



ICES Phytoplankton and Microbial Plankton
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Editors

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10. PHYTOPLANKTON OF THE NORTH ATLANTIC BASIN

Martin Edwards and Rowena Stern

The Continuous Plankton Recorder (CPR) survey is a long-term, subsurface, marine plankton monitoring programme consisting of a network of CPR transects towed monthly across the major geographical regions of the North Atlantic. It has been operating in the North Sea since 1931 with some standard routes existing with virtually unbroken monthly coverage back to 1946. After each tow, the CPR samples are returned to the laboratory for routine analysis, including the estimation of phytoplankton biomass (Phytoplankton Colour Index, PCI) and the identification of up to 500 different phytoplankton and zooplankton taxa (Warner and Hays, 1994). Direct comparisons between the Phytoplankton Colour Index and other chlorophyll *a* estimates, including SeaWiFS satellite estimates, indicate strong positive correlations (Batten et al., 2003; Raitsos et al., 2005). The second step of the phytoplankton analysis involves counting phytoplankton cells under high magnification (x450) to identify and count taxa. Each CPR sample represents ~3 m³ of filtered seawater. Using this analysis method, 200 phytoplankton taxa have been routinely identified and counted by the CPR survey since 1958.

Because of the mesh size of CPR silks, many phytoplankton species are only semi-quantitatively sampled owing to the small size of the organisms. There is, thus, a bias towards recording larger armoured flagellates and chain-forming diatoms, and smaller-species abundance estimates from cell counts will probably be underestimated in relation to other water sampling methods. However, the proportion of the population that is retained by the CPR silk reflects the major changes in abundance, distribution, and specific composition (i.e. the percentage retention is roughly constant within each species even with very small-celled species; Edwards *et al.*, 2006). The CPR now has a water sampler housed on board certain units to provide additional data and sample the whole size-spectrum of plankton using molecular techniques from bacteria and viruses to flagellates and other taxa not normally identified using standard CPR analysis.

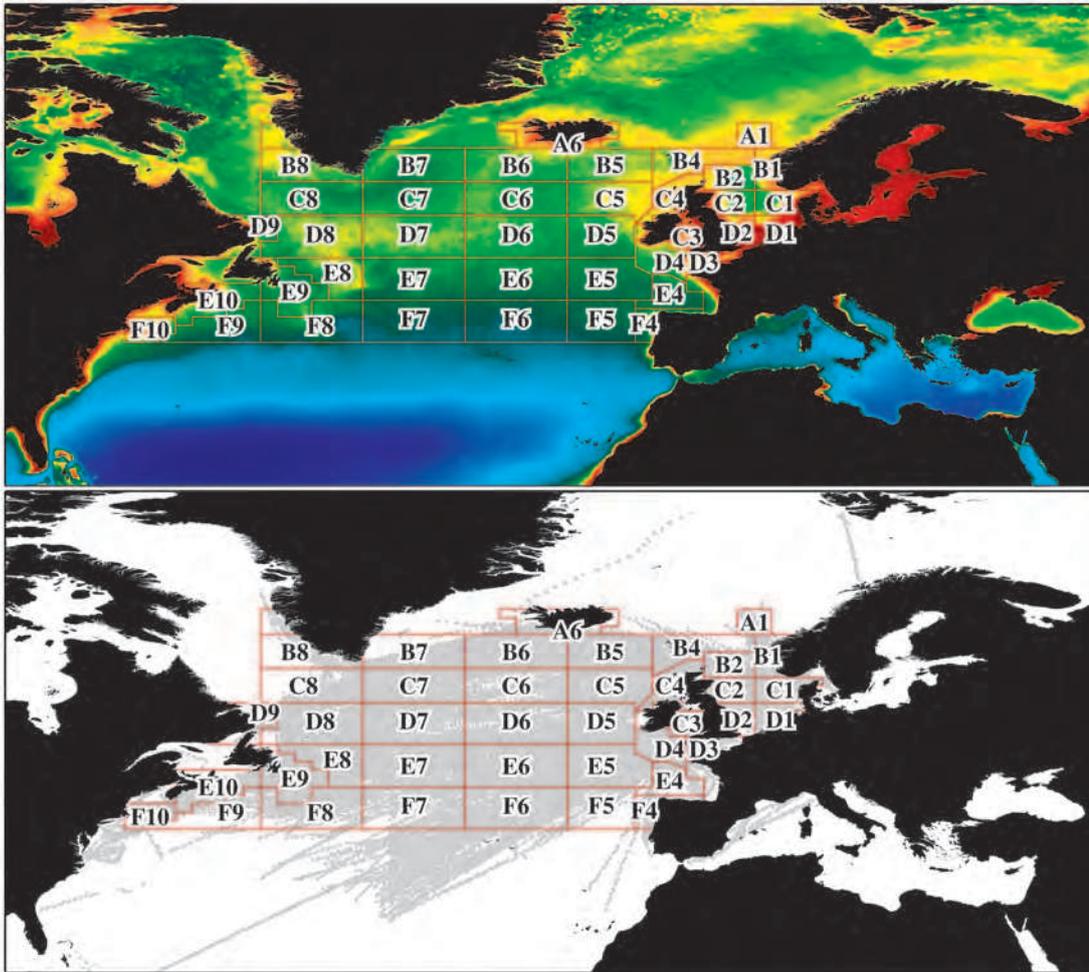


Figure 10.1
Locations of Continuous Plankton Recorder (CPR) standard areas (outlined in red). The top panel shows these areas on a map of average chlorophyll concentrations (see Section 2.3.2). The bottom panel shows the CPR transect and sampling coverage (grey dots) available within each of these areas.

For the purpose of the assessment in this report, the North Atlantic Basin has been geographically subdivided into different spatial regions (Figure 10.1). The 40 geographical regions shown in the figures are known as CPR standard areas and are referenced by their alphanumeric identifiers (e.g. “B2”, “D8”). Included in this assessment are some trends in the phytoplankton and microzooplankton, as well as trends in marine pathogens derived from molecular analysis of samples in the CPR sample archive.

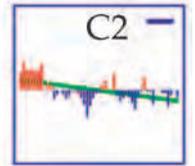
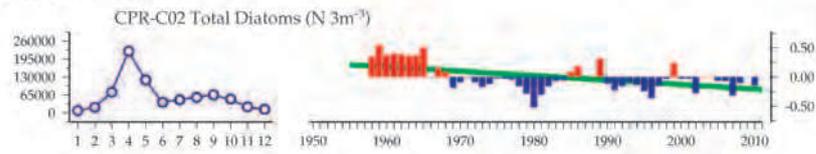
The CPR data from the standard areas were processed using standard report methods (see Section 2.1) as applied to the other plankton time-series presented in this report. For the purpose of viewing the long-term CPR trends in a spatial context, the standard report graphics (see Section 2.2) were truncated into the forms described in Figure 10.2 and used in the “Spatial Trends Plots” of this section (Figures 10.3–10.9).

Figure 10.2

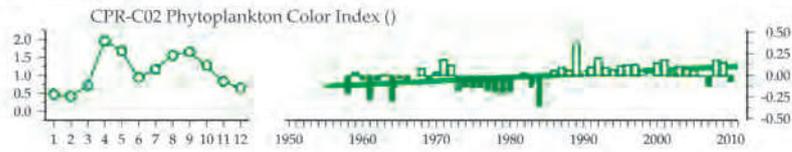
Examples of CPR standard area data shown in the standard report plot format (left column, see Section 2.2.2) and their corresponding truncated forms (right column) as presented in the "Spatial Trends Plots" shown later in this section.

The truncated form incorporates the standard annual anomaly trend representation (e.g. the green and grey slope lines) as described in Section 2.2. Positive significant trends ($p < 0.01$ or $p < 0.05$) are indicated with a red box outline, negative significant trends are indicated with blue box outline. Solid box outlines indicate $p < 0.01$, dashed boxed outlines indicate $p < 0.05$. Non-significant trends are outlined in grey. Trend directions ("+", "-") are also indicated in all cases.

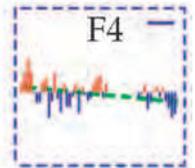
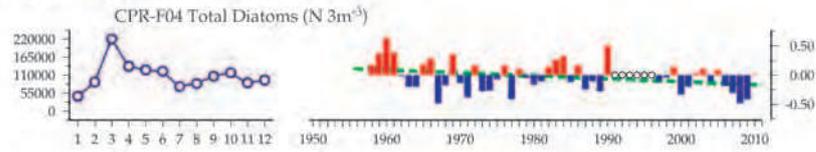
Strong Negative Trend ($p < 0.01$):



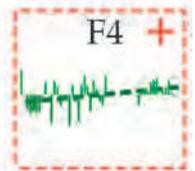
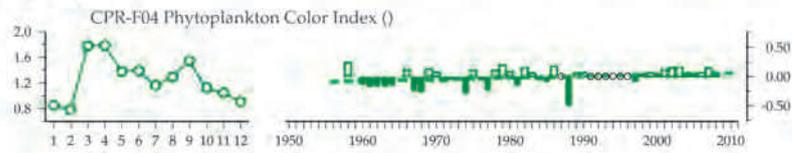
Strong Positive Trend ($p < 0.01$):



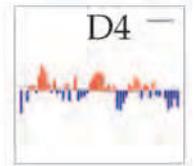
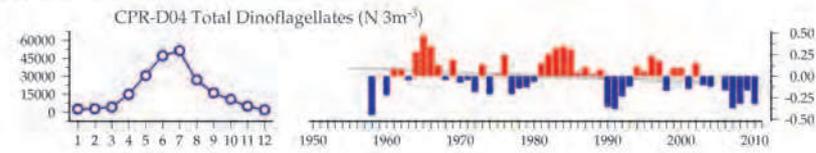
Negative Trend ($p < 0.05$):



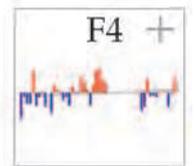
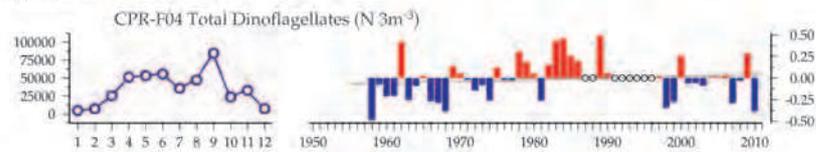
Positive Trend ($p < 0.05$):



Non-significant Negative Trend:



Non-significant Positive Trend:



10.1 Basin-scale trends in phytoplankton

To summarize the long-term trends in phytoplankton in the North Atlantic Basin, we used indices of phytoplankton that included the CPR Phytoplankton Colour Index and the sum of the abundance of all counted diatoms ("Total Diatoms") and all counted dinoflagellates ("Total Dinoflagellates"). Bulk indices like these are less sensitive to environmental change, and will quite often mask the subtleties that individual species will give you; however, it is thought that these bulk indices represent the general functional response of phytoplankton to the changing environment. In the North Atlantic, at the ocean basin-scale and over multidecadal periods, changes in phytoplankton species and communities have been associated with Northern Hemisphere Temperature (NHT) trends, the Atlantic Multidecadal Oscillation (AMO), the East Atlantic Pattern (EAP), and variations in the North Atlantic Oscillation (NAO) index. These have included changes in species distributions and abundance, the occurrence of subtropical species in temperate waters, changes in overall phytoplankton biomass and seasonal length, changes in the ecosystem functioning, and productivity of the North Atlantic (Edwards *et al.*, 2001, 2002; Reid and Edwards, 2001; Beaugrand *et al.*, 2002; Edwards and Richardson, 2004).

Contemporary observations using ten years of blended satellite and *in situ* chlorophyll records indicate that global ocean net primary production has declined over the last decade, particularly in the oligotrophic gyres of the world's oceans (Behrenfeld *et al.*, 2006). In contrast, trends based on 50 years of Phytoplankton Colour Index records (a proxy for chlorophyll) indicate there has been a steady increase in phytoplankton biomass for the whole temperate Northeast Atlantic (Richardson and Schoeman, 2004), which is visible in Figure 10.3. Both studies correlate these increases with sea surface temperatures (Figure 10.4). This increase in phytoplankton biomass is presumably the result of an initial increase in phytoplankton metabolic rates caused by these warmer temperatures in otherwise cooler-water regions. This positive response to warming is not unlimited, however, as nutrient limitations can take effect as warming of the surface layers increase water-column stability, enhancing stratification, and requiring more energy to mix deep, nutrient-rich waters into surface layers. Particularly warm winters will also limit the degree of deep convective mixing and thereby limit nutrient replenishment necessary for the following spring phytoplankton bloom. The amount of nutrients available in surface waters directly dictates

phytoplankton growth and is the key determinant of the plankton size, community, and foodweb structure.

Climate variability has a spatially heterogeneous impact on phytoplankton in the North Atlantic and not all regional areas are correlated to the same climatic index. For example, trends in the AMO are particularly prevalent in the oceanic regions and in the Subpolar Gyre of the North Atlantic, and the NAO has a higher impact in the southern North Sea where the atmosphere–ocean interface is most pronounced. This is also apparent with respect to the Northern Hemisphere Temperature, where the response is also spatially heterogeneous with areas of the Northeast Atlantic and shelf areas of the Northwest Atlantic warming faster than the North Atlantic average and some areas like the Subpolar Gyre actually cooling. Similarly, regime shifts or abrupt ecosystem shifts do not always occur in the same region or at the same time. The major regime shift that occurred in phytoplankton colour in the late 1980s was particularly prevalent in the North Sea and was not seen in oceanic regions of the North Atlantic. However, a similar regime shift occurred in the phytoplankton colour ten years later in the Icelandic Basin and in oceanic regions west of the British Isles. The different timing and differing regional responses to regime shifts have been associated with the movement of the 10°C thermal boundary as it moves north in the North Atlantic (Beaugrand *et al.*, 2008).

In examining the long-term trends in the three phytoplankton indices (PCI, Total Diatoms, and Total Dinoflagellates), the general pattern is an increase in PCI for most regions in the North Atlantic (Figure 10.3), with differing timings for the main stepwise increase being later in oceanic regions compared with the North Sea. Within the dinoflagellates (Figure 10.6), there has been a general increase in abundance in the Northwest Atlantic and a decline in the Northeast Atlantic over a multidecadal period. In particular, some regions of the North Sea have experienced a sharp decline over the last decade, mainly caused by the dramatically reduced abundance of the *Ceratium* genus in the North Sea. However, *Ceratium* abundance has recovered in the North Sea over the last two years. For the diatoms (Figure 10.5), there is not really a predominant trend for the North Atlantic Basin as a whole, but some regions show a strong cyclic behaviour over the multidecadal period. The time-signal resembles an oscillation of ca. 50–60 years and a minimum around 1980, reflecting changes in the AMO signal. In summary, although climate warming is a major driver for the overall biomass

of phytoplankton, diatoms are less influenced by temperature and show a strong correlation with the AMO signal and wind intensity in many regions. The increase in diatoms associated with the positive phase of the AMO and the decline in dinoflagellate abundance over the last ten years in the Northeast Atlantic can be reflected as an increase in the diatoms:diatoms+dinoflagellates ratio. Figure 10.7 shows a strong positive increase in this ratio in the North Sea, but a strong negative decrease in the Labrador Sea region.

Indirectly, the progressive freshening of the Labrador Sea region, attributed to climate warming and the increase in freshwater input to the ocean from melting ice, has resulted in the increasing abundance, blooms, and shifts in seasonal cycles of dinoflagellates because of the increased stability of the water column (Johns *et al.*, 2001). Similarly, increases in coccolithophore blooms in the Barents Sea and harmful algal blooms (HABs) in the North Sea are associated with negative salinity anomalies and warmer temperatures, leading to increased stratification (Edwards *et al.*, 2006; Smyth *et al.*, 2004). It seems likely that an important environmental impact caused by climate change is an increase in the presence of haline stratification in regions susceptible to freshwater inputs, resulting in an increase in bloom formation.

Globally, eutrophication is considered a major threat to the functioning of nearshore ecosystems, as it has been associated with the occurrence and perceived increase of HABs. HABs are, in most cases, a completely natural phenomenon and occur regularly throughout recorded history. Disentangling these natural bloom events, caused by natural hydroclimatic variability, from unnatural bloom events caused by global climate change or eutrophication, can be very difficult. For example, increasing temperature, nutrient input fluctuations in upwelling areas, eutrophication in coastal areas, and enhanced surface stratification all have species-specific responses. Prediction of the impact of global climate change is, therefore, fraught with numerous uncertainties. There is some evidence that biogeographical range extensions caused by regional climate change have increased the presence of certain HABs in some regions (Edwards *et al.*, 2006). Regional climate warming and hydrographic variability in the North Sea has also been associated with an increase in certain HABs in some areas of the North Sea, particularly along the Norwegian Coastal Current (Edwards *et al.*, 2006). The abundance of *Prorocentrum* spp. and *Noctiluca scintillans* abundance is strongly correlated with increasing SST, and the increase in

a number of diatom species in the North Sea over the last decade has been associated with increasing wind intensity (Hinder *et al.*, 2012), which has been increasing across the majority of the North Atlantic Basin (Figure 10.8). Phenological studies have also found strong correlations between the movement of dinoflagellates (up to 1 month earlier) in their seasonal cycle and regional climate warming (Edwards and Richardson, 2004). In summary, at the large ecoregional and provincial scale, trends in phytoplankton are associated with hydroclimatic variability. This is not to say, however, that eutrophication is not a problem; it may, in fact, be the primary driver in certain coastal regions and at the more localized scale.

10.2 Basin-scale trends in microzooplankton

Tintinnids are ciliates, often grouped under microzooplankton, and they are an important group of marine micrograzers of nanophytoplankton. Tintinnids help transport nutrients to higher trophic levels and remove 10–27% of phytoplankton from coastal waters (Verity, 1987). They show a pelagic distribution, highest between 20 and 30°N or S, and there is often a correlation in tintinnid abundance and chlorophyll *a* (Dolan *et al.*, 2006). The CPR tintinnid time-series (1993–2010) are significantly shorter than the other CPR variables (1958–2010), but some initial trends emerge (Figure 10.9). Tintinnids in the western North Atlantic, bordering Newfoundland and Labrador (standard area D8), are exhibiting an overall positive increase, whereas standard area boxes in the southern (C1, D2) and northern (B2) North Sea show an overall decline.

Total tintinnid measurements do not reflect individual genus or species patterns. Tintinnid species have specific abundance and seasonality (Urrutxurtu, 2004), which may be masked by assessing phenology at a higher taxon level (i.e. “totals”). Several genera of tintinnids, such as *Tintinnopsis*, were found to expand their winter seasonal presence into UK coastal waters (Hinder *et al.*, 2011). Surprisingly, the total tintinnid patterns in this study do not follow PCI trends or SST (which are universally increasing), but their phenology can potentially be related to dinoflagellate abundance, which may be a food source. As the CPR tintinnid time-series are relatively short, these trends may become more evident as monitoring continues.

10.3 Phytoplankton biodiversity and invasive species

At the ocean basin scale, biodiversity of phytoplankton is related to temperature, and an increase in warming over the last few decades has been followed by an increase in diversity, particularly for dinoflagellates (Beaugrand *et al.*, 2010). Phytoplankton as a whole show a relationship between temperature and diversity, which is linked to the phytoplankton community having a higher diversity, but an overall smaller size-fraction and a more complex foodweb structure (i.e. microbial-based vs. diatom-based production) in warmer, more stratified environments. Climate warming will, therefore, increase planktonic diversity throughout the cooler regions of the world's oceans as temperature isotherms shift poleward. Apart from thermal boundary limits moving progressively poleward and, in some cases, expanding, the rapid climate change observed in the Arctic may have even greater consequences for the establishment of invasive species and the biodiversity of the North Atlantic.

The thickness and areal coverage of summer ice in the Arctic have been melting at an increasingly rapid rate over the last two decades, reaching the lowest-ever recorded extent in September 2007. In spring, following the unusually large ice-free period in 1998, large numbers of a Pacific diatom *Neodenticula seminae* were found in samples taken by the CPR survey in the Labrador Sea in the North Atlantic. *N. seminae* is an abundant member of the phytoplankton in the subpolar North Pacific and has a well-defined palaeo history based on deep-sea cores. According to the palaeological evidence and modern surface sampling in the North Atlantic since 1948, this was the first record of this species in the North Atlantic for at least 800 000 years. The reappearance of *N. seminae* in the North Atlantic, and its subsequent spread southwards and eastwards to other areas in the North Atlantic, after such a long gap, could be an indicator of the scale and speed of changes that are taking place in the Arctic and North Atlantic oceans as a consequence of climate warming (Reid *et al.*, 2007). The diatom species itself could be the first evidence of a transarctic migration in modern times and be a harbinger of a potential inundation of new organisms into the North Atlantic. The consequences of such a change to the function, climatic feedbacks, and biodiversity of Arctic systems are, at present, unknown.

10.4 Trends in marine pathogens

As sea surface temperatures increase, predictions favour an increase in the number and range of pathogenic microorganisms. Such changes are difficult to determine over short periods, as one cannot separate short-term variations from long-term climate-change trends. In a unique long-term time-study, Vezzulli *et al.* (2011) investigated the spread of the pathogenic bacteria *Vibrio*, the causative agent of cholera, in the North Sea using 54 years of CPR-collected samples. Using DNA extract from CPR samples, the relative proportion of *Vibrio* bacteria in relation to total bacteria was calculated. This *Vibrio* Abundance Index (VAI) was found to have steadily increased over four decades, and the trend was correlated with SST and copepod abundance, but not PCI. *Vibrio* thrives best in water temperatures over 18°C (Vezzulli *et al.*, 2004). Within the southern Rhine region of the North Sea, an area which frequently has summer SST values over 18°C, the correlation between SST and VAI was significant. Within the northern Humber region, an area where SST never exceeds 18°C, there was no significant increase or clear trend. *Vibrio* attach to chitin surfaces, such as the shells of copepods and other chitinous zooplankton. The correlation with copepod abundance indicates this relationship is both a pathway for the pathogen and a potential monitoring proxy.

Phytoplankton Colour Index

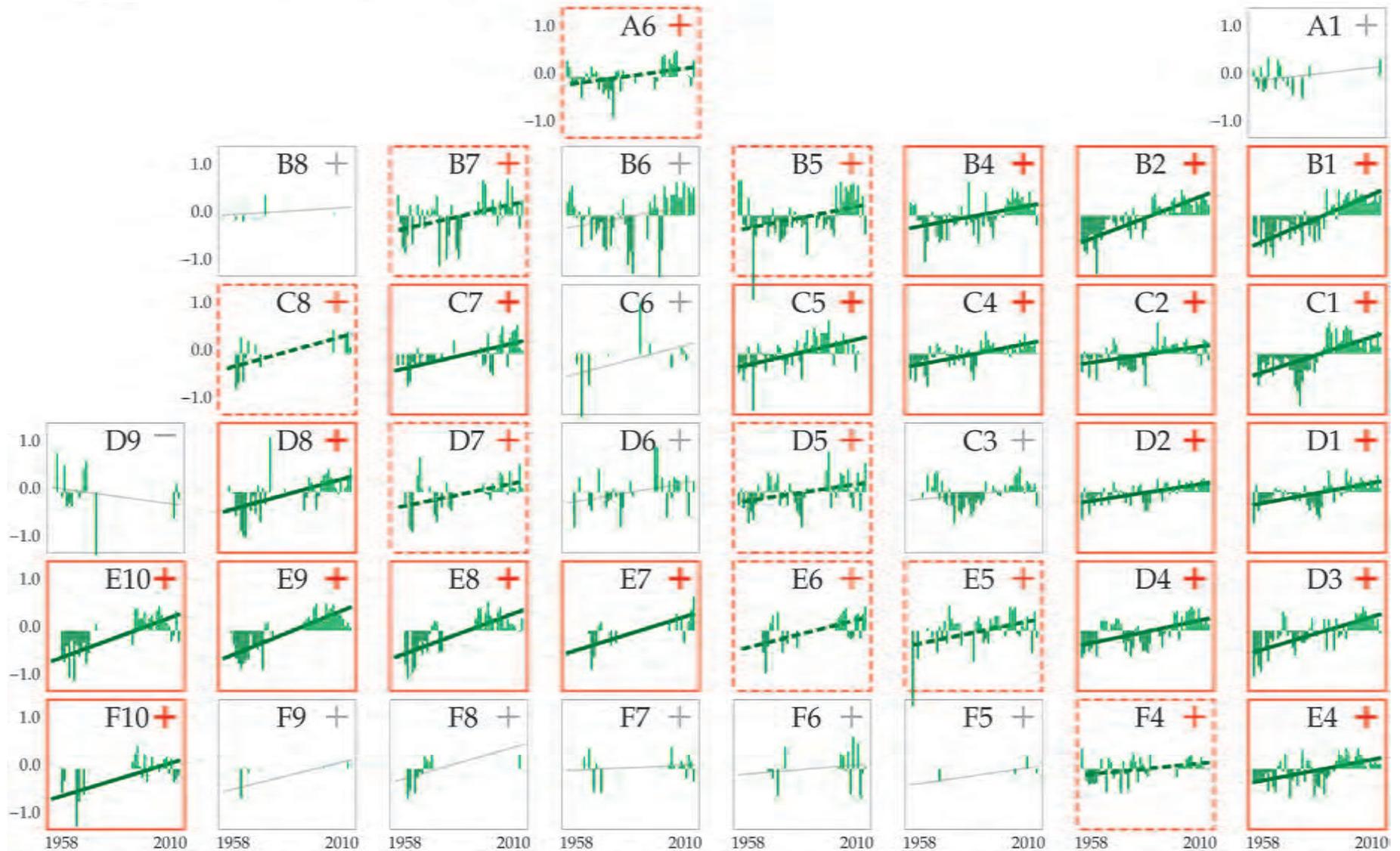


Figure 10.3
 Spatio-temporal trends plot for
 Phytoplankton Colour Index
 time-series in the CPR standard
 areas of the North Atlantic Basin
 based on data for 1958–2010.

Sea Surface Temperature

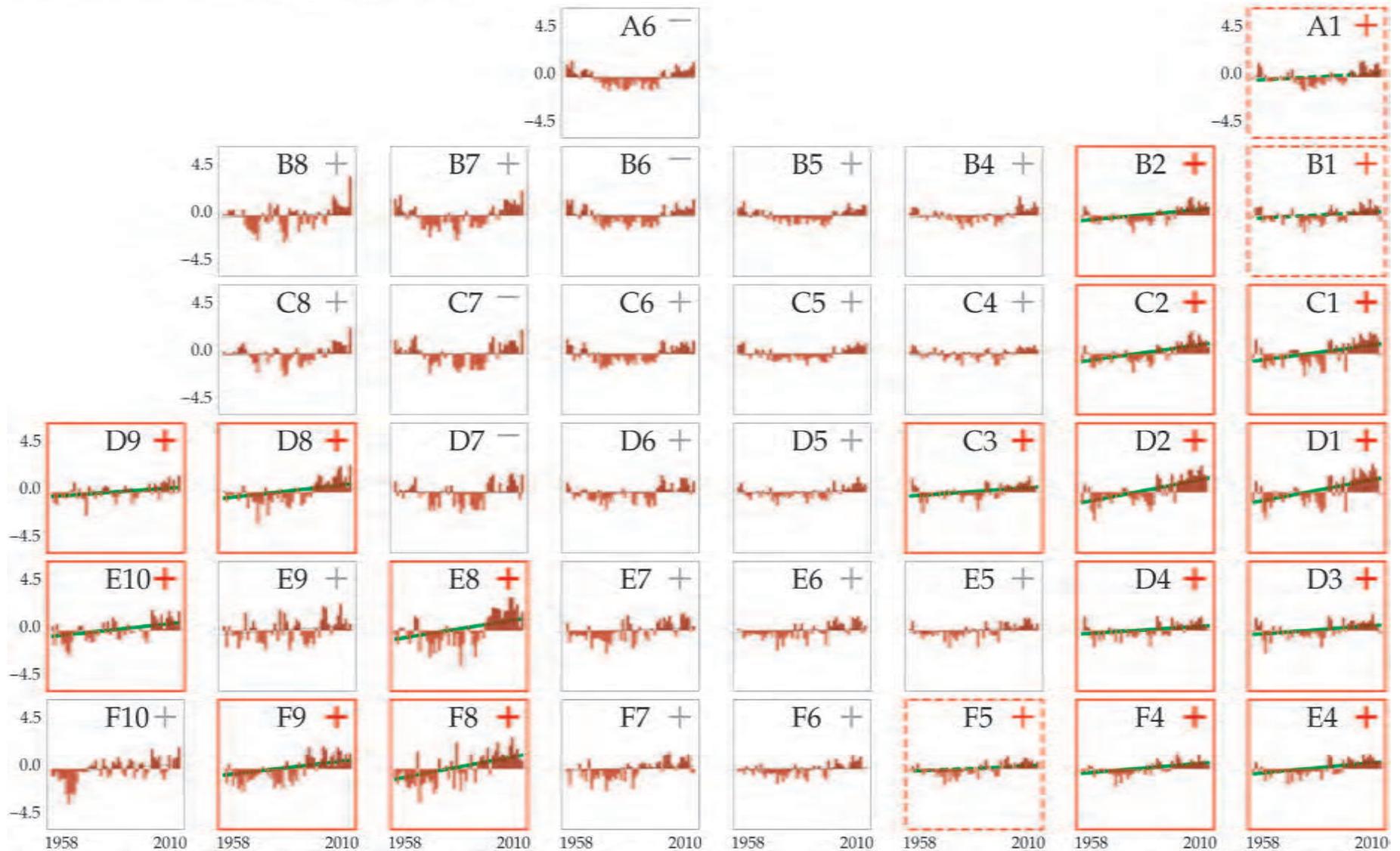


Figure 10.4
Spatio-temporal trends plot for sea surface temperature time-series in the CPR standard areas of the North Atlantic Basin based on data for 1958–2010.

Total Diatoms

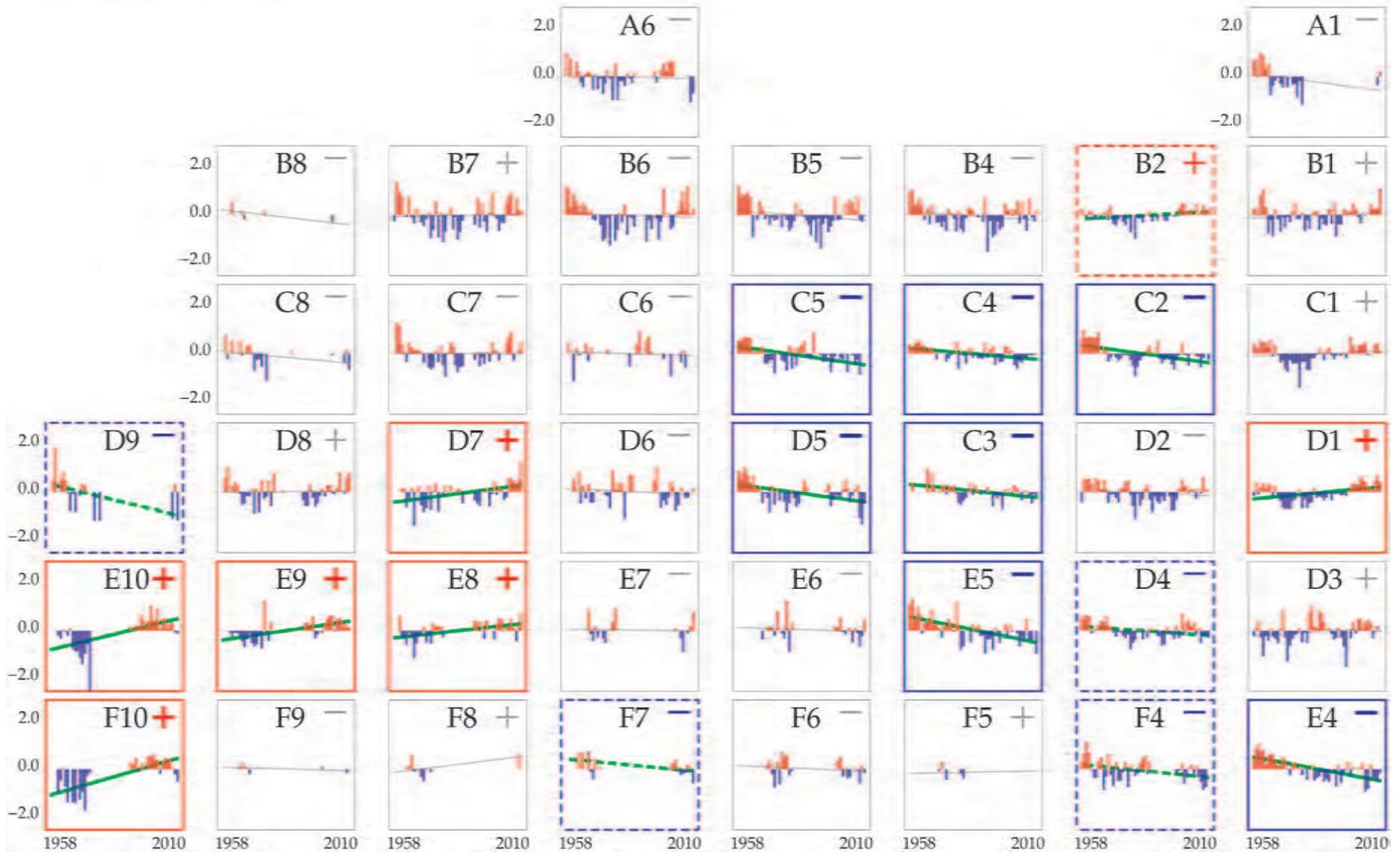


Figure 10.5
 Spatio-temporal trends plot for Total Diatoms time-series in the CPR standard areas of the North Atlantic Basin based on data for 1958–2010.

Total Dinoflagellates

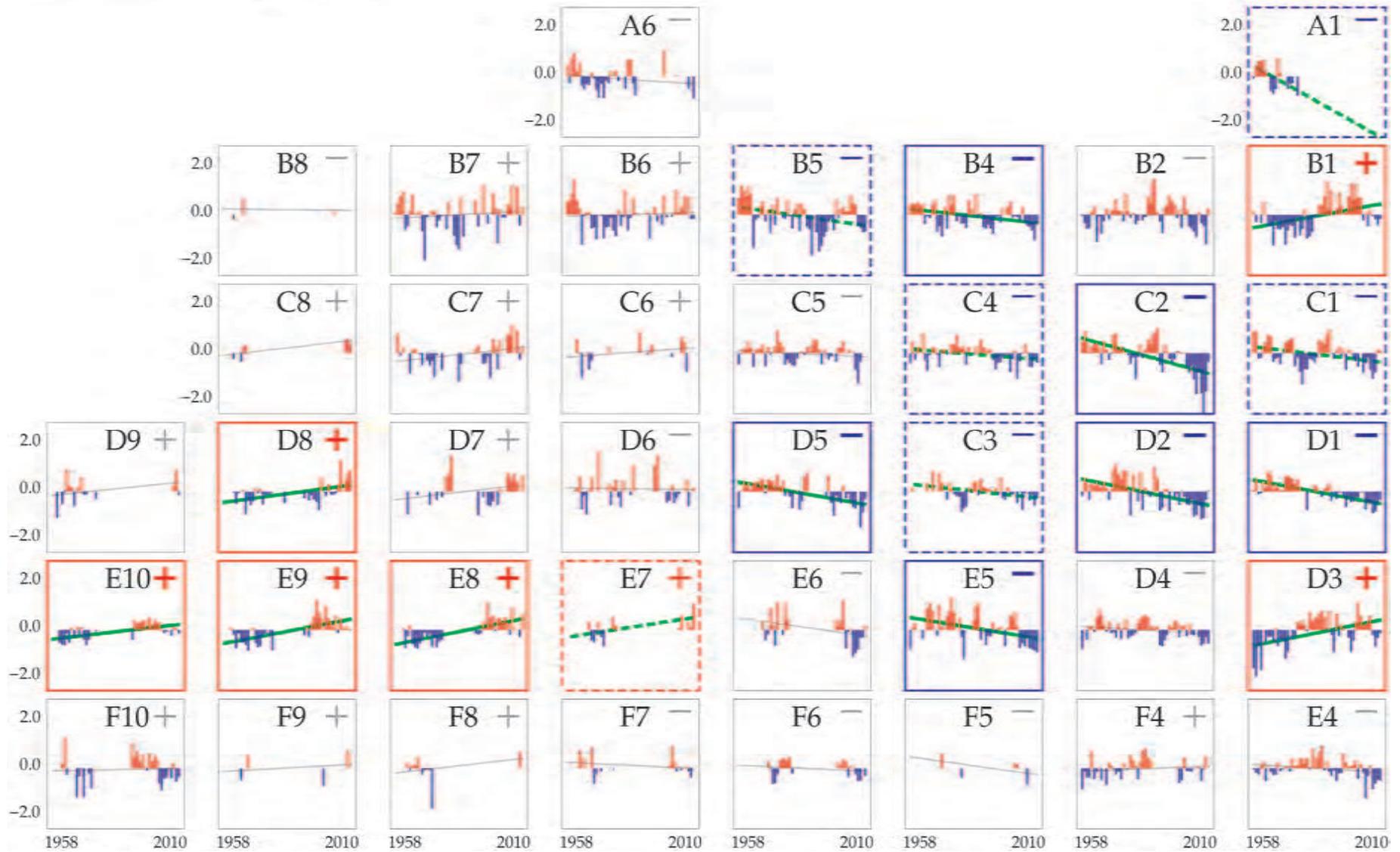


Figure 10.6
 Spatio-temporal trends plot for Total Dinoflagellates time-series in the CPR standard areas of the North Atlantic Basin based on data for 1958–2010.

Diatoms:Diatoms+Dinoflagellates Ratio

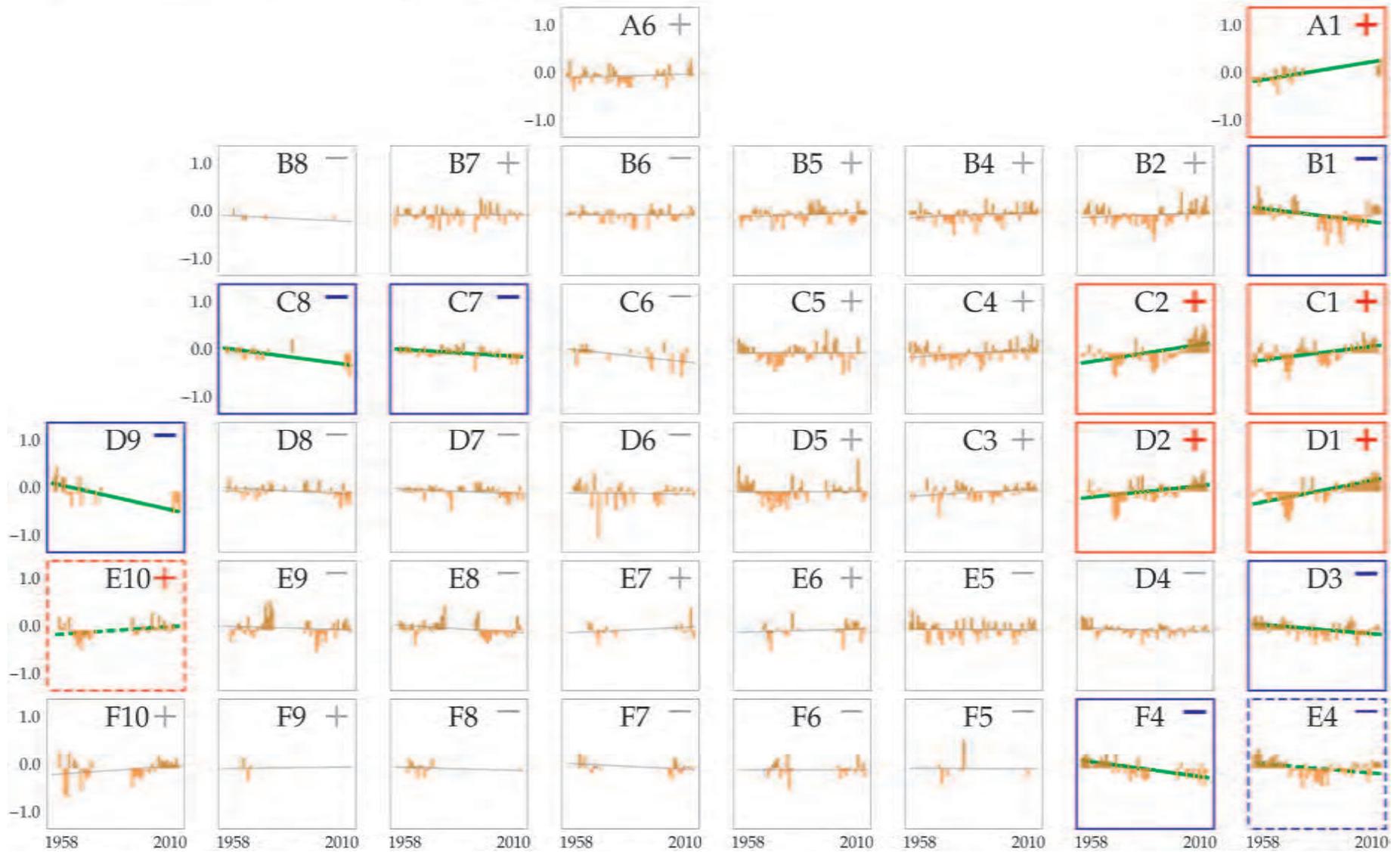


Figure 10.7
 Spatio-temporal trends plot for Diatoms:Diatoms+Dinoflagellates Ratio time-series in the CPR standard areas of the North Atlantic Basin based on data for 1958–2010.

Wind Speed

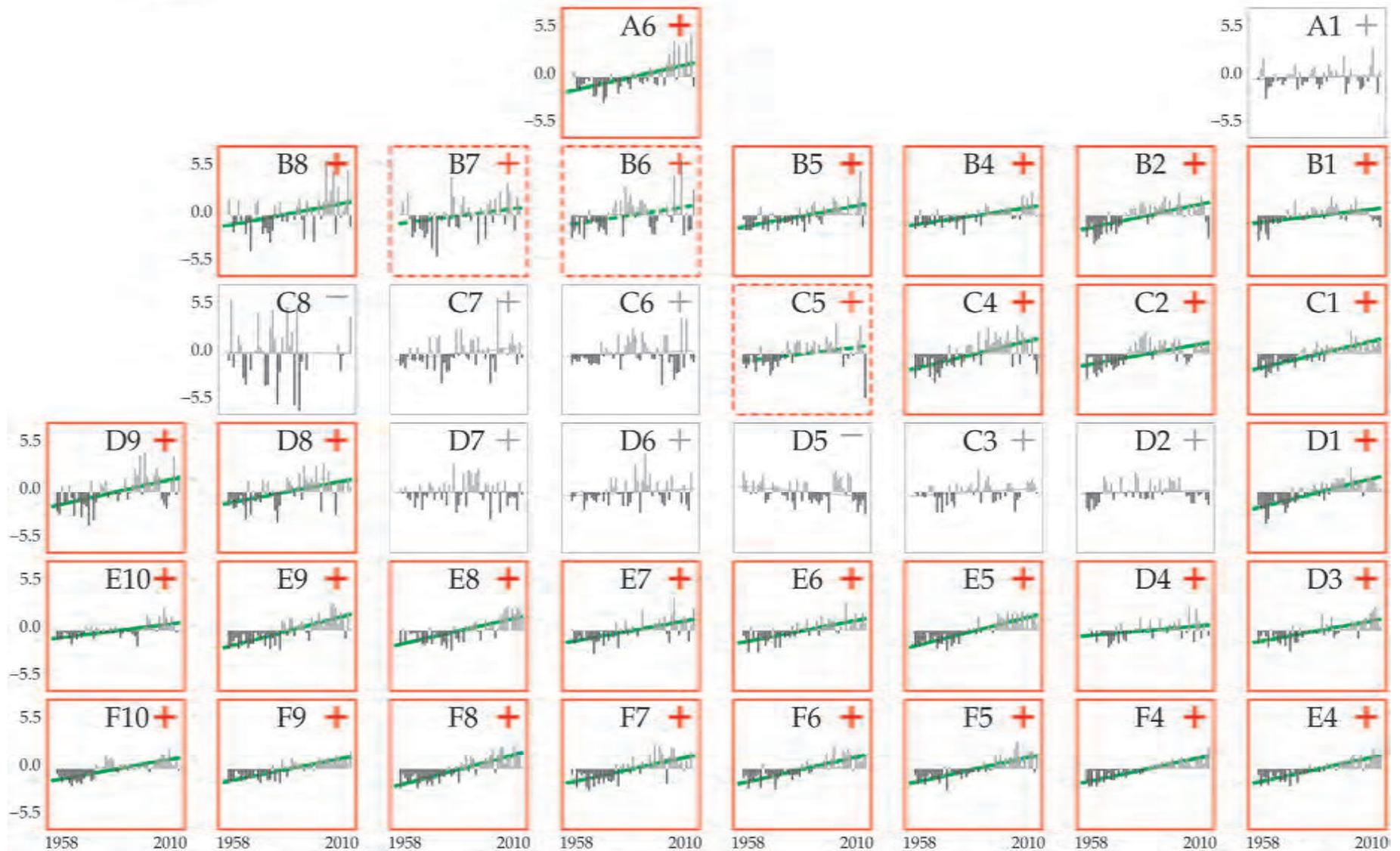


Figure 10.8
Spatio-temporal trends plot for COADS Wind speed time-series in the CPR standard areas of the North Atlantic Basin based on data for 1958–2010.

Total Tintinnids

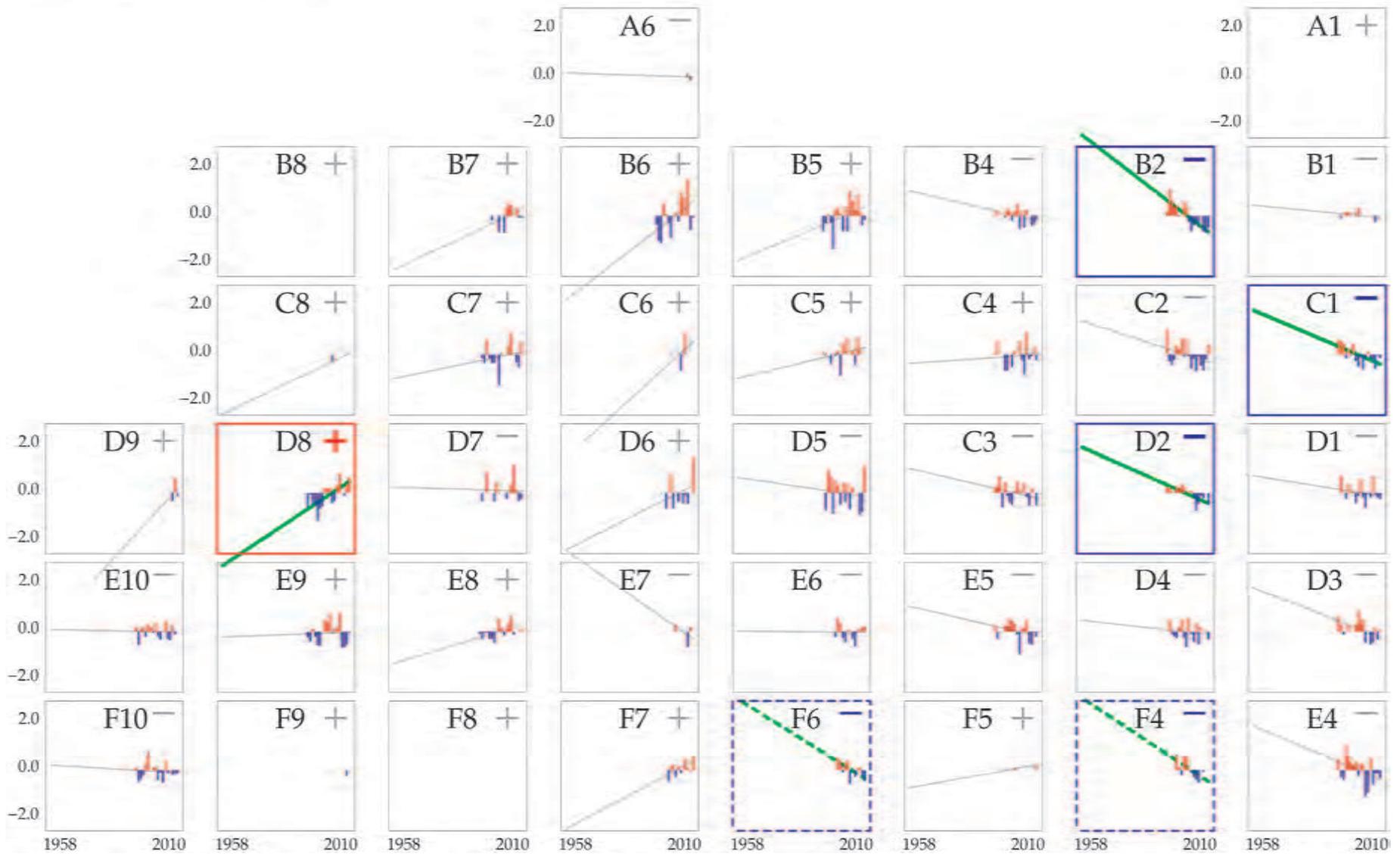


Figure 10.9
 Spatio-temporal trends plot for Total Tintinnids time-series in the CPR standard areas of the North Atlantic Basin based on data for 1993–2010.