± 0.09% yr^{-1}; Figure 5).

Among segments, the recent 5 year cumulative change (ending with 2024) varied from −50% to +30% with a strong geographic pattern (Figure 5). In Washington's Olympic Peninsula and western Strait of Juan de Fuca, the average among segments was near zero, indicating recent stability. All but three of the Oregon kelp segments had 5 year losses, with an overall average of −1%. The northern California kelp segments were more varied, as nine segments had recent

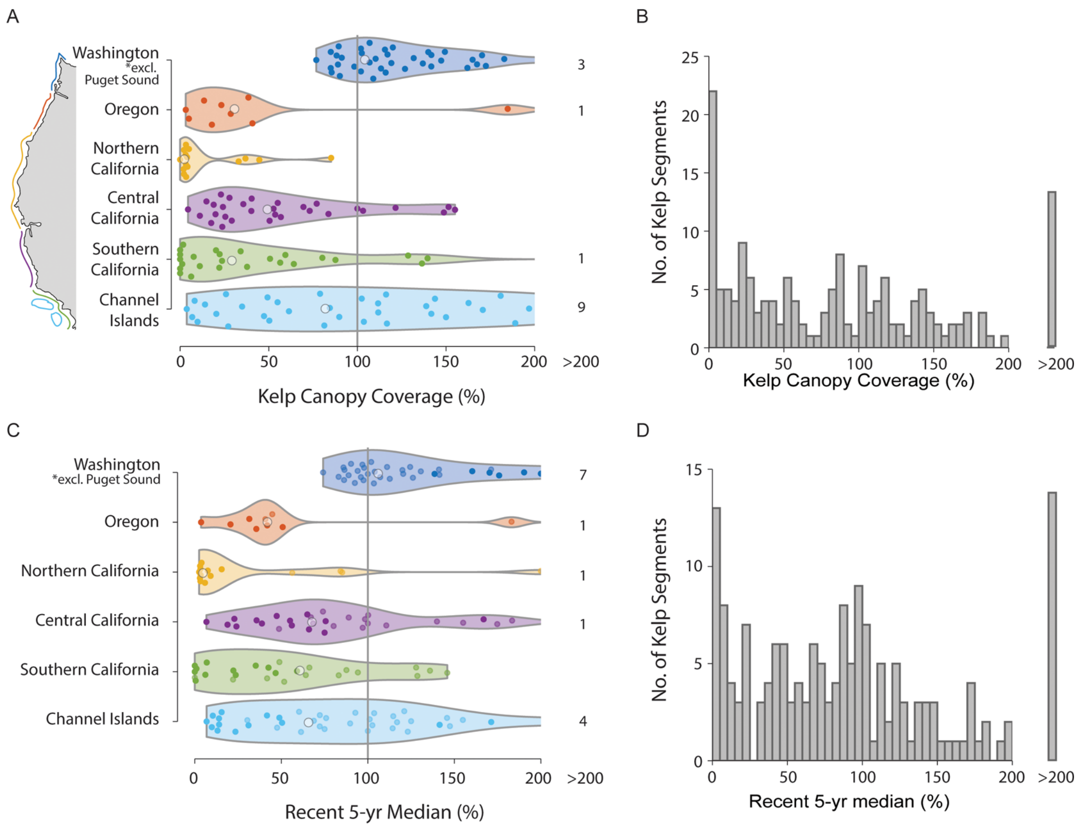

Figure 4. (A) Segment-level kelp canopy status (*S*) for 2024 by geographic region. Individual points represent the percentage of kelp canopy coverage relative to the median of the historical period for individual segments and average for a region indicated (transparent white circle). Shaded region is a violin plot inclusive of all segments. (B) Histogram of segment-level *S*. (C,D) Same as (A,B) but shown for the most recent 5 year median relative to the reference period. For (A,C), *x*-axes are limited to values between 0 and 200% and the number of segments with status beyond 200% are indicated to the right of the *x*-axis.

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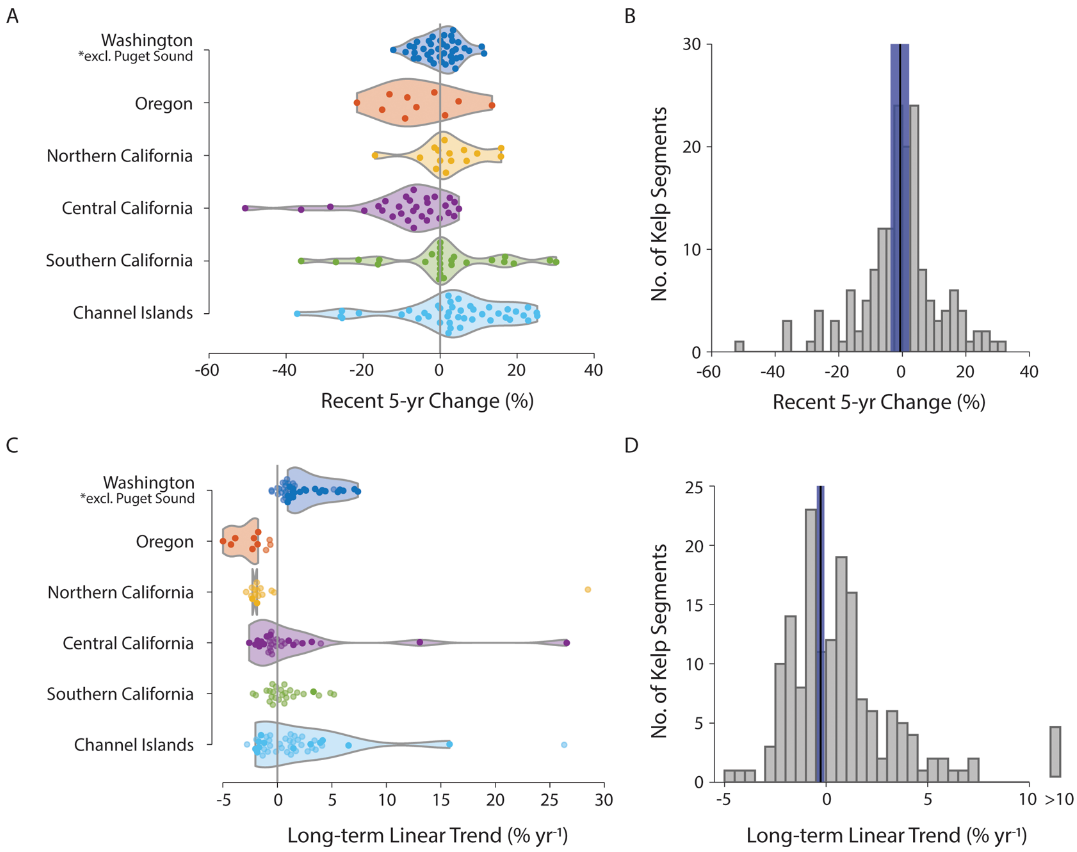

Figure 5. (A) Segment-level recent 5 year change (%) by geographic region (for years 2019–2024). Individual points represent the cumulative five year change as a percentage of the kelp canopy coverage. Shaded region is a violin plot inclusive of all segments. (B) Histogram of the segment-level 5 year change and the coast-wide average as a black line with 95% CI shaded in blue. (C) Segment-level trends by geographic region. Individual points represent slopes, as percent change in kelp canopy coverage per year, of the long-term linear fit to the historical data. Significant slopes ($p \leq 0.05$) indicated with bold circles. Shaded region is a violin plot inclusive of the segments with significant slopes to depict the distribution of the segments with significant changes. (D) Histogram of the segment-level slopes and the coast-wide slope as a black line with 95% CI shaded in blue.

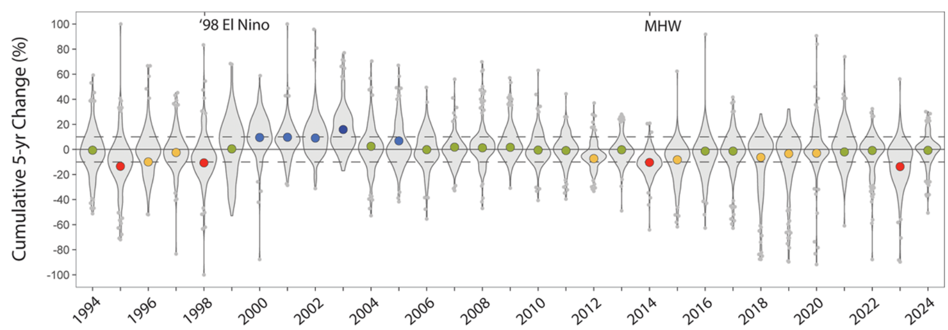

Figure 6. Cumulative 5 year changes (eq 2) for individual kelp-containing segments (violin plots with outliers indicated as circles) across the time series. Year on the x-axis represents the final year of the calculation (e.g., 1994 is the cumulative 5 year change from 1989 to 1994 and henceforth). Dashed reference lines for 10 and −10% change included. Green-filled averages indicate years where coast-wide 5 year changes were no different than zero. Yellow and blue-filled averages indicate decreasing and increasing 5 year changes, respectively. Red and dark, blue-filled averages indicate years when those changes exceeded −10 and +10%, respectively. Significant climatic events resulting in kelp losses indicated; MHW is marine heat wave.

increases, and five segments had recent losses with an overall average of 1%. All but six segments in central California had recent losses with a regional average change of −6%, while southern California and the Channel Islands off southern California had a more varied response, with averages of −7% and +8%, respectively.

In 2023, the 5 year change metric was much worse at −14% (95% CI; [−11%, −16%]; Figure 5). The only other years on record that exceeded −10% included 1995, 1998, and 2014 (Figure 6). After the 5 year cumulative changes ending in 1998, there was a return to coast-wide increases within just one year, and changes exceeded +10% within two years, indicating quick recovery. This contrasts with the declines that began in 2014 where kelp changes through the lens of this 5 year change metric did not become positive for another six years. Further, continued losses after 2014 resulted in 5 year change metrics that remained negative coast-wide for eight of the next 11 years (2014–2024).

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The majority (66%) of kelp-containing segments exhibited no long-term linear change (Figure 5). Long-term linear declines were detected in 23 of the kelp-containing segments. They were mostly geographically scattered, except for some groups of losses in Oregon and central California. The seven declining segments in Oregon were on the scale of 2−5% per year. The eight declining segments in central California were between 1 and 3% per year. In contrast, there were 33 kelp-containing segments that had long-term linear increases. Over half of those, 20, were along Washington's Olympic coast and western Strait of Juan de Fuca, with increases in kelp canopy cover ranging between 1% and 7.4% per year. There were no kelp segments in Oregon that exhibited a long-term linear increase. In central California, there were three segments near Santa Cruz exhibiting increases. Two of the segments had trends that exceed 10% per year and appear to be emergent over the past decade. In southern California, there were seven noncontiguous segments with increasing trends on the order of 1.5−16% per year.

4. DISCUSSION

The impetus for the Kelp Indicator presented here was that managers and policy makers need metrics that are simple and easy to interpret, and any individual indicator (like this one) has a common presentation with other ocean health indicators. Similarly, the Kelp Indicator needs to rely on robust local and regional data yet be summarized into a single value extending across broad geographic areas (Figure 1). There were several key decisions made in doing this. The first was which data sources to rely on, prioritizing temporal and spatial coverage. Remotely collected data streams were selected given the density of data relative to that of diver surveys. Kelp canopy cover is a widely recognized method to estimate and track kelp abundance with the caveat that this neglects understory kelps.[9,12] Diver surveys can capture understory kelps as well as ecosystem metrics. However, the limited spatial and temporal coverage of diver surveys limited their utility as an indicator that preferred long reference periods and broad geographic extent. Airborne observations are temporally and spatially limited relative to that of satellite observations but confer improved sensitivity associated with finer spatial resolution. For example, comparisons between airborne photogrammetry and satellite unsupervised classifications indicate sensitivity thresholds for satellite retrievals of *N. luetkeana* cover on the order of 10% intrapixel coverage, or 90 m^2 within a Landsat pixel.[14]

Among remotely sensed data types, there are multiple data streams available for either the full coast or a portion of the coast. For satellites, the Landsat program was preferred because it offers the longest historical perspective with many demonstrated validations and applications to kelp canopy coverage (examples include refs 9, 13−18). Landsat observations were used for California and Oregon due to the sparsity of applicable aerial observations.[8] We carried out additional comparative analyses in Oregon between Landsat and airborne kelp canopy observations to confirm our choice of using Landsat (Supporting Information). Briefly, validation assessments were conducted using matchups between satellite imagery and aerial flights in 2010 and 2022 for Oregon reefs, including Orford, Rogue, and Brookings. Overall, the findings indicated that the satellite and airborne methods shared applicability for the current purpose of coastal-segment-scale comparisons with historical reference points. Scenarios where in the satellite and aerial records produced varying performances were identified. Key differences likely included site-specific instances of overclassification of the aerial imagery and low sensitivity (underclassification) around small and fringing kelp beds in the satellite analysis. The results of the satellite and airborne comparisons for the Oregon matchups are presented in the Supporting Information. Washington fixed-wing aerial imagery supports time series observations extending back to 1989, which was applied to the Washington kelp canopy observations. This data set was preferred as it allowed us to align with existing kelp assessments for Washington State.[19] For other applications, Landsat observations of the Washington Olympic coast are also available and accessible via the LTER data set or Kelpwatch.org.[8,13]

Another key decision was to construct the indicator as a series of segment assessments rather than as a single cumulative number of kelp canopy coverage. This method is already in use for the Washington Floating Kelp Indicator, which employs different kelp bed area data streams.[19] This approach retains the flexibility to use the most appropriate data source for each segment if data have sufficient temporal history to establish a baseline. Further, because giant kelp generally forms larger emergent canopies than bull kelp, taking a cumulative value of the coast-wide cover would bias patterns to giant kelp and be primarily representative of regions with larger, continuous giant kelp forests, obscuring patterns in fringing coastal beds. Another advantage of segment-level assessments is that geographic information is retained so that spatial patterns can be explored. Retaining local-level information in parallel with a coast-wide gauge makes this tool more useful for policy makers across political scales, from local and regional, to state, tribal, and national governance. Already, the California Ocean Protection Council has adopted this kelp indicator for its first ever Coast and Ocean Report Card. The status of kelp is being evaluated relative to that of over a dozen other California-prioritized ocean metrics. In this case, the outcome intended is to help audiences understand the state of the ocean across a range of important issues and support decision-makers in broadly considering options when prioritizing areas for action.

We also had to confirm the robustness of the segment-level scoring rubric to obtain a coast-wide score. The scoring rubric was preferred by the report card framework, as it is amenable to comparing outcomes from multiple indicators assessed in a similar manner. We compared the outcome for the gauge when using the scoring rubric (Figure 2 and Table 1) versus that of statistical metrics (Figure S6). For all metrics, there was agreement that kelp canopy coverage in 2024 was below historical conditions. However, there was disagreement in the magnitude of that deviation, with two metrics categorizing kelp as Meeting Expectation and the other two metrics categorizing kelp as Below Expectation for 2024. This highlights the general challenge of spatially integrating data where underlying spatial patterns, like kelp canopy, are heterogeneous. While we have chosen one integration method here, we present outcomes for all to support interpretation.

This Kelp Indicator relies on the expression of the current annual status relative to a reference, which we chose to be a "historical" within the period of the available data streams (eq 1). The reference period was defined as all years for which kelp canopy coverage data are available prior to the 2014 onset of "The Blob" marine heat wave.[20] The Blob was a recent major disturbance event for most kelp forests along the U.S. West

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Coast[21−24] and is robustly detected by our indicator (Figure 6). We do find that the outcome of the indicator is sensitive to whether the baseline includes all years of available data (e.g., 1989−2023) versus the reference period chosen (Figure S7). Kelp coverage since 2014 has been generally lower than the time period before (as supported by the recent 5 year median shown in Figure 3C,D) and represents a shifting baseline in the inner quantile of kelp canopy coverage. We chose to restrict our reference period to all years prior to the marine heat wave after expert consensus on the ecological importance of this time period. We make the code to reproduce the indicator publicly available, including the selection of reference years (https://github.com/SCCWRP/KelpAreaIndicator).

Four decades of kelp canopy coverage is an invaluable resource that encapsulates the ups and downs of contemporary ocean-climate states (en sensu El Nino-Southern Oscillation and Pacific Decadal Oscillation), likely capturing the full range of natural patterns of kelp canopy variability for much of the coastline. Further, four decades of data improves our ability to detect the long-term declines facing global kelps.[1] However, we acknowledge this is a small window of kelp history, which has existed since the Eocene-Oligocene transition (34+ million years)[25] and have supported human populations for 16,000 years, probably longer.[26] Off Santa Cruz, California, there is evidence that a century ago kelp canopy existed at 12-fold its current extent.[27] This is also a region where our indicator is detecting recent increases (Figure 5), what we have termed emerging kelp canopy areas. Similarly, there is evidence that the current level of exceptionally low kelp canopy along the Monterey Coast happened before, ∼125 years ago.[27] In southern Puget Sound, Washington, kelp canopy has declined to about a third of its historical extent, with losses documented as early as the 1880s.[28] This area and other inland waters of Washington are not tracked by this Kelp Indicator but are assessed by the Washington Floating Kelp Indicator.[19] While this change metric uses current-level expectations, deeper baselines, when available, give an additional layer of context to improve interpretation.

Assessing changes in kelp cover over time also required several key decisions as well. The first being whether to focus on recent trends or ones over the ∼40 year extent of the available data sets. For long-term changes, we considered multiple statistical approaches including long-term linear trends (Figure 5) and others, like break-point analysis and temporal autoregressive models. While we present findings from long-term linear trends, some managers expressed greater interest in recent trends for which we examined the last five years. Because that is a small number of years, instead of using a linear trend analysis, we developed a year-on-year change metric (eq 2) that calculates a segment's 5 year cumulative change relative to its kelp coverage over that same period. This metric is sensitive to broad-scale climate forcings such as ENSO and PDO (Figure 6) while still being capable of detecting recoveries in response to management and restoration activities.

The outcome of the Kelp Indicator presented here largely aligns with other kelp assessments. Briefly, the Washington Floating Kelp Indicator also assesses kelp canopies to be stable over recent years along Washington's Olympic coast and western Strait of Juan de Fuca.[10] The Oregon Kelp Alliance, using primarily drone-based surveys, has reported substantial losses in kelp in Oregon, aligning with our outcomes of continued low canopy coverage for many years now.[29] In southern California, the Region Nine Kelp Survey Consortium, using aerial overflights, assessed kelp most recently for 2023 and also reported some of the lowest kelp canopy coverage among all years assessed dating back to 1967.[30] Also, region-by-region the Kelpwatch report card for 2024, which relies on the same data stream used here but differing analytical methodology, assessed similar kelp status values as we have here (Figure 4).[31] Despite differences that exist in data streams, analytical methodologies, metrics, or otherwise, used by each of these programs, the programs are reporting similar outcomes, and the high-level messages are consistent.

The construction of this indicator considered the prescribed framework of an ocean health report card being adopted among state, tribal, and federal regional partnerships along the U.S. West Coast through the West Coast Ocean Alliance. It provides a final integration and categorization to communicate kelp status and trends to a nontechnical audience how kelp is doing and how it has been changing. When assessed vis-à-vis a suite of ocean health indicators, report cards can be used as a tool to inform resource management, improve policy, and prioritize scientific research and monitoring.

■ ASSOCIATED CONTENT

Data Availability Statement

An R package to produce the Kelp Indicator is available at https://github.com/SCCWRP/KelpAreaIndicator.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.5c07501.

Supplemental methods, tables, figures, and results for the evaluation of statistical metrics to support the Kelp Indicator, sensitivity analysis for long-term trend analysis methods, and satellite and airborne comparisons for detection of kelp canopies in Oregon (PDF)

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Notes

The authors declare no competing financial interest.

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