

## CARBON PATHWAYS AND EXPORT ASSOCIATED WITH THE SOUTHERN BENGUELA UPWELLING SYSTEM: A RE-APPRAISAL

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A network of six  $\text{NO}_3\text{-N}$ -driven carbon pathways between the ocean, shelf and sediments was described in a paper published in 1992. A budgetary approach at the annual scale meant that, if three of the pathways were quantified, solutions could be found algebraically for those remaining. The network of pathways in the present study remains unchanged in principle, but in respect of long-term carbon sequestration, there has been a shift in emphasis from ocean to continental shelf. This results from an adjusted estimate for carbon exported seawards of the continental shelf, mainly owing to a re-examination of the typical offshore penetration of upwelling-derived water. Whereas the 1992 paper used a study based on grey-scale contrast, from Meteosat imagery, to designate a region up to and occasionally beyond the 2 000 m isobath where water of upwelling origin was present on a quasi-permanent basis, the present study used actual sea surface temperatures (SSTs) from NOAA imagery and found comparatively little water  $<17^\circ\text{C}$  beyond the 350 m isobath. This adjustment has important implications for the quantification of offshore potential new production calculated from the derived relationship between SST and  $\text{NO}_3\text{-N}$  integrated over the nominal euphotic zone. The proportion of southern Benguela new production thought to be sequestered at time-scales which constitute a long-term loss to the system remains at 70%, but it is now proposed that approximately 66% is incorporated in continental shelf sediments and 4% is lost below the offshore permanent thermocline. The remaining 30% is re-cycled over shorter time-scales within the southern Benguela system.

Carbon export associated with the Benguela upwelling system and a proposed network of  $\text{NO}_3\text{-N}$  (and hence potential new production) pathways between the ocean, shelf and sediments was the subject of a study by Waldron *et al.* (1992). The variables included in that network were:

- (a) imported new production (*sensu* Roemmich 1989);
- (b) local new production (*sensu* Roemmich 1989);
- (c) southern Benguela new production;
- (d) southern Benguela new production exported seawards of the continental shelf break;
- (e) southern Benguela new production sink over the continental shelf;
- (f) the proportion of (e) sequestered in continental shelf sediments.

Budgetary considerations at the annual scale implied algebraic relationships between certain of the above variables (re-stated in Methods). Providing estimates for three of the variables permitted calculation of the remaining fluxes. In Waldron *et al.* (1992), an estimate of annual new production exported seawards of the continental shelf break (d) was made by applying measured rates of integrated  $\text{NO}_3\text{-N}$  uptake in aged upwelled water to the area of upwelling-derived water thought to occur outside the 200 m isobath (based on the interpretation of Meteosat images of sea surface temperature in Lutjeharms and Stockton [1987]). A

first estimate of Benguela annual potential new production (c) was taken from Waldron and Probyn (1992) and local new production (b) was estimated from the  $\text{NO}_3\text{-N}$  concentration difference between South Atlantic Central Water (upwelling source water) and water which upwells in the coastal zone following its passage over the shelf.

In the present study, local new production (b) has been estimated in a similar manner as previously and a refined estimate of southern Benguela annual potential new production (c) has been taken from Waldron *et al.* (1997). The main point of departure was in the estimate of southern Benguela new production exported seawards of the continental shelf break (d). It is now thought that this variable had been overestimated in Waldron *et al.* (1992). The method of estimation presented here resulted in a reduced rate and hence a modification to the annual flux of  $\text{NO}_3\text{-N}$  (and hence carbon) attributed to the algebraically linked pathways in the network.

## METHODS

### The proposed network

Imported new production (a) results from the  $\text{NO}_3\text{-N}$  content of South Atlantic Central Water (SACW, the

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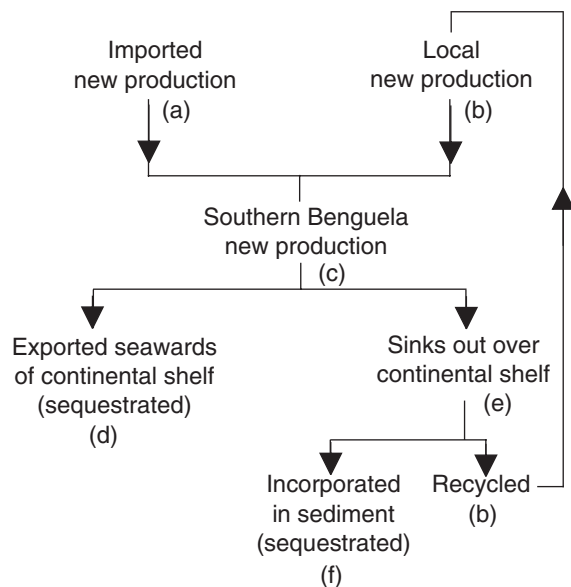


Fig. 1: Proposed network of carbon pathways (based on  $\text{NO}_3\text{-N}$ ) between the ocean, shelf and sediments in the southern Benguela upwelling system)

offshore source water for upwelling). This source water is supplemented with additional  $\text{NO}_3\text{-N}$  as it moves into the continental shelf domain (a result of local recycling processes). This enhancement has been termed local new production (b). These inputs of  $\text{NO}_3\text{-N}$  combine to form the potential new production of the southern Benguela (c). This potential new production was subdivided between that advected offshore beyond the continental shelf domain (d) and the new production which sinks out locally (e). A proportion of the latter is sequestered in continental shelf sediments (f) and the remainder is recycled as local new production (b). From this proposed network (Fig. 1), it was possible to identify links between certain variables.

- (i) Southern Benguela new production = imported new production + local new production.
- (ii) Southern Benguela new production = Southern Benguela new production exported beyond the shelf + Southern Benguela new production sink over the shelf.
- (iii) Southern Benguela new production sink over the continental shelf = Proportion of new production sink sequestered in shelf sediments + local new production.

In simple terms:  $c = a + b$ ;  $c = d + e$ ;  $e = f + b$ .

If three of the variables are known (or estimated), then solutions can be found for the remainder. The mean southern Benguela annual potential new production (c) for the 1980s has been estimated in Waldron *et al.* (1997). This estimate was obtained by relating the intensity and/or extent of upwelling events (manifested via satellite imagery as euphotic zone  $\text{NO}_3\text{-N}$  content) to coastal sea-level fluctuation filtered of tide and atmospheric pressure effects. This permitted the use of the sea-level record as a proxy for upwelling from which was obtained the estimate of mean annual potential new production. It was possible to provide an estimate for local new production (b) by comparing the  $\text{NO}_3\text{-N}$  concentration in SACW with the higher concentrations found in Benguela upwelled water (resulting from its passage over the continental shelf). In this way the proportion of southern Benguela potential new production attributable to local  $\text{NO}_3\text{-N}$  inputs could be quantified.

The southern Benguela new production exported seawards of the continental shelf break (d), which is assumed to be subject to long-term sequestration, was estimated by quantifying the potential new production in upwelling-derived water seawards of a designated isobath. The temperature range of this water was designated as 10–16.99°C inclusive (Waldron *et al.* 1997). It is not the seaward limit of new production *per se*, but that of potential new production attributable to the southern Benguela. It was decided that 350 m was a representative shelf-break depth. This is deeper than that used in Waldron *et al.* (1992), but it takes into account the shelf-break bathymetry typical of the southern Benguela upwelling system. From 10 satellite images of upwelling events (Waldron *et al.* 1997), it was possible to quantify the areas of upwelling-derived water outside the 350 m isobath and to calculate its potential new production using the same method as that described in that paper. Having provided estimates of southern Benguela potential new production (c), local new production (b) and southern Benguela new production exported seawards of the continental shelf (d), it was possible to provide estimates of the remaining variables through algebraic substitution.

## RESULTS

### Southern Benguela potential new production (c)

The mean potential new production for the southern Benguela was estimated to be  $5.60 \times 10^{13}$  gC·year<sup>-1</sup> (Waldron *et al.* 1997). This estimate is greater than the  $4.70 \times 10^{13}$  gC·year<sup>-1</sup> provided in Waldron and

Table I: Areas (km<sup>2</sup>) of 12 – 16°C inclusive water seawards of the 350 m isobath from 10 NOAA satellite images of sea surface temperature taken at times coincident with upwelling events

Year	Area (km <sup>2</sup> ) of water of different temperatures				
	12°C	13°C	14°C	15°C	16°C
1984/85	115	780	1 341	2 721	5 230
1985/86	0	3	210	1 183	3 299
1986/87	0	0	4	49	274
1987/88	0	0	0	0	0
1988/89	0	0	230	521	1 768
1989/90	0	0	35	274	956
1990/91	0	6	16	344	1 342
1991/92	0	0	28	975	2 642
1992/93	0	0	0	0	48
1993/94	0	0	31	286	3 020

Probyn (1992), even though the latter study considered the whole Benguela upwelling system. The Waldron *et al.* (1997) study, which employed a combination of satellite imagery and an upwelling proxy, was a refinement of the method of Waldron and Probyn (1992), which used one satellite image of SST during a system-wide upwelling event and an annual estimate of the number of events from synoptic weather charts. This approach provided a reasonable first estimate but assumed equivalence between events and ignored the smaller-scale upwelling signal evident in the record of coastal sea-level fluctuation.

#### Local new production (b)

Bailey (1985) quoted the NO<sub>3</sub>-N concentration of SACW as 10–15 mmol·m<sup>-3</sup>. Jones (1971) and Henry (1975) gave values of 10–18 mmol·m<sup>-3</sup>. Andrews and Hutchings (1980) reported southern Benguela upwelled water (Cape Peninsula upwelling cell) with a NO<sub>3</sub>-N signature of 20 ± 4 mmol·m<sup>-3</sup>. The median value for SACW (14 mmol·m<sup>-3</sup>) and the mean value for upwelled water (20 mmol·m<sup>-3</sup>) implies that there has been a 43% increase in NO<sub>3</sub>-N during its passage over the continental shelf and that 30% of southern Benguela potential new production can be attributed to local new production. This being the case, the potential for local new production (b) was estimated as 1.7 × 10<sup>13</sup> gC·year<sup>-1</sup>.

#### Southern Benguela new production exported seawards of the continental shelf break (d)

An analysis of the 10 satellite images of prominent upwelling events used in Waldron *et al.* (1997)

Table II: Potential new production (expressed in carbon) seawards of the 350 m isobath and its percentage of the event-scale estimate of potential new production

Year	Off-shelf new production (gC)	Event new production (gC × 10 <sup>12</sup> )	Percentage
1984/85	1.35 × 10 <sup>11</sup>	1.08	12.5
1985/86	5.73 × 10 <sup>10</sup>	1.11	5.2
1986/87	3.85 × 10 <sup>9</sup>	0.52	0.7
1987/88	0.00	0.62	0.0
1988/89	3.09 × 10 <sup>10</sup>	0.85	3.6
1989/90	1.52 × 10 <sup>10</sup>	0.78	2.0
1990/91	2.04 × 10 <sup>10</sup>	1.11	1.8
1991/92	4.40 × 10 <sup>10</sup>	0.61	7.2
1992/93	5.43 × 10 <sup>8</sup>	0.59	0.1
1993/94	3.87 × 10 <sup>10</sup>	1.20	3.2

revealed no 10 or 11°C water outside the 350 m isobath and that 12°C water was present on only one occasion. The 1987/88 image of SST showed no upwelling-derived water seawards of the 350 m isobath. A summary of the areas (km<sup>2</sup>) of 12–16°C inclusive water outside the shelf break for each image is given in Table I.

Using the integrated NO<sub>3</sub>-N (mmol·m<sup>-2</sup>) values applicable to these temperature bands (Waldron *et al.* 1997), it was possible to calculate the quantity of NO<sub>3</sub>-N available to the biota in these off-shelf waters and to convert it to potential new production (gC). These potential estimates of new production can then be expressed as a percentage of the event-scale potential new production (Table II).

From these results it is estimated that up to 12.5% of southern Benguela potential new production per upwelling event takes place seawards of the continental shelf. The mean percentage for the 10 events (admittedly within the context of a wide range) is 3.6%. The mean annual potential new production of the southern Benguela has been estimated as 5.6 × 10<sup>13</sup> gC, and therefore it is calculated that, on average, 2.0 × 10<sup>12</sup> gC·year<sup>-1</sup> is exported beyond the continental shelf and sequestered below the permanent thermocline. The arguments presented herein do not preclude the offshore transport of particulate organic carbon seawards of the continental shelf. When presenting NO<sub>3</sub>-N assimilation as being equivalent to a sink for carbon, the argument only holds over appropriate time-scales (in this case the annual scale of nitrate flux).

#### Network of carbon pathways

With southern Benguela potential new production (c) being 5.60 × 10<sup>13</sup> gC·year<sup>-1</sup>, local new production

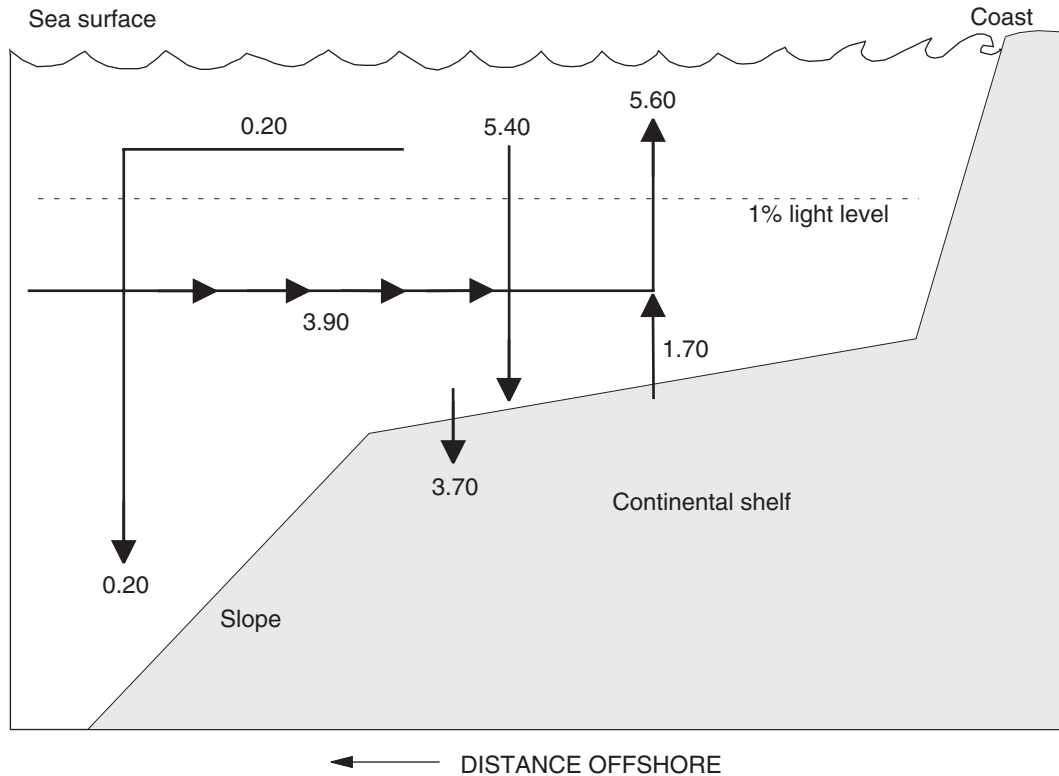


Fig. 2: Two-dimensional network of  $\text{NO}_3\text{-N}$ -driven carbon pathways in the southern Benguela upwelling system. Annual estimates of carbon flux ( $\text{gC} \times 10^{13}$ ) have been assigned to each pathway as imported new production (3.90); local new production (1.70); southern Benguela new production (5.60); southern Benguela new production exported seawards of the continental shelf break (0.20); southern Benguela new production sink over the continental shelf (5.40); proportion of southern Benguela new production sink over the continental shelf sequestered in continental shelf sediments

(b) being  $1.70 \times 10^{13} \text{ gC} \cdot \text{year}^{-1}$ , and southern Benguela new production exported seawards of the continental shelf break (d) being  $2.00 \times 10^{12} \text{ gC} \cdot \text{year}^{-1}$ , the remaining variables in the network of new production (carbon) pathways can be calculated algebraically.

Thus, imported new production (a) is (c) – (b), or  $3.9 \times 10^{13} \text{ gC} \cdot \text{year}^{-1}$ , southern Benguela sink over the continental shelf (e) is (c) – (d) or  $5.40 \times 10^{13} \text{ gC} \cdot \text{year}^{-1}$ , and the proportion of (e) sequestered in continental shelf sediments (f) is (e) – (b), or  $3.7 \times 10^{13} \text{ gC} \cdot \text{year}^{-1}$ .

A two-dimensional schematic of these carbon pathways, with annual estimates included, is given in Figure 2.

## DISCUSSION

The network of carbon pathways presented in this

chapter is the same, in principle, as that of Waldron *et al.* (1992). The values assigned to certain of the input variables, however, have been modified in the light of an adjusted estimate for carbon exported beyond the shelf (d) and the resulting algebraic carry-on effect. The new estimate for carbon exported seawards of the continental shelf in the southern Benguela ( $0.20 \times 10^{13} \text{ gC} \cdot \text{year}^{-1}$ ) should be compared with the  $3.2 \times 10^{13} \text{ gC} \cdot \text{year}^{-1}$  for the whole Benguela given by Waldron *et al.* (1992). The reason for this re-appraisal stems partly from the designation of a deeper shelf break in the present study (350 v. 200 m), but mainly from a redefinition of the typical seaward extent of upwelling-derived water. The areal extent of the upwelling system relevant to the regional export of carbon in Waldron *et al.* (1992) was derived from some of the conclusions of Lutjeharms and Stockton (1987). Their Figure 3 showed a montage of the frontal boundary of the upwelling system compiled

from thermal infra-red data obtained from the METEOSAT II satellite. From this, Waldron *et al.* (1992) designated a region where cold water of upwelling origin was present system-wide on a quasi-permanent basis, as well as a more offshore region in the northern Benguela where the presence of such water was intermittent.

The earlier study (Waldron *et al.* 1992) was conducted in the same manner as the present study, so resulting in an estimate for off-shelf new production. The seaward extension of upwelling-derived water on a quasi-permanent and intermittent basis was found in the earlier study to be up to, and occasionally beyond, the 2 000 m isobath. However, the analysis performed on the 10 NOAA images of SST in the current study found comparatively little water  $\leq 17^\circ\text{C}$  beyond the 350 m isobath. It should be noted that, if the Waldron *et al.* (1992) study had only considered the southern Benguela, the offshore presence of upwelling-derived water would still have been overestimated when compared with the method using the sequence of NOAA images.

In Lutjeharms and Stockton (1987), daily METEOSAT II images in the form of photographic negatives were interpreted in such a manner that the line of greatest grey-scale contrast in the South-East Atlantic Ocean was assumed to be the boundary between the cold upwelled water and the offshore South Atlantic Surface Water. This was probably the best option available in the context of METEOSAT II images, but the subsequent objective analysis of temperature-defined NOAA images (albeit only 10) of prominent upwelling events seems to indicate that it resulted in overestimation of the extent of upwelling-derived water and concomitant overestimation of carbon export beyond the shelf by Waldron *et al.* (1992). In that calculation, the lower estimate of carbon exported seawards of the continental shelf break (d) resulted in a higher estimate of the sink of carbon over the shelf (e), invoking the requirement for increased sequestration in shelf sediments (f), given that local new production (b) had remained much the same.

Having attempted to explain the main discrepancy between the results of Waldron *et al.* (1992) and those in this paper satisfactorily, it was thought appropriate, where possible, to test the validity of certain of the algebraically calculated variables. The imported new production was estimated as the difference between the entire southern Benguela potential new production and potential new production attributable to local shelf inputs of  $\text{NO}_3\text{-N}$ . The  $3.9 \times 10^{13} \text{ gC}\cdot\text{year}^{-1}$  calculated for this variable relied upon the  $\text{NO}_3\text{-N}$  content of SACW, which has a  $\text{NO}_3\text{-N}$  concentration  $\cong 14 \text{ mmol}\cdot\text{m}^{-3}$  (Henry 1975, Bailey 1985), or some  $1.1 \text{ gC}\cdot\text{m}^{-3}$  ( $14 \times 6.6 \times 12/1\ 000$ ).

It can be calculated that the volume of water required to account for imported new production would be  $3.5 \times 10^{13} \text{ m}^3\cdot\text{year}^{-1}$ . Scaling this volume transport to a more convenient unit of oceanic flux gave a value of 1.1 Sv (over 365 days) or 1.5 Sv (over 274 days, which excluded winter). Stramma and Peterson (1989) found an imbalance in the transport field between 24 and 32°S of 2 Sv, which they attributed to coastal upwelling. Their latitudinal range was shifted farther north than the range of this study (southern Benguela, 29–35°S) and hence included the prominent Lüderitz upwelling cell, but at the expense of the Cape Columbine and Cape Point upwelling cells. Taking these compensating factors into account implies agreement at a broad scale with the  $\text{NO}_3\text{-N}$  derived volume flux of 1.0 – 1.5 Sv.

The estimate given here for the southern Benguela carbon sink over the continental shelf (e) is  $5.40 \times 10^{13} \text{ gC}\cdot\text{year}^{-1}$ . The dimensions of the continental shelf between 29 and 35°S give a length of approximately 670 km and a mean width of approximately 150 km. The shelf area of  $1 \times 10^{11} \text{ m}^2$  invokes a sedimentation rate of  $540 \text{ gC}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$ , i.e.  $1.5 \text{ gC}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ . Bailey (1987), from sediment trap studies, found a sedimentation rate of  $4.8 \text{ gC}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$  in the productive St Helena Bay region and a mean rate of  $3.7 \text{ gC}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$  on the lee side of Benguela upwelling centres. The shelf average presented here ( $1.5 \text{ gC}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ ) seems appropriate in the present context.

The remaining algebraically calculated variable, the proportion of (e) sequestered in the continental shelf sediments, cannot be verified easily owing to a lack of independent evidence. The flux of this pathway resulted from a high rate of sedimentation (and assumed sequestration) and may not be borne out by a comparison of, say, the organic carbon content of the sediment and its rate of deposition. This possibility opens an avenue of future research into biogeochemical recycling. It may be necessary to invoke (and investigate) a pathway for organic carbon between the continental shelf and slope similar to that proposed in the Shelf Edge Exchange Processes (SEEP) hypothesis (Walsh *et al.* 1981). Although support for the hypothesis was not found in relation to the shelf off the east coast of North America, Rowe (1987) stated that other shelves, especially those of upwelling systems, have a greater potential for the export of organic carbon. The work of Monteiro (1996) suggests that such a study would have to take into account the possibility of spatial heterogeneity in shelf accumulation of organic carbon and sites of selective deposition in its export to the slope.

This future avenue of research notwithstanding, the main variable of interest was the quantity of carbon sequestered as a consequence of southern



Benguela potential new production. This was equivalent to the carbon sequestered on the continental shelf (f), a proportion of which may be subject to shelf/slope exchange, plus the new production, initially exported in the euphotic zone, beyond the shelf boundary (d). This gives a combined value of  $3.9 \times 10^{13}$  gC·year<sup>-1</sup>. The finding of the present study is that approximately 70% of southern Benguela potential new production was sequestered at time-scales which constituted a long-term loss to the system.

The complexity of carbonate chemistry (which lies outside the scope of this paper), different methods of approach and a shift from two to three dimensions may result in future research redefining the pathways and/or assigning different rates within the network. For example, this has been the case in the present study, when compared to Waldron *et al.* (1992). Modification of the method used to quantify new production exported beyond the continental shelf has resulted in a greatly increased local sink of new production, with greater sequestration in shelf sediments.

It should be emphasized here that the carbon pathways and their attributed rates relate to the transport of NO<sub>3</sub>-N converted to carbon. The status of the upwelling system as a net source or sink of CO<sub>2</sub> has not been addressed. Recent studies (P. M. S. Monteiro, S. A. Council for Scientific and Industrial Research, pers. comm.) may point to the southern Benguela as a net source, resulting from the superimposition of non-organic pathways within the system. This being the case, the pathways described here only act to offset biologically the system's carbon status.

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