# Impact of the 2011 Fukushima Disaster on Plankton Health

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## Abstract

This study investigates the impact of the 2011 Fukushima Daiichi nuclear disaster on marine plankton health, with a specific focus on changes in chlorophyll concentration as a proxy for phytoplankton vitality. Utilising a comprehensive dataset spanning from 1988 to 2018, sourced from the COPEPODITE database and supplemented by data from the Fukushima World Meteorological Organisation (WMO) Station, the pre- and post-disaster chlorophyll levels near the disaster zone was examined. Employing the FBProphet forecasting tool, a series of analyses was conducted, including forecasting chlorophyll levels absent the disaster, residual analysis, and changepoint detection, to discern the ecological ramifications of the disaster on chlorophyll trends. Results revealed an unexpected rise in chlorophyll levels immediately following the disaster, possibly due to the biochemical influence of released caesium, which shares chemical properties with potassium, a crucial nutrient for plankton. Subsequent analyses revealed a gradual decline in chlorophyll levels, contrary to the anticipated immediate sharp drop, suggesting a complex interplay between radioactive contamination and plankton health. Comparative analysis with other nuclear incidents and the phenomenon of radioactive leaching into the ocean were explored to further understand the observed trends. The study concludes that the impact of the Fukushima disaster on plankton health is more gradual than expected but with an unclear endpoint, raising important questions about the long-term ecological consequences of nuclear contamination. Recommendations for global plankton data collection and further research underscore the need for a sustained, data-driven approach to assessing the effects of environmental disasters on marine ecosystems.

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# Introduction

## The Critical Role of Plankton in Global Ecosystems

The word "plankton" comes from the Greek for "drifter" or "wanderer." An organism is considered plankton[1] if it is carried by tides and currents, and cannot swim well enough to move against these forces. Plankton are usually microscopic, often less than one inch in length, but they also include larger species like some crustaceans and jellyfish. The most basic classification divides plankton into two groups: phytoplankton (plants) and zooplankton (animals). Phytoplankton are the foundation of the aquatic food web[2], the primary producers, feeding everything from microscopic zooplankton to multi-ton whales. Through photosynthesis, they are also essential contributors to oxygen production and carbon sequestration, significantly influencing the global carbon cycle. In addition, they are the unsung sentinels of our seas; their health is a mirror reflecting the vitality of marine ecosystems. This study will focus on phytoplankton, using chlorophyll levels as the primary measure of their health and abundance; 'plankton' shall generally mean 'phytoplankton' unless stated, or contextually indicated, otherwise.

## Data Science and Oceanic Health

Due to the importance of plankton in both the global food chain and global climate, unsurprisingly, data scientists are keen to study them. A paucity of data and lack of standardisation in sampling and analytical methods appear to be key issues. Newer technologies offer opportunities to meet the need for high resolution and continuous plankton data. Narrow photo chambers, thin tubing connected to dosage pumps, combined with image recognition algorithms and DNA-based techniques increasingly offer automatic sample collection and analysis to be combined and speeded up[3]. Working within the frameworks of European research infrastructures such as LifeWatch and the European Marine Biodiversity Resource Centre (EMBRC), the Flanders Marine Institute (VLIZ) has employed such newer technology to initiate a long-term plankton time series in Belgian coastal waters and sand bank systems.

## The Fukushima Disaster

On March 11, 2011, the Fukushima Daiichi nuclear power plant suffered catastrophic damage following a massive earthquake and subsequent tsunami, leading to one of the most severe nuclear accidents in history. The disaster resulted in the release of significant amounts of radioactive materials into the surrounding environment, including the Pacific Ocean. This event raised global concerns about the potential impact of radioactive contamination on marine life, particularly on the intricate ecosystems within the ocean.

## Objective and Scope of this Study

Given the limitations of data availability and time, the objective of this study is to gain an understanding of the impact of the 2011 Fukushima disaster on the health of nearby ocean plankton

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[1] https://oceanservice.noaa.gov/facts/plankton.html

[2] https://earthobservatory.nasa.gov/features/Phytoplankton#:~:text=Importance%20of%20phytoplankton,-By%20Rebecca%20Lindsey&text=Phytoplankton%20are%20the%20foundation%20of,are%20eaten%20by%20bigger%20ones

[3] Exploring New Technologies for Plankton Observations and Monitoring of Ocean Health | Oceanography (tos.org)

populations. Focusing on changes in chlorophyll levels, this study seeks to ascertain whether the radioactive contamination resulting from the disaster has led to significant alterations in nearby plankton health and, if so, to what extent these effects persist. The analysis uses data spanning from 1988 to 2018, obtained from the COPEPODITE database at the geographic point close to the Fukushima Daiichi plant (Longitude 141.1, Latitude 37.3) and the Fukushima World Meteorological Organisation (WMO) Station. This period encompasses data from before and after the disaster, providing a comprehensive timeline to observe potential impacts and changes in the marine ecosystem near the Fukushima Daiichi nuclear power plant.

# Literature Review

## Impact of Nuclear Disasters on Marine Life, with a Focus on Plankton

The inadvertent introduction of radioactive materials into oceanic realms consequent to nuclear disasters has raised alarms regarding the wellbeing of marine life, most notably plankton. Post-Fukushima inquiries have shed light on the severity of such incidents. Buesseler and colleagues illuminated the intricate web of distribution and bioaccumulation of radioactive caesium within the marine food chain, bringing to the fore the potential for enduring ecological repercussions[4]. Complementing this, Aoyama et al. utilised cesium-137 as a tracer, uncovering patterns of movement and dilution of the contaminant, which is crucial to discerning the pollution's range impacting plankton[5].

## Chlorophyll Concentration as an Indicator of Plankton Biomass and Health

Chlorophyll-a concentration has long stood as a reliable measure of phytoplankton biomass and a proxy for the health of these microorganisms. Behrenfeld et al. delineated the significance of chlorophyll metrics in gauging global oceanic primary production, thus underscoring the pivotal role phytoplankton play in the grand cycles of carbon and the sustenance of marine food webs[6]. It is this fundamental correlation that renders chlorophyll a salient indicator for examining fluctuations within plankton populations and broader ecosystem productivity.

## Environmental Factors Influencing Plankton Health

A myriad of environmental factors interplay to influence plankton dynamics, of which sea surface temperature and salinity are paramount. Polovina et al. dissected the influence of sea surface temperature anomalies on phytoplankton, correlating climate variations with shifts in marine productivity[7]. In a similar vein, Sunda and Huntsman delved into the interplay between salinity,

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[4] Buesseler, K., Aoyama, M., & Fukasawa, M. (2012). "Impacts of the Fukushima nuclear power plants on marine radioactivity." Environmental Science & Technology, 45(23), 9931-9935.

[5] Aoyama, M., Uematsu, M., Tsumune, D., & Hamajima, Y. (2016). "Surface pathway of radioactive plume of TEPCO Fukushima NPP1 released ^134Cs and ^137Cs." Biogeosciences, 13(3), 1955-1965.

[6] Behrenfeld, M. J., O'Malley, R. T., Siegel, D. A., McClain, C. R., Sarmiento, J. L., Feldman, G. C., ... & Boss, E. S. (2005). "Climate-driven trends in contemporary ocean productivity." Nature, 444(7120), 752-755.

[7] Polovina, J. J., Howell, E. A., & Abecassis, M. (2008). "Ocean's least productive waters are expanding." Geophysical Research Letters, 35(3).

nutrient accessibility, and phytoplankton distribution, further emphasising the community's susceptibility to environmental alterations[8].

# Methodology

## Data Set Description and Rationale

This study utilises an extensive dataset spanning from 1988 to 2018 to assess the impact of the 2011 Fukushima disaster on plankton health, as indicated by chlorophyll concentration changes. Data were sourced from the COPEPODITE[9] database, focusing on a geographical point within the radioactive contamination zone near the Fukushima Daiichi Nuclear Power Plant (Longitude 141.1, Latitude 37.3). This location was selected to directly assess the environmental impact of the Fukushima disaster on marine life. Additionally, data from the Fukushima World Meteorological Organisation (WMO) Station[10] were incorporated to account for local atmospheric conditions that may influence marine environments.

The analysis period starts from 1988, predating the disaster by over two decades, to establish a robust baseline of environmental conditions and plankton health. The endpoint of 2018 was chosen based on the availability and reliability of the data. The OCCCI satellite chlorophyll time series v5.0 informs the selection of this period, ensuring consistency in chlorophyll concentration measurements. The use of data up to 2018 is critical for assessing both the immediate and prolonged effects of the Fukushima incident on marine ecosystems.

## Variables for Analysis

The study examines several environmental variables expected to influence chlorophyll concentration and, by extension, plankton health:

- **Sea Surface Temperature (SST):** Derived from the HadISST sea surface temperature time series. SST is a primary driver of phytoplankton growth and seasonal cycles in marine ecosystems.
- **Salinity:** Sourced from the Hadley EN4 salinity time-series. Salinity affects water density and buoyancy, influencing nutrient mixing and availability for phytoplankton.
- Additional variables from the Fukushima WMO Station include **monthly total precipitation**, **monthly mean daily maximum and minimum temperatures**, **monthly total sunshine duration**, **monthly mean relative humidity**, and **monthly mean global solar radiation**. These factors provide a comprehensive view of the local climate's influence on marine conditions.

## Initial Model- Training and Variable Selection

The mathematical model was initially trained using data from the period 1998-2007, with a subsequent test phase covering 2007-2011. This approach was designed to evaluate the statistical significance of various environmental variables in modelling chlorophyll concentration. Initial results

[8] Sunda, W. G., & Huntsman, S. A. (1995). "Iron uptake and growth limitation in oceanic and coastal phytoplankton." Marine Chemistry, 50(1-4), 189-206.
[9] COPEPODITE database, https://www.st.nmfs.noaa.gov/copepod/toolkit/
[10] Fukushima WMO Station data, https://www.data.jma.go.jp/obd/stats/etrn/view/monthly_s3_en.php?block_no=47595&view=1

indicated that maximum and minimum temperatures did not significantly impact the model, prompting a re-evaluation of these variables' roles.

## Adjusting Variables for Plankton Survivability

To refine the model, valuable insights were gained from established research on the ecological and physiological needs of plankton. Thomas et al. (2012)[11] outlined the optimal temperature ranges for plankton growth and survival, demonstrating that marine plankton communities exhibited optimal growth within a temperature window of 10°C to 28°C. Armed with this knowledge, the model's temperature variables were recalibrated to more accurately reflect the ecological stress exerted on plankton by temperatures outside their optimal tolerance range.

New variables were thus defined: if the observed maximum temperature exceeded 28°C (the upper threshold of plankton's survivable temperature), the variable was computed as $\max\,[0, (\text{maximum recorded temperature} - 28)]$. Conversely, when the observed minimum temperature fell below 10°C (the lower survivable threshold), the variable was calculated as $\min\,[0, (\text{minimum recorded temperature} - 10)]$. These adjustments were intended to quantify the ecological stress on plankton due to temperature extremes, providing a more nuanced understanding of environmental impacts on chlorophyll concentration.

Post-adjustment, the model demonstrated a marked improvement in explanatory power, as evidenced by an $R^2$ value of 0.63. This indicates that 63% of the variance in chlorophyll concentration could be accounted for by the model. Given the complexity of marine ecosystems and the myriad of unaccounted variables potentially influencing plankton health, this $R^2$ value signifies a substantial explanatory capacity within the context of our focused environmental variables.

## Seasonality Model

The final models employed FBProphet, a forecasting tool developed by Facebook for time series analysis that excels in handling seasonality, trends, and holidays. FBProphet was chosen for its robust handling of non-linear trends and its ability to incorporate seasonality over a one-year period, aligning with the cyclical nature of marine biological processes. A pivotal feature of FBProphet for this analysis was its facility of changepoints to reflect shifts in data generating processes, such as the 2011 Fukushima disaster, allowing for a nuanced examination of its impacts.

Comparative analysis of SARIMAX, Generalised Additive Models (GAMs), and other seasonality models highlighted FBProphet's simplicity and superior performance in accommodating irregular observational intervals and predicting based on seasonality and specified changepoints.

## Final Model- Application and Analysis

### Initial Configuration

The foundational phase of the analysis involved configuring the FBProphet model with data spanning from 1998 to 2011[12]. This initial iteration focused on aligning the model with the cyclical nature of

[11] Thomas, M. K., Kremer, C. T., Klausmeier, C. A., & Litchman, E. (2012). A global pattern of thermal adaptation in marine phytoplankton. Science, 338(6110), 1085-1088.

[12] March 2011, before impact of the Fukushima disaster is discerned

seasonal patterns and fine-tuning the selection of environmental variables. Restricting the training set to pre-disaster data allowed capture of the inherent seasonality in chlorophyll levels without the confounding effects of the Fukushima event.

### *Selection and Treatment of Variables*

The initial phase of the analysis evaluated a comprehensive set of 10 environmental variables, including Temperature, Salinity, Windspeed, Precipitation, New Max Temperature, New Min Temperature, Sunshine Duration, Humidity, Solar Radiation, and Vapor Pressure. The selection process for incorporating variables into the final model was rigorous, relying on stepwise regression to identify variables with a statistical significance at the 10% level. This method ensured that only variables with a demonstrable impact on chlorophyll concentration fluctuations were chosen, resulting in a refined set of four key variables:

- **Temperature**: Incorporated additively to account for its baseline effect on plankton growth rates.

- **Salinity**: Also fit additively, reflecting its role in influencing water density and, consequently, the distribution of nutrients and plankton.

- **New_Max_Temp** and **New_Min_Temp**: Fit multiplicatively to capture the potential stress exerted on plankton populations when temperature values deviate beyond the survivable range. The rationale behind the multiplicative fit lies in the nonlinear impact of temperature extremes on plankton health, with effects potentially amplifying under severe deviations from optimal conditions.

From the original assortment of variables, this meticulous selection process distilled the list down to four essential factors that the model utilised to predict chlorophyll concentrations. This disciplined approach ensured that the model focused on the most impactful environmental drivers of chlorophyll variability, optimising its predictive accuracy and relevance to the study objectives.

## Final Model- Forecasting

In the second iteration of the analysis, the FBProphet model was calibrated using the historical data spanning from 1998 to 2011 to forecast chlorophyll levels through to the year 2018. This projection window was deliberately chosen, balancing the breadth of historical data against the forecast horizon. With approximately thirteen years of training data, extending predictions seven years into the future strikes a considered balance, especially given the model's $R^2$ value of 0.63. This value, while indicative of a model with substantial explanatory power, also cautions against overextending predictions due to the increasing uncertainty in longer-term forecasts.

For this forecasting phase, the model harnessed recorded meteorological data to estimate expected chlorophyll concentrations. This process was pivotal in defining a counterfactual scenario—a projection of plankton health trajectories in a world undisturbed by the disaster. Such a counterfactual provides a crucial benchmark against which to measure the actual post-disaster chlorophyll trends, allowing for a clearer attribution of observed deviations to the impact of the Fukushima disaster.

## Final Model- Changepoint Analysis for Disaster Impact

In the third iteration of the analysis, the FBProphet model's capacity for automatic changepoint detection was employed to examine if the Fukushima disaster had an impact on chlorophyll concentration trends. To ensure objectivity and minimise bias, the model was configured to autonomously determine changepoints without manual intervention. This approach ensured that the model's identification of shifts in the data was based solely on statistical evidence rather than preconceived expectations about the disaster's effects.

Notably, the model independently identified 5 changepoints one of which was in April 2011, temporally soon after the Fukushima disaster. The proximity of this changepoint to the event underscores its potential as a pivotal marker for studying the disaster's ecological implications. The utilisation of this automated feature was essential for distinguishing the specific perturbations attributable to the disaster amidst the typical seasonal fluctuations and other variabilities present in the marine environment.

### Insight Generation

The iterative application of FBProphet enabled comprehensive exploration of the dataset, generating a layered understanding of the variables at play. Through this process, valuable insights were gained into the extent of the Fukushima disaster’s impact on the health of plankton populations as inferred from chlorophyll concentrations. The analysis not only offered a window into the ecological aftermath of the disaster but also established a methodological blueprint for assessing the impact of similar environmental perturbations in marine ecosystems.

# Results and Discussion

## Forecasting Model: In the absence of 2011 Fukushima Disaster

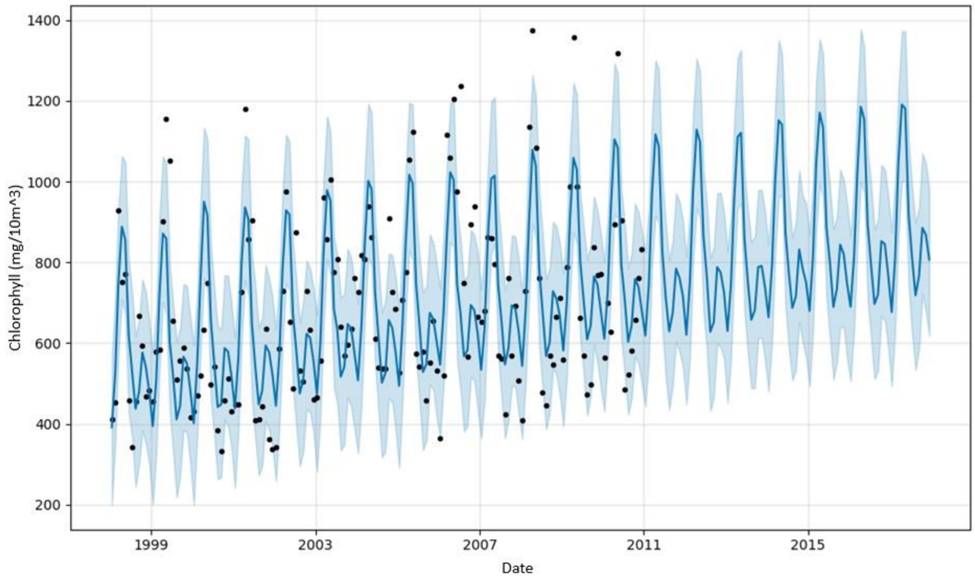


*Figure 1 FBProphet Forecast using 1998-2011 data*

Utilising actual recorded values of temperature, salinity, new maximum temperature, and new minimum temperature to forecast chlorophyll concentration trends, the predictive power of the FBProphet model was used to generate Figure 1. The model forecast that, absent the Fukushima event, chlorophyll levels would have likely continued their ascent or remained constant from 2011 to 2018, congruent with the environmental variables observed. This hypothetical trajectory, represented in Figure 1, establishes a baseline against which the actual post-disaster trends can be assessed, highlighting the pronounced deviation from expected patterns and the profound ecological shifts precipitated by the disaster.

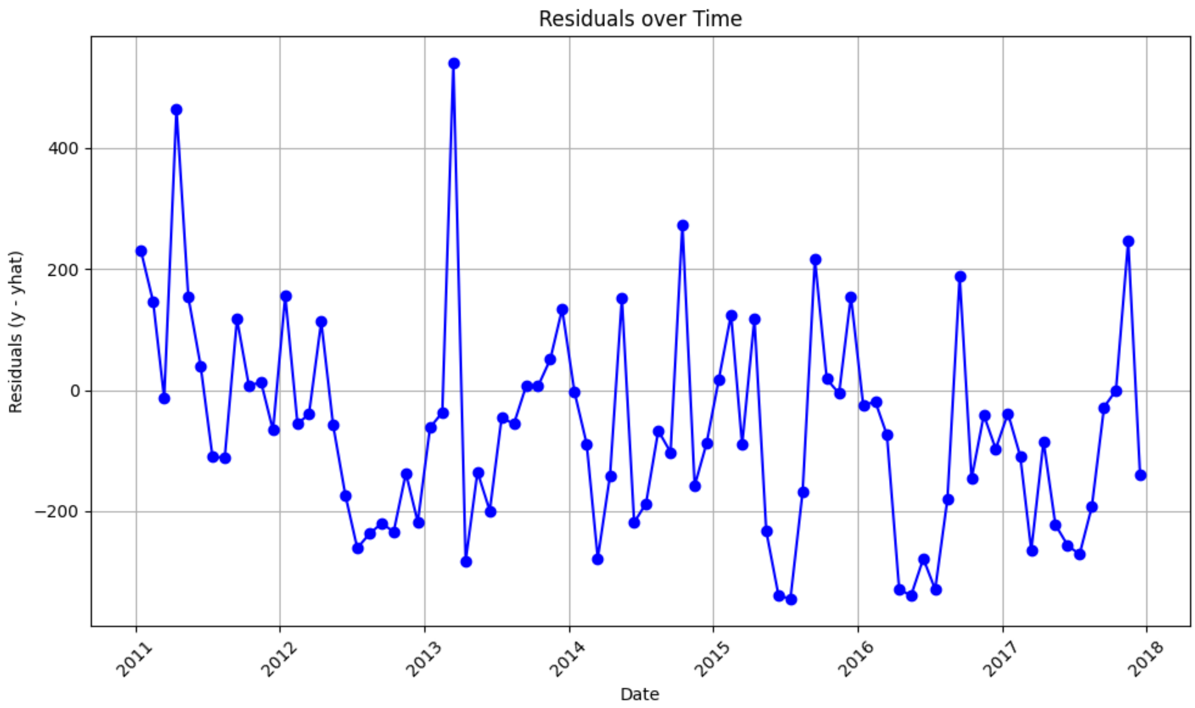


*Figure 2 Residual Plot using FBProphet Model Forecast*

The residual plot seen in Figure 2 displays the difference between actual and predicted chlorophyll values from the forecasting model. The plot shows that, post-Fukushima 2011, a majority of the residuals are negative meaning that, if the Fukushima disaster had not occurred, chlorophyll levels would have been expected to be higher for the period up to 2018.

## Changepoint Analysis for Disaster Impact

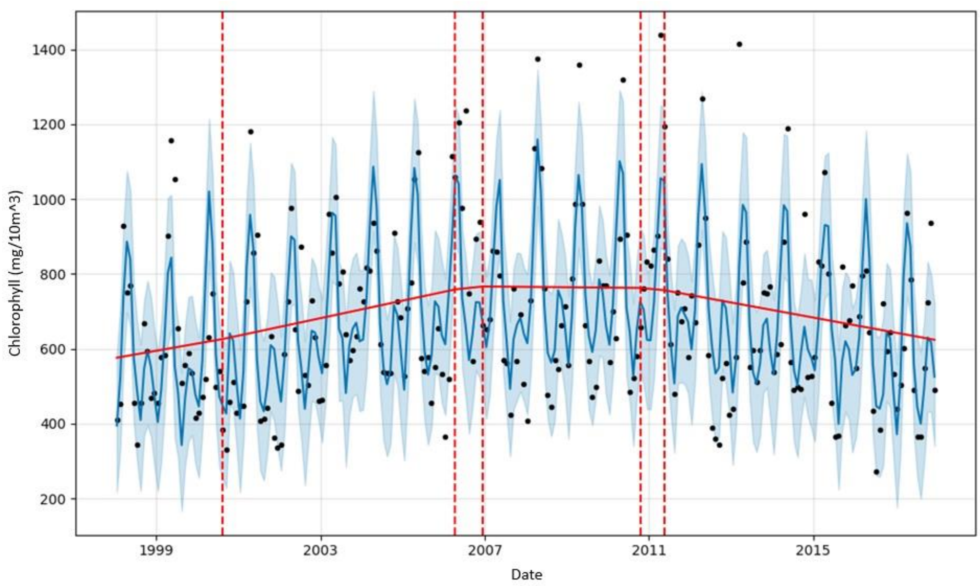


*Figure 3 FBProphet Changepoint Analysis*

Figure 3 shows the predicted chlorophyll trends produced by the model. The central forecast is depicted by a solid line, while the surrounding shaded area represents the 95% confidence interval, offering a visual representation of predictive uncertainty. Notably, the red dashed vertical lines—changepoints automatically determined by the model—denote moments of significant shifts in the chlorophyll trends. The precise alignment of observed data points within this confidence interval underscores the model's capacity to accurately capture the nuanced dynamics between biological and environmental influences on chlorophyll levels.

Analysing the data chronologically from left to right on the chart, we observe a pattern of increasing to flat chlorophyll levels from the onset of the dataset in 1998 up to the early months of 2011. This pattern suggests a period of growth to equilibrium within plankton populations. A pivotal changepoint in April 2011—coinciding with the Fukushima disaster—heralds a marked transition to a downward trend. This change from flat to declining chlorophyll levels post-Fukushima could logically be attributed to the change in the plankton's environment, i.e. sudden introduction of substantive radioactive materials into the nearby ocean.

Contrary to initial expectations of a step-change decrease in chlorophyll levels immediately following the 2011 Fukushima disaster, actual measurements tell a different story. In the months immediately after the disaster, chlorophyll levels were observed to remain unexpectedly high. Notably, on March 15th, 2011—just four days post-disaster—a significant data point was recorded above the 95% confidence interval, indicating an anomaly in the expected trend.

This deviation prompted a closer examination of the potential impacts of the disaster on planktonic biology. One plausible explanation centres around the release of caesium, a radioactive element dispersed during the Fukushima incident. Caesium bears a chemical resemblance to potassium, an essential nutrient for many living organisms, including plankton. It is hypothesised that this chemical similarity might have led plankton to inadvertently assimilate caesium giving a temporary boost to biological processes dependent on potassium, thus explaining the unusual rise in chlorophyll levels shortly after the disaster.

To better understand why there was no step-change decline in chlorophyll levels immediately following the Fukushima incident, another severe nuclear accident was looked into to see if there is any parallel with respect to nuclear contamination on plants. In the April 1986 Chernobyl Disaster[13], there is observation that even in the most radioactive areas of the nuclear disaster zone, vegetation was recovering within three years whereas mammals and birds would have been killed many times over by the radiation that plants in the most contaminated areas received. So, it is plausible that the genetic make-up of phytoplankton resulted in the less-impactful observations.

Another factor that might have influenced the observed gradual chlorophyll decline is leaching of radioactive material into the Pacific Ocean. A 2017 study[14] found some of the highest levels of radioactive cesium-137, a major by-product of nuclear power generation, in groundwater beneath sand beaches tens of kilometres away from the Fukushima disaster site. It is thought that in the wake of the 2011 accident, seawater tainted with high levels of cesium-137 travelled along the coast and lapped against these beaches. Some caesium stuck to the sand and, over time, percolated down to the groundwater beneath before steadily making its way back into the ocean. At the time of the 2017 study, it was assessed that the rate of leakage was on par with the leakage of caesium into the ocean from the reactor site itself. It is not known when this leaching could have started.

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[13] https://www.bbc.com/future/article/20190701-why-plants-survived-chernobyls-deadly-radiation

[14] Radioactive material from Fukushima disaster turns up in a surprising place (sciencenews.org)

### Current State of Plankton Health due to the 2011 Fukushima Disaster

As measured by chlorophyll levels, plankton health near the Fukushima disaster area, changed from equilibrium to declining due to the sudden introduction of substantive radioactive materials into the nearby ocean. Contrary to the author's initial hypothesis, there was no step-change drop in plankton health immediately after the disaster; rather there was a gradual decline in chlorophyll levels over time after the disaster through 2018. From figure 3, in 2018, chlorophyll levels were similar to those in 2001. Several significant uncertainties remain: (1) When could the declining trend be expected to stop and at what chlorophyll levels? (2) When could chlorophyll levels be expected to rise again and to reach the equilibrium levels seen just prior to the Fukushima disaster?

Rather than dispersal of the radioactive substances over time, the observed leaching of trapped radioactive material into the Pacific Ocean (discussed earlier) would complicate answering these questions.

To navigate the uncertainties unveiled by the study, a data science approach could leverage comparative analyses with similar plankton studies from regions unaffected by nuclear contamination. This would involve identifying a location that mirrors the pre-disaster environmental conditions of Fukushima, serving as a control to understand natural variations in plankton growth and equilibrium. Such a comparative study would offer insights into the baseline health of plankton populations, providing a clearer context for the changes observed post-Fukushima. Thinking ahead, it would be invaluable to the global community to establish several key stations around the world for long-term plankton data collection, especially when science and technology today allows automatic data collection and processing.

Outside the realm of this study, the author observes that a healthy plankton population, by itself, would not necessarily mean healthy for animals further up the food chain. E.g. it is unclear whether nuclear-contaminated plants – which might seemingly reproduce – won't contaminate and harm animals that eat them and those further up the food chain.

## Conclusions and Recommendations

While it is clear that the sudden introduction of substantive radioactive materials into its environment (arising from the Fukushima disaster) would negatively impact marine plankton health, it would appear that this impact is more gradual than initially expected. In addition, it is unclear whether, in the absence of the Fukushima disaster, the plankton levels would not have increased and decreased over long periods, even after accounting for seasonality.

Given the importance of plankton in the global food chain and climate, it would be invaluable to the global community to establish several key stations around the world for long-term plankton data collection, especially when science and technology today allows automatic data collection and processing.