

Fig. 2 Downstream bend apex, discharge: a, $1.7 \text{ m}^3 \text{ s}^{-1}$; b, $4.0 \text{ m}^3 \text{ s}^{-1}$. Dashed channel section represents that at the previous measurement section, $\sim 4 \text{ m}$ upstream.

bend apices are reported here. However, these sections do typify the different patterns found in the two bends. The long and cross-stream velocities were resolved into primary and secondary components using the method based on three-dimensional continuity recommended by Dietrich and Smith⁹. The results are shown in Figs 1, 2.

At both sections and flows the salient feature of the secondary circulation is the helical, skew-induced cell. However, close to the outer bank, a small cell of reverse rotation is clearly present, especially at bankfull flow. These cells are associated with distortion of the primary isovels and depression of the maximum primary velocity below the free surface in the outer bank region. The outer bank cell occupies the channel to a distance 1–2 times the bank height away from the outer bank, as observed elsewhere^{5,9,10} and predicted theoretically¹³.

The pattern of primary and secondary flows in the outer half of the channel changes little with stage at a bend, and is similar at both apices. This robustness is not present in the flow pattern in the inner half of the channel, where the two bends react differently to changing stage.

At intermediate flow, secondary flow over the point bar is directed radially outwards over the whole depth, as predicted and observed by Dietrich and Smith and by Bridge^{9,10}. The reason for this is the dominance of the centrifugal force acting outwards over the hydrostatic pressure gradient, acting inwards. Also, the flow is shelving and narrowing in the longstream direction at the inner bank, as indicated in Figs 1a and 2a by the dashed lines showing the cross-section just upstream from the bend apex. Consequently, water is driven radially outwards to maintain continuity, leading to outward secondary flow. These

arguments agree with the explanation put forward by the previous researchers^{9,10}.

At bankfull stage, the two bends show different flow patterns in the inner half of the channel. At the upstream bend, outward flow has been replaced by helical flow over most of the width, as predicted by Bridge¹⁰. The point bar has been scoured and reprofiled by the high flow and this, combined with the increased stage at almost constant width, has significantly increased the importance of the cross stream hydrostatic pressure gradient, which is now able to drive bed flow inwards. This is not the case at the downstream bend. Here, outward flow over the point bar persists up to bankfull discharge. The reason for this is that the width increases markedly with stage at the downstream bend, so that both the depth and the hydrostatic pressure gradient over the point bar remain small (Fig. 2b). Also, the point bar is more prominent in the downstream bend, so that shelving in the downstream direction is maintained at bankfull flow (Fig. 2b). This is not the case at the upstream bend, where high flow scouring produces deepening downstream at the inner bank (Fig. 1b).

We conclude that both patterns of flow in the inner half of the channel are possible and do occur in nature, depending on the morphology of the channel cross-section. Of particular importance is the stage-width relationship. Where there is marked widening with stage, outward flow persists to bankfull flow, but where width is almost constant with stage, helical flow expands almost to the inner bank. A quick survey of the Fall River bends revealed about equal numbers of bends falling into each category. As all the bends have the same bankfull discharge, sediment load, and bed and bank materials, there seems to be no obvious reason for the different morphologies, raising the possibility of there being two stable bend sections for a given set of independent controls. Clearly, point bar-flow interaction is a topic deserving further consideration and study.

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Enhancement of marine primary production by nitrogen-enriched acid rain

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The effect of acid rain on the pH of freshwater habitats is well known¹. The acidity of rainwater is largely due to hydrated oxides of sulphur, nitrogen and carbon², which also constitute nutrients essential for plant growth. Most freshwater and marine environments contain sufficient quantities of inorganic carbon and sulphur to satisfy plant growth needs, but nitrogen inputs can at times fall short of growth demands^{3,4}. Nitrogen limitation of phytoplankton growth is widespread and chronic in some marine waters^{5–7}. I

report here that nitrogen-limited conditions in North Carolina near-surface waters are ameliorated following rainfall inputs; the most acidic rainfall events led to the greatest stimulation of phytoplankton growth. Continentally-derived acid rain consistently contained more inorganic nitrogen (NO_3^- , NO_2^- and NH_4^+) than near neutral rainfall generated from oceanic fronts. Marine primary production can thus be influenced by the source of rainfall in marginal environments.

Nutrient limitation and impacts of rainfall on phytoplankton growth were examined at three Atlantic Ocean locations on the east coast of North Carolina. Bogue Sound, a euhaline (30–34 parts per 10^3 (p.p.t)) sound separating the mainland from a barrier island (Bogue Island) served as an inshore location. Continental slope waters ~1 km offshore from Bogue Banks provided a near-shore habitat, while Gulf Stream waters 25 km offshore represented a more pelagic habitat. All three locations commonly receive both acidic (continental origin) and near-neutral (oceanic origin) rainfall. Continental rain pH characteristically ranged from pH 3.5 to 5.5, while oceanic rain ranged from pH 5.5 to 6.8. Surface waters from these locations were collected in 20-l pre-cleaned polyethylene carboys throughout 1983–84, immediately brought to the Institute of Marine Sciences (IMS) and analysed for the soluble nutrients $\text{NO}_3^- + \text{NO}_2^-$, $\text{NH}_3/\text{NH}_4^+$, PO_4^{3-} and chlorophyll *a* content. Samples were collected during periods of minimal riverine runoff (salinities of at least 33 p.p.t.); however, Bogue Sound was occasionally sampled after freshwater runoff episodes, as experienced after the landfall of hurricane Dianna during mid-September 1984 (salinity = 27 p.p.t.).

Rainwater was routinely collected on the rooftop of IMS using pre-cleaned polyethylene buckets. Rainfall amounts and pH were recorded and nutrient chemistry was performed on rainwater used in bioassays.

Bioassays were performed in triplicate in 1-l pre-cleaned polyethylene Cubitainers, which were 85% transparent to photosynthetically active radiation (PAR = 400–700 nm). They were incubated in natural surface light and temperature conditions in a saltwater pond at IMS. Incubation periods lasted between 1 and 7 days. Freshly collected seawater was dispensed, followed by additions of either 10 or 20% v/v rainwater (RW) or distilled deionized water (DDW). Total bioassay volume was 900 cm^3 . Parallel N- NO_3^- (100 and 200 parts per 10^9 (p.p.b.), P- PO_4^{3-} (50 and 100 p.p.b.), and combined $\text{NO}_3^-/\text{PO}_4^{3-}$ additions were also made. A 10- μCi aliquot of ^{14}C - NaHCO_3 (68 μCi μmol ICN Corporation) was also added to each Cubitainer to monitor photosynthetic ^{14}C assimilation as a growth-response parameter. All ^{14}C assimilation results were corrected for abiotic ^{14}C precipitation and liquid scintillation quenching. The fluorometric determination of chlorophyll *a* in 90% v/v MgCO_3 -buffered acetone extracts served as an additional phytoplankton growth-response parameter.

Both oceanic and continental rain significantly ($P < 0.001$) stimulated phytoplankton primary production as observed by both ^{14}C fixation and chlorophyll *a* production (Fig. 1). Stimulation was evident with both 10 and 20% v/v additions. The more acidic continental rainfall led to much higher magnitudes of stimulation (Fig. 1). Typically, 30–70% higher phytoplankton growth yields were observed in response to acidic as opposed to near-neutral rainfall additions. Parallel NO_3^- and PO_4^{3-} additions consistently revealed exclusive NO_3^- stimulation of phytoplankton production during 1983–84. Acidic rain also led to more sustained periods of stimulation. Generally, enhanced (over control) phytoplankton growth, as monitored by chlorophyll *a* production, continued for 6–7 days in response to acid rain additions (Fig. 2). Near-neutral rainfall led to initial growth stimulation, which decreased after 2–3 days (Fig. 2). Differential growth stimulation was not directly attributable to pH; neutralized (with NaOH) acid rain yielded results identical to untreated acid rain. Similarly, near-neutral rain made more acidic did not reveal greater stimulation. Furthermore, the addition of either acid or neutral rain failed to alter ($P < 0.001$) the pre-existing pH of seawater significantly (pH = 8.36). Accord-

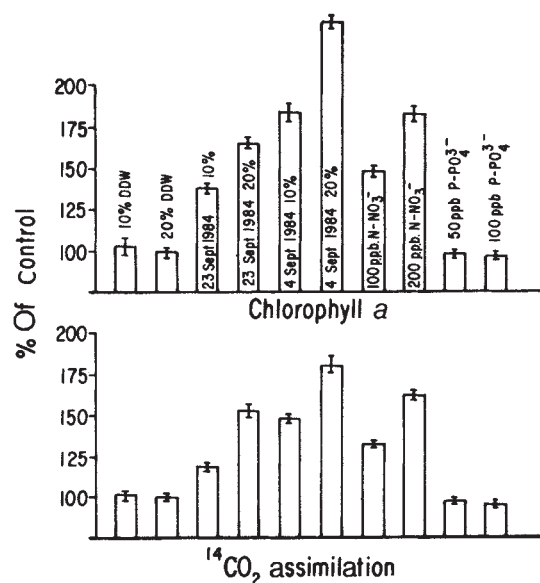


Fig. 1 Impacts of rainwater on Bogue Sound chlorophyll *a* production, and ^{14}C CO₂ assimilation following a 5-day *in situ* Cubitainer bioassay. All treatments were compared with controls (no additions). Both 10% and 20% v/v additions are shown. Rainwater collected on 4 September 1984 had a pH of 4.05, while 23 September 1984 rainwater had a pH of 5.85. Parallel 10% and 20% v/v distilled deionized water (DDW) additions revealed the impacts of equi-volume nutrient-free freshwater dilutions on Bogue Sound Water. Parallel N- NO_3^- (100 and 200 p.p.b.) and P- PO_4^{3-} (50 and 100 p.p.b.) additions consistently showed exclusive stimulation of phytoplankton growth by nitrogen. Error bars indicate variability among triplicate samples for each treatment. Biostimulation by all rainwater and N- NO_3^- additions was significant ($P < 0.001$) among the two growth parameters.

ingly, I attribute differential stimulation among, as well as between, treatments and controls to contrasting levels of dissolved inorganic nitrogen enrichment.

Chemical analyses of sea water from all sampling locations and bioassays demonstrated: (1) consistent NO_3^- depletion but PO_4^{3-} sufficiency during the main phytoplankton growth period (April–October); (2) rapid depletion of NO_3^- and $\text{NH}_3/\text{NH}_4^+$ enrichments supplied in rainwater, but a lack of concurrent PO_4^{3-} depletion either supplied in rainwater or as an individual nutrient, and (3) good agreement between the initial amount of NO_3^- , $\text{NH}_3/\text{NH}_4^+$ present in rainwater and the duration of phytoplankton growth stimulation. Lastly, a positive correlation existed between $\text{NO}_3^- + \text{NO}_2^-$ content and acidity of rainfall samples collected ($r^2 = 0.87$; $n = 15$).

Five additional bioassays, complementing those shown in Figs 1, 2, revealed that phytoplankton growth was nitrogen limited throughout the spring and summer of 1984. Atomic ratios of dissolved inorganic N : P ranged from 1 to 5 (weighted mean of 2.8), further evidence for consistent nitrogen-depleted conditions of these waters.

The choice of 10–20% (v/v) rainwater additions was based on the impacts of rainwater dilutions on near-surface (0–5 m depth) salinities following large (1–5 cm) rainfall events in coastal waters, before the dilution observed by enhanced terrigenous freshwater runoff. Near-surface salinities were commonly depressed by 2–3 p.p.t. immediately after such rainfall events. A 10% v/v bioassay rainwater addition depressed the salinity of coastal water by ~2.2 p.p.t. Hence, such additions provide reasonable approximations of natural rainwater dilution effects on near-surface seawater. Large storm systems are likely to mix rainfall inputs to depths >5 m; therefore, the estimates presented here apply to more localized short-lived storm activities, including the numerous summer thunderstorms and rapidly dissipating winter cold fronts often observed in this area.

Periodic offshore chlorophyll *a* samplings before and after storm events in 1984, substantiate bioassay-derived conclusions,

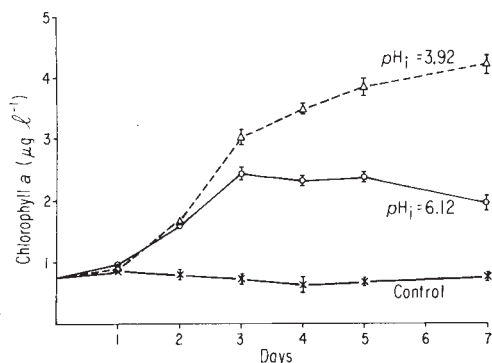


Fig. 2 Chlorophyll *a* production in Cubitainer bioassays subsampled daily following acidic versus near-neutral rainwater (10% v/v) additions. Acidic rainfall ($pH = 3.92$) characteristically showed higher magnitudes and longer-lasting stimulatory effects than near-neutral ($pH 6.12$) rainfall. Chemical analyses of acidic rainfall yielded the following results: $N-NH_4^+ = 233$ p.p.b., $N-NO_3^- + NO_2^- = 459$ p.p.b., $P-PO_4^{3-} = 9.1$ p.p.b. Near-neutral rainfall: $N-NH_4^+ = 251$ p.p.b., $N-NO_3^- + NO_2^- = 219$ p.p.b., $P-PO_4^{3-} = 3.7$ p.p.b. Control was untreated Bogue Sound water incubated in parallel. Error bars show variability among triplicate samples. Beyond day 2, all treatments were significantly ($P < 0.001$) different from each other as well as from the control.

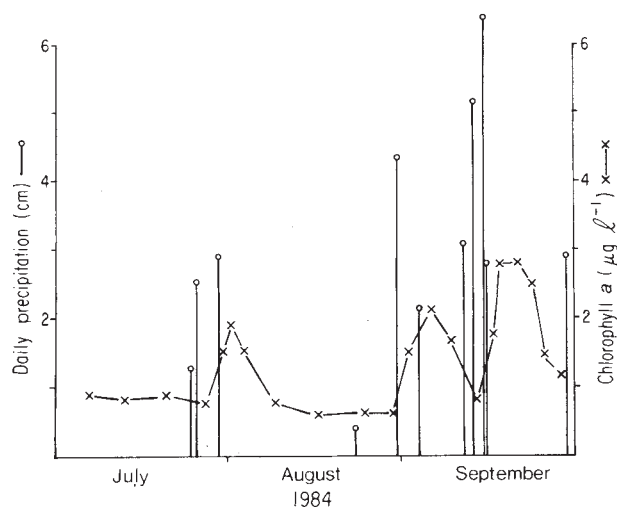


Fig. 3 Major (>0.1 cm per day) precipitation events recorded at Morehead City, North Carolina versus surface chlorophyll *a* concentrations sampled at an offshore location 5 km south-east of Bogue Banks during July, August and September 1984. All chlorophyll *a* samples were from non-turbid waters free of runoff plumes and sediment resuspension. Extensive rainfall during mid-September was due to the passage of hurricane Dianna near the North Carolina coast.

namely, that precipitation nitrogen inputs lead to significant localized enhancement of phytoplankton production in these nitrogen-depleted waters. Characteristically, a 2-day lag occurs between extensive rainfall and enhancement of near-surface chlorophyll *a* levels (Fig. 3). Chlorophyll *a* enhancement can last from a few days to several weeks. The initial (within 3 days) enhancement closely follows direct precipitation inputs, leading to small but detectable increases in NO_3^- and NH_3/NH_4^+ concentrations. Freshwater runoff sources, as delineated by suspended fine-sediment plumes and the appearance of brackish water phytoplankton species and detritus, typically do not appear in these waters until 2–3 days after the onset of chlorophyll *a* enhancement. While direct precipitation inputs seem to be responsible for initial chlorophyll *a* enhancement, terrigenous runoff probably sustains such enhancement beyond a period of several days.

Experimental and observational findings indicate that localized inorganic nitrogen enrichment attributable to direct precipitation inputs can lead to enrichment of marine primary production in near-surface waters. Annually, chlorophyll *a* concentration ranges from >1 to $5 \mu g L^{-1}$ in these waters. The observed buildup of chlorophyll *a* concentrations following direct precipitation inputs (Fig. 3) therefore constitutes a substantial fraction of maximum levels. Acidic rainfall, being enriched in NO_3^- and NO_2^- , preceded the highest magnitudes of primary production stimulation. I therefore conclude that although pH impacts of acid rain are largely insignificant in well-buffered marine habitats, nutritive impacts are both detectable and may be of long-term consequence in shaping both patterns and magnitudes of phytoplankton production. Such potential impacts are expected to be of greatest importance in waters bordering the eastern margins of land masses supporting extensive industrial and urban development. These would include the eastern seaboard of the United States and the United Kingdom, the Baltic region and the Western Pacific waters bordering Japan, Korea and China.

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Weak neutral current and β radiolysis effects on the origin of biomolecular chirality

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The possibility of a connection between the parity non-conserving weak interactions and the handedness of biomolecules has received recent attention¹. Although the asymmetric effects of the weak interactions in molecules have been estimated to be very small^{2–9}, Kondapudi and Nelson (KN)^{10–13} have shown that autocatalytic chemical systems that spontaneously break chiral symmetry^{14–19} can effectively amplify systematic chiral perturbations as small as those produced by weak neutral currents^{2–4,20}, despite the simultaneous presence of larger randomly fluctuating chiral perturbations, and hence provide a mechanism for producing the observed homochirality of biomolecules. I show here, in the light of new estimates of the asymmetric decomposition of racemic mixtures by β radiation⁹, that the chiral selection parameter due to β radiolysis can be up to six orders of magnitude larger than that resulting from weak neutral currents. This suggests that β radiolysis is more likely to be the selector of biomolecular chirality than weak neutral currents.

The same chemical kinetic model is used as in KN^{10–13} but the reactants S and T in the model are taken to be chiral, rather than achiral as assumed by KN, and only homochiral combinations of reactants with each other and with the autocatalytically formed product X are assumed to occur, for example, $S_L + T_L + X_L \rightarrow 2X_L$, $S_D + T_D + X_D \rightarrow 2X_D$. Here S and T could be, for example, chiral monomers which react to form a dimer X. Alternatively, this simple model could be interpreted as an