Chapter 3

C, N, P Fluxes in the Coastal Zone

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3.1 Introduction

Human activities have profoundly altered the global biogeochemical cycles of many elements and compounds. These changes have not only direct effects on environmental quality, in terms of ecosystem productivity, biodiversity and sustainability for human use, but also indirect effects on climate change. A major consideration in LOICZ, and indeed throughout IGBP, concerns the biogeochemical interactions among various major compartments of the Earth system. Viewing the Earth system as an array of coupled biogeochemical cycles allows us to simplify the movements of material on Earth and their couplings to climate (Jacobson et al. 2000). While many elements play a role in these biogeochemical reactions, the elements carbon, nitrogen and phosphorus stand out for several reasons:

- All three elements are required for life processes. Carbon is the basic building block of life, nitrogen is a key element in protein and phosphorus is a key element in ATP (see Schlesinger 1997, for a review of the biogeochemistry of these elements).
- All three have major global compartments (land, ocean, atmosphere) that are depleted in the open ocean by biogeochemical processes, potentially altering ecological function. For example, the atmosphere has a sufficiently low concentration of C (largely in the form of CO_2) that atmospheric concentrations vary both seasonally and inter-annually in response to global metabolism – uptake to and release from biomass (e.g., Keeling et al. 1995). Nitrogen and phosphorus are depleted to near analytical detection limits in many parts of the surface ocean (Sverdrup et al. 1942). While both carbon and nitrogen are rapidly circulated via the atmosphere, phosphorus has no significant gas phase (Schlesinger 1997).
- A long-recognised paradigm for budgeting C, N and P is that there tend to be rather well-preserved consistent composition and flux ratios among these elements for the buildup and decomposition of organic matter. Thus, information about one of the elements carries information about the other elements as well. Perhaps the best-known example of this tendency towards a constant composition ratio, or stoichiometry, is the Redfield Ratio (Redfield 1958). Planktonic organisms in the sea tend towards a constant C:N:P molar composition ratio of 106 : 16 : 1. As these organisms decompose in the water column below the photic zone, they release C, N and P in this ratio. A result is that the dissolved inorganic C, N and P content of the deep water column increases in this ratio (see also Takahashi et al. 1985, Watson and Whitfield 1985).
- Environmental changes associated with human activities are altering the abundance of these elements in one or more of the major global compartments. For example, fossil fuel and biomass burning liberates CO_2 and elevates the atmospheric concentrations (Prentice et al. 2001). Discharge of waste products from human activities elevates concentrations of all of these elements in surface waters (Meybeck 1982, Meybeck et al. 1989). Land-use practices associated with activities such as agriculture, deforestation, dam construction and urban development also alter these concentrations, resulting in dramatic disruptions of coastal and estuarine ecosystems (Cooper and Brush 1991, Caraco and Cole 1999, Rabalais et al. 2002).
- Fundamental differences in the geochemical processes of C, N and P control how these elements are distributed between gas, solid and dissolved inorganic and organic phases in water, sediments and soils (Schlesinger 1997). Changes in their relative proportions may further enhance eutrophication by favoring noxious and harmful algal blooms (Officer and Ryther 1980, Smayda 1990, Conley et al. 1993, Justic et al. 1995, Dortch et al. 2001, Rabalais et al. 2002, Smith et al. 2003).

Other elemental constituents are also important. For example, silicon (Si), if limiting, may change the compositions of phytoplankton and the entire food web (Officer and Ryther 1980, Turner et al. 1998, Humborg et al. 2000). Iron (Fe) may in some oceanic regions limit overall primary productivity or certain taxa (cyanobacteria) (see Boyd and Doney 2003).

Many inventories or models of the Earth system simply treat the coastal zone as an integral part of larger land, ocean and atmosphere compartments (e.g., Schlesinger 1997, Prentice et al. 2001). Such a simple division is heuristically persuasive, and indeed many traditional university earth science departments are organised roughly along these lines. Such a division, carried to the extreme in models and inventories, misses important information discussed below and in Sect. 3.2.

3.1.1 The Coastal Zone and Fluxes

There is no well-defined boundary between the land and ocean in terms of global biogeochemical function. Human population density and many activities associated with humans show strong gradients of change near the coastline. About half the world's population, most of the world's large cities, much of the world's agriculture, and a high proportion of the infrastructure associated with transport lie within about 100 km of the coastline (Scialabba 1998, WRI 2000). While humans are, for the most part, constrained to live on the landward side of the coast compartment, the zone of intense human activity and influence crosses it. Aquaculture, fisheries, marine transport, mineral extraction and other human activities occur along the continuum of the coastal compartment and generally decrease with distance from the coastline.

Within the coastal ocean, the sea floor is a second important component. Organisms live there, in abundance. Organic material, either produced in the coastal ocean or delivered from outside (from land, largely via rivers; from the ocean, largely via upwelling), settles on the bottom and decomposes there. This sets up strong chemical reactions leading to oxygen depletion and gradients (especially oxygen) in the water column and into the sediments. These gradients profoundly influence the chemistry of material decomposition, regeneration and flux (Reeburgh 1983, Seitzinger 1988, Canfield 1989).

With distance away from the coastline, human influence diminishes and water becomes deeper. Biogeochemical processes become dominated by the water column with relatively little land and sea-floor sediment influence. In much of the ocean, direct human influence and sea-floor influence are most intense along the edge of the continental shelf – an average depth of about 130 m (see Text Box 1.1, Chap. 1), which may occur anywhere from a few kilometers to hundreds of kilometers offshore. About 8% of the world ocean area lies on the shelf (Sverdrup et al. 1942), and most human and sea-floor influences occur within this relatively small area of the ocean. Any conceptual model that describes the land as a homogeneous box connected to a homogeneous ocean misses these important gradients in biotic composition and ecosystem function. Most human activity on Earth

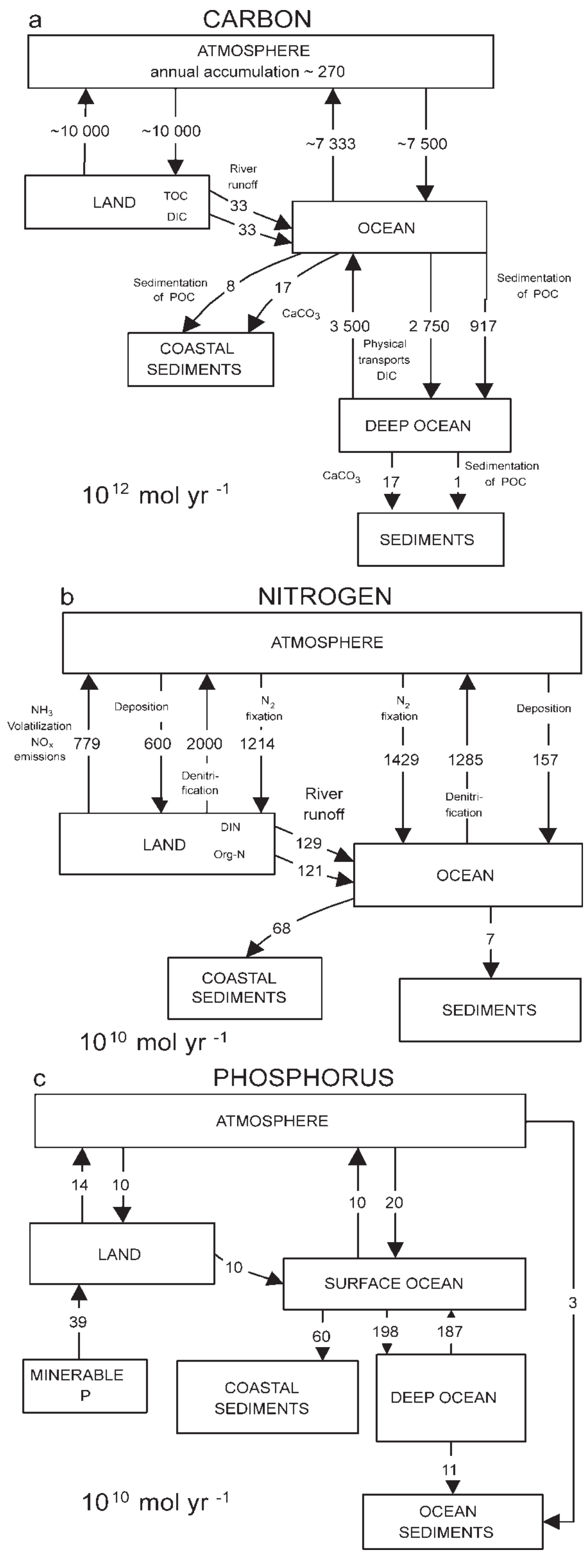

Fig. 3.1. Global budgets. "Conventional wisdom" on global C, N and P cycles. **a** Global carbon cycle, with particular emphasis on the coastal ocean (modified from Prentice et al. 2001). **b** Global nitrogen cycle, with particular emphasis on the coastal ocean (modified from Jaffe 2000). **c** Global phosphorus cycle, with particular emphasis on the coastal ocean (modified from Jahnke 2000)

occurs in this gradient zone between land and sea on both the landward and seaward sides of the coastline.

Standard models of the Earth system deal mostly with vertical fluxes; this has influenced the structure of the IGBP programme and the structure of most global models. In part, this conceptualisation has been driven by the observation that the global carbon budget is dominated by vertical transports (Fig. 3.1a). However, delivery of other materials to the coastal zone and fluxes within the coastal zone are dominated by horizontal transports. This can be recognised from Figs. 3.1b and c if it is assumed that less than 50% of the atmospheric deposition fluxes are likely to occur in the coastal zone.

Flow of both surface runoff and groundwater from land is the dominant source of material delivery from land. A combination of mixing and advection creates bi-directional processes that exchange materials between the coastal zone and the ocean interior. Vertical fluxes of some materials are important. For example, fluxes of gaseous materials (especially CO_2 and O_2) are driven by partial pressure differences between the atmosphere and surface water. The driving mechanisms include both elevation of atmospheric CO_2 due to fossil fuel combustion and internal biogeochemical processes altering local water composition both spatially and temporally. Nitrogen gas also exchanges vertically, largely due to the metabolic processes of nitrogen fixation and denitrification. Fallout of nitrogenous pollutants is also locally important (see Text Box 3.1).

Clearly, the oceanic hydrological cycle includes not only flow from land but also direct precipitation and direct evaporation. It should be emphasised that for C, N and water, the important internal processes regulating fluxes include forward and back reactions that largely cancel one another and, at the scale of the coastal zone, are not important net reactions.

For the vertical fluxes across the air-sea interface, it may be reasonable to treat the whole ocean as a single box; however, the coastal ocean clearly processes organic matter, nutrients and sediments delivered (horizontally, largely by freshwater discharge or runoff) from the land very differently than the open ocean processes the same materials. In effect, the land and coastal ocean are tightly coupled horizontally; the coastal ocean and open ocean are also coupled horizontally. In contrast, the land–open ocean coupling is mainly vertical (via the atmosphere) and is largely restricted to gases and aerosols.

The factors characterising the coastal zone, including its heterogeneity of environments, are the coastal interactions of the marine environment (the composition and rate of the ocean water entering the system), terrestrial inputs (primarily in the form of freshwater inflow and its associated dissolved and suspended loads), and the geomorphology of the coastal system (depth, coastal complexity). Taken together, these factors determine not only the fluxes into the system, but also the residence time of water within the system. If we view the coastal water mass and its associated ecosystems as a biogeochemical reactor, the residence time is a measure of how long the reactions are allowed to proceed, which in turn will strongly affect the relative net rates of conservative and non-conservative reactions (fluxes) within and through the system. Because of the freshwater inputs, estuarine conditions in the coastal zone cover a much broader range of salinities than is common in the open ocean, supporting very different ecosystems and sustaining a wider variety of geochemical as well as biochemical reactions. Some of these issues are discussed in more detail in Sect. 3.2.

3.1.2 Elemental Cycles and Fluxes

Box diagrams illustrating slight modifications of recently published versions of the global C, N, and P cycles are presented as Figs. 3.1a–c. Three characteristics of the three cycles are presented here for consideration:

- First, none of the cycles balances very well. Imbalance in the carbon cycle, which is probably the most intensively studied of the three, is manifested in the so called *missing carbon sink* that has frustrated researchers for more than 20 years (e.g., Schimel 1995, Schindler 1999). The nitrogen cycle is particularly poorly balanced, apparently largely reflecting the problem of deriving confident global estimates of nitrogen fixation and denitrification both on land and in the ocean.
- A second characteristic of the budgets is the contrast of their dominant terms. For example, carbon fluxes are overwhelmingly dominated by atmospheric transfers to and from the land and ocean, while phosphorus fluxes largely represent horizontal (hydrological) transfers. For phosphorus, dust transport can be locally important. Nitrogen, with the aforementioned caveats about uncertainties in nitrogen fixation and denitrification, has strong vertical and horizontal flux components.
- Finally, with sediments being the net repository for land-derived materials that do not accumulate in the atmosphere, most sediments accumulate in the coastal zone. One significance of this observation is that chemical reactions in shallow-water sediment are largely anoxic, in contrast with largely oxic reactions in the water column and the very slow sedimentation regime of the open ocean. The chemical reaction pathways and products differ substantially, so the products of the coastal zone differ markedly from those of the open ocean.

Human activities have greatly perturbed fluxes of some materials to the coastal ocean. Fluxes of both N and P have increased worldwide by more than a factor of two over pre-human estimates (Meybeck 1982, 1998, Howarth et al. 1996, Galloway and Cowling 2002, Smith et al. 2003). Knowledge about nutrient retention and transformations on land and in the coastal zone is, to a large extent, based on studies from the north temperate regions (Billen et al. 1991, Howarth et al. 1996, Jickells 1998, Nedwell et al. 1999, Nixon 1995, Nixon et al. 1996), but knowledge and predictions for tropical regions are increasing (Downing et al. 1999, Seitzinger et al. 2002).

Dramatic changes in the global nitrogen (N) cycle have occurred during the last 100 years due to an increase in easily utilisable N inputs by human activities (Vitousek et al. 1997, Caraco and Cole 1999). It has been estimated that the transfer of riverine reactive nitrogen to the coastal ocean has increased three to four times (Galloway and Cowling 2002, Smith et al. 2003). Human impacts on the global P cycle are less clear, but have apparently more than doubled the inputs to the ocean and caused accumulation of fertiliser P in cultivated soils. This accumulation eventually leads to increased water-borne loads to aquatic ecosystems (Bennett et al. 2001, Smith et al. 2003).

A fourth element, silicon (Si), which has not been a focus of LOICZ studies, warrants attention. Under pristine conditions, Si levels in freshwater tend to be high. Human activities tend to elevate N and P concentrations in water, but do not ordinarily elevate Si concentrations. Instead, elevated N and P in freshwater often cause blooms of siliceous plankton (dominantly diatoms) in lakes, reservoirs and other freshwater bodies. This in turn can lower Si concentrations well below normal concentrations (Turner and Rabalais 1991, Ittekkot et al. 2000). The depletion of Si reaching coastal waters can alter the composition of plankton blooms that occur there, away from typical domination by diatoms to non-diatoms with subsequent alterations to trophic structure (Conley and Malone 1992, Conley et al. 1993, Turner et al. 1998). An alternative to the widely-held view that Fe limits primary production in some oceanic regions replete with N and P (e.g., Coale et al. 1996) is the possibility that low Si concentration limits primary production under these conditions (Dugdale and Wilkerson 1998).

Carbon (C) flux is probably the most complex of the elements which have formed the focus of LOICZ interest to date (Fig. 3.1a). By far the largest flux of C to and from the ocean is via the gas phase (CO_2). This is a bi-directional flux, driven by both biogeochemical reactions within the water and elevated CO_2 in the atmosphere. Under pristine (pre-human impact) conditions, this flux would be slightly negative (Smith and Mackenzie 1987, Sarmiento and Sundquist 1992, Smith and Hollibaugh 1993), due to the net oxidation of organic matter in the ocean and consequent release of CO_2 to the atmosphere. Human activities, largely burning of fossil fuel, have driven this flux rather strongly positive by elevating atmospheric CO_2 partial pressure and causing pressure-driven transfer to the ocean water column. This flux dominates the delivery of C to the ocean. In addition, organic C (about half dissolved, half particulate) is delivered via rivers. While soil erosion has tended to elevate this flux, sediment trapping in the landscape has apparently tended to counter it (Stallard 1998, Smith et al. 2001, 2003). Finally, dissolved inorganic C in river water has probably been elevated somewhat due to enhanced weathering associated with acid precipitation. Of these fluxes, the organic carbon flux, especially the particulate organic carbon flux, is apparently largely retained or processed in the coastal ocean (Smith and Hollibaugh 1993, Berner 1982, Hedges and Keil 1995). Fluxes involving the calcium carbonate minerals (see Fig. 3.1: $CaCO_3$) are numerically small compared with the organic and dissolved inorganic C fluxes, but are disproportionately important as ocean ecosystem indicators and in terms of their significance to low-latitude coastal zone structure and function.

Almost all marine carbonates that are formed in today's ocean are the result of biogenic precipitation in the surface layer. Carbonate contributions to sediments are about equally divided between the oceanic and coastal domains, but this balance appears sensitive to climatic variations (Milliman and Droxler 1996). Noteworthy car-

Text Box 3.1. Nitrogen deposition and the LOICZ nutrient budgets

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Nitrogen deposition should, in principle, be included as a vertical input flux to the nitrogen budgets. Except for a few site budgets for which the authors had estimates of nitrogen deposition, this has not been included in the LOICZ nutrient budgets. In general, this flux is small relative to the horizontal flux terms (horizontal inputs from land; exchanges with the ocean), so this omission should not be a major error. This does not imply that nitrogen deposition is not globally important but rather that, at the scale of individual coastal zone budgets, direct deposition is usually not important. Of course, the horizontal input from land includes nitrogen deposited on, then washed off, the landscape.

When most of the budgets were developed, we did not have a global map of N deposition. We have recently obtained such a map (Fig. TB3.1.1a, from van Drecht et al. 2001). Note the "hot spots" of deposition in the eastern US, much of Europe and much of Asia. Note also that measurable deposition can extend well offshore in some regions. Rather than revising all of the budgets, we have examined the budgets to compare the horizontal loading and vertical deposition of nitrogen. As illustrated in Fig. TB3.1.1b, there is a large range in terrigenous nitrogen load, from <10 to $>10^4$ mmol $m^{-2} yr^{-1}$. The data in Figs. TB3.1.1a and b can be used to calculate atmospheric deposition as a percentage of the LOICZ budgeted load (Fig. TB3.1.1c). Most budget sites with a significant percentage of nitrogen deposition are characterised by very low N load; in these systems non-conservative DIN flux is also relatively low. Our conclusion is that failure to include nitrogen deposition in most of the budgets is not a particular shortcoming.

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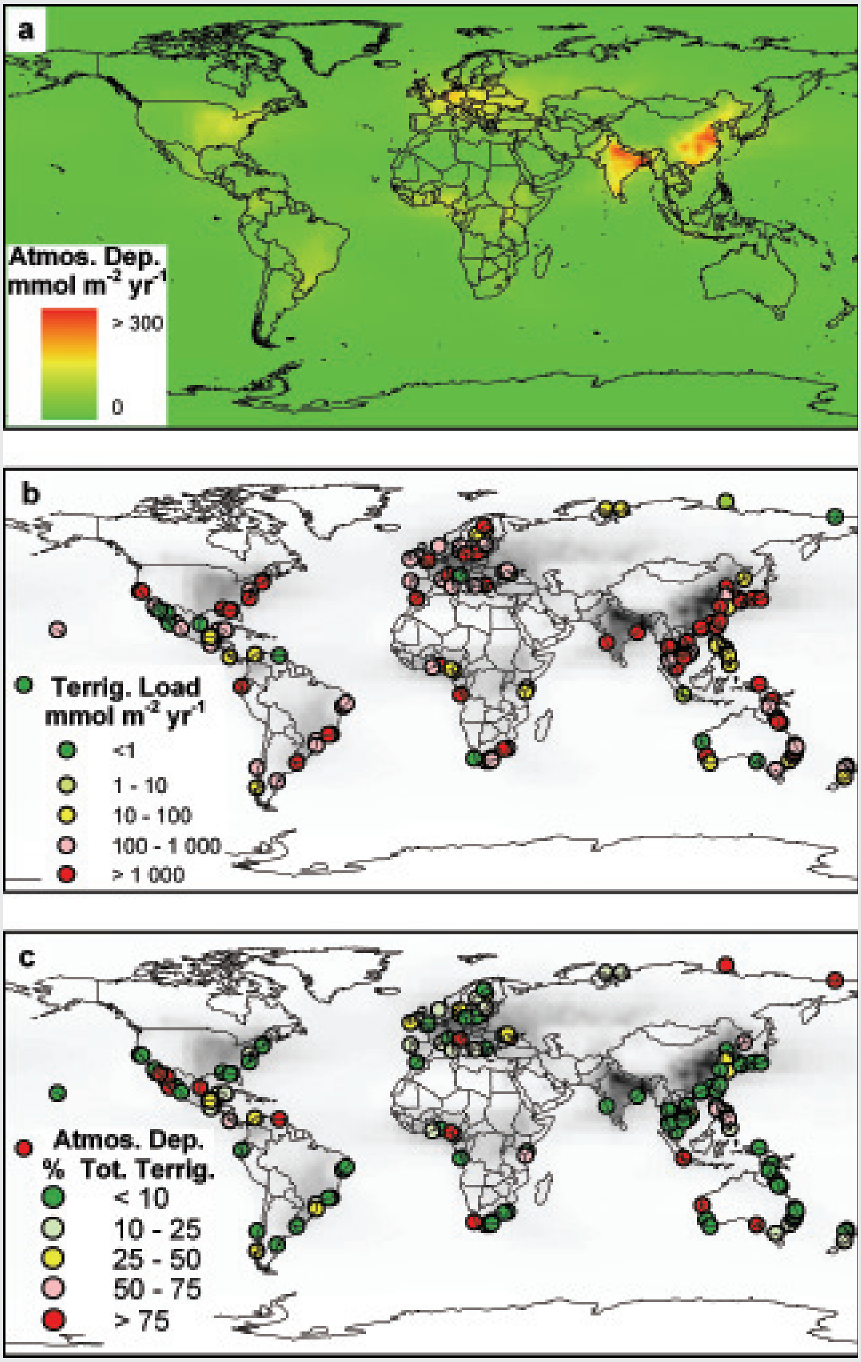
Fig. TB3.1.1.
a Global variation in estimated atmospheric nitrogen deposition (fluxes in mmol $m^{-2}\,yr^{-1}$, from van Drecht et al. 2001).
b Terrigenous nitrogen loading at the budget sites, as estimated during the budgeting and scaled to the area of the sites (fluxes in mmol $m^{-2}\,yr^{-1}$).
c Atmospheric N deposition as a percentage of the budgeted DIN load



bonate producers in shallow tropical waters are the organisms that make up coral reef ecosystems, which are important as habitats, economic resources and biogeomorphic agents and thus determine the physical structure of many coastal environments (Pernetta and Milliman 1995). The exchange of rising atmospheric CO_2 concentrations with the surface ocean shifts the inorganic carbon equilibrium to reduce pH and carbonate ion (CO_3^{2-})

Text Box 3.2. CO_2, calcification and coastal zone issues

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Intuitively, it would appear that the precipitation of $CaCO_3$ is a sink for atmospheric CO_2. That is not the case. There are various ways that the $CaCO_3$ precipitation reaction can be represented. The following form of the reaction equation demonstrates that the carbon used during the precipitation reaction is derived from bicarbonate (HCO_3^-) in solution, and that the reaction drives CO_2 out of the water.

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O \qquad (1)$$

As discussed in detail by Smith (1985), Ware et al. (1992), Frankignoulle et al. (1998), Froelich (1988), and Gattuso et al. (1999), the precipitation of $CaCO_3$ truly does release CO_2 to the atmosphere.

In freshwater and as represented by Eq. 1, one mole of CO_2 is released to the atmosphere for each mole of $CaCO_3$ precipitated. The situation is somewhat more complicated for seawater. At the present atmospheric pCO_2 of about 380 µatm and with the buffer capacity of seawater, some of the "CO_2" and "H_2O" produced back-react to HCO_3^- and H^+, so that only about 0.6 moles of CO_2 escapes to the atmosphere for each mole of $CaCO_3$ precipitated.

The chemical behaviour of CO_2 in ocean water is well understood, but it is complex and may seem counterintuitive. In water, dissolved CO_2 forms an equilibrium system described by Eq. 2. The more acid the water, the higher the concentration of CO_2; the more basic, the higher the relative proportion of carbonate ion (CO_3^{2-}), with the bicarbonate ion (HCO_3^-) acting as an intermediate species. Ocean water chemistry is dominated by the bicarbonate ion, with relatively minor amounts of CO_2 and carbonate ion.

$$H_2O + CO_2 \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-} \qquad (2)$$

Increased CO_2 gas in the atmosphere drives more gas into the ocean, across the air-sea interface. Hence, the top 100 or so meters of the ocean has absorbed much of the anthropogenic CO_2. When additional carbon dioxide dissolves in water, it forms H_2CO_3 (carbonic acid), a weak acid that tends to shed a hydrogen ion, which in turn will reduce the concentration of carbonate ion by enhancing the reaction in Eq. 3:

$$H^+ + CO_3^{2-} \leftrightarrow HCO_3^- \qquad (3)$$

Carbonate mineral saturation state (Ω) is related to the product of the concentrations of the carbonate and calcium ions. If the water is in thermodynamic equilibrium with the solid phase (i.e., neither dissolution nor precipitation tends to occur), then $\Omega = 1$. Most surface ocean waters are supersaturated with respect to calcium carbonate minerals ($\Omega > 1$). The tropical waters where coral reefs occur have commonly had $\Omega > 4$ for the past several million years.

Figure TB3.2.1 illustrates the calculated changes occurring as a result of rising atmospheric CO_2 levels. By the time atmospheric CO_2 doubles later in this century (as projected by the International Panel on Climate Change 2000), oceanic carbonate ion concentrations will be about two-thirds of their pre-industrial value. Figure TB3.2.2 illustrates with maps the effects of rising atmospheric CO_2 on carbonate (aragonite) saturation state over two centuries of human influence.

Many calcifying organisms in the ocean depend on the carbonate ion concentration in water to build their skeletons. When its concentration is reduced, calcification rates reduce, resulting in either smaller or structurally weaker organisms, or both, with resultant effects on structure of coastal habitat. The calcification effects of changing CO_2 levels have been experimentally documented for corals and coralline algae (reviewed by Gattuso et al. 1999, Marubini et al. 2003), ecosystems (Langdon et al. 2000), coccolithophores (Riebesell et al. 2000) and foraminiferans (Barker and Elderfield 2002).

Some of the ecological implications for coral reef systems have been described by Kleypas et al. (2001). The potential alteration or loss of reef communities has implications ranging from biodiversity to fisheries and tourism. The structural degradation of reefs has the potential to affect coastal protection (and hence habitability of coasts and especially of small islands) and the geomorphic controls on water circulation and residence times – major factors in coastal zone biogeochemistry.

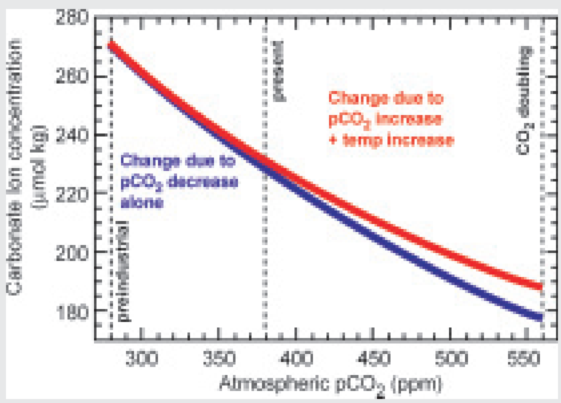

Fig. TB3.2.1. Changes in carbonate ion concentration in typical tropical surface ocean water in response to changes in atmospheric CO_2 concentrations

concentration. This has been shown to decrease the calcification rates of corals, coralline algae and other organisms (Kleypas et al. 1999, see also Text Box 3.2). CO_2 emissions over the past and coming centuries are likely to have significant effects on ecosystems dependent on calcifying organisms. In the coastal zone, changes in these ecosystems may influence both the natural system dynamics and the activities of humans in ways that result in large second-order changes in sedimentary and organic carbon fluxes. Originally identified as important issues for consideration by LOICZ, these aspects of both carbon fluxes and the biological and environmental implications of changes in the coastal carbonate carbon sinks are among the important topics remaining to be addressed.

3.2 Estimates of C, N and P Fluxes in the Coastal Zone

The LOICZ objectives focus on understanding the role and contributions of the coastal zone in the global cycles. Such an understanding requires measurement or modelling of the cumulative effects of system-level fluxes over the entire globe – a daunting task, given the dimensions, heterogeneity and general lack of information about the biogeochemistry of the approximately 1 million km-long world coastline (see Text Box 1.8, Chap. 1). We have approached this as a problem of upscaling the local and regional measurements or estimates of flux to the global scale.

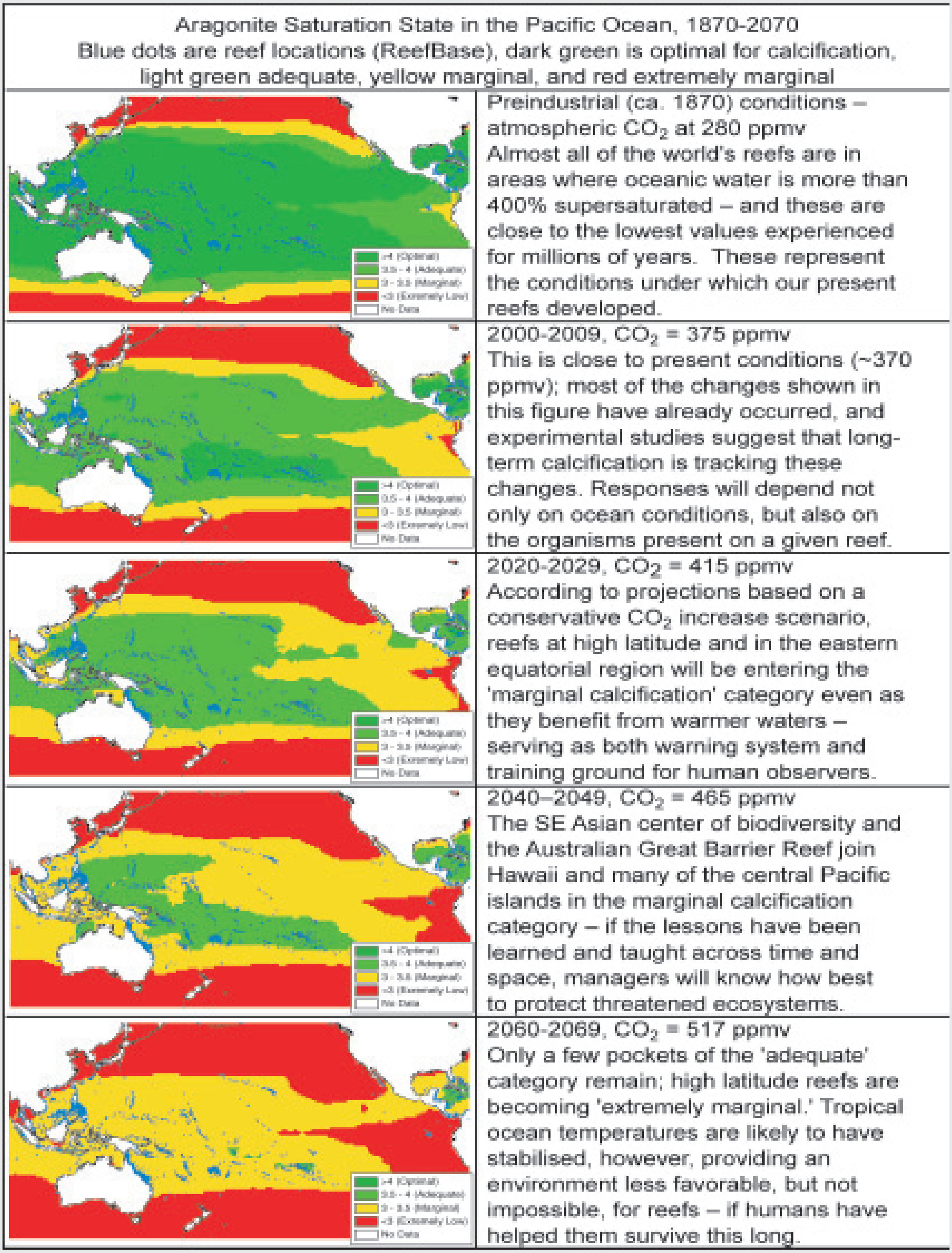

Fig. TB3.2.2. Mapping the effects of rising atmospheric CO_2 on carbonate (aragonite) saturation state over two centuries of human influence (Guinotte et al. 2003)

Text Box 3.3. Key Abbreviations – LOICZ Nutrient Budgets (see Gordon et al. 1996)

Nutrients and nutrient flux:

- DIC Dissolved inorganic carbon
- DOC Dissolved organic carbon
- DIN Dissolved inorganic nitrogen
- DON Dissolved organic nitrogen
- DIP Dissolved inorganic phosphorus
- DOP Dissolved organic phosphorus
- ΔDIN net flux (non-conservative) flux of DIN for the budgeted system
- ΔDIP net flux (non-conservative flux) of DIP for the budgeted system

System performance:

- *p* Primary production (of the system)
- *r* Respiration (of the system)
- [*p* – *r*] Net ecosystem metabolism (NEM) or net ecosystem production (NEP)
- [denit] Denitrification
- [nfix] Nitrogen fixation
- [nfix – denit] Net nitrogen metabolism (of the system)

System physics:

- V_Q Volume of river flux, runoff, or non-point sources from the local drainage basin
- V_G Volume of groundwater
- V_R Residual flow of the system
- V_X Mixing volume of the system
- S_{SYS} Salinity of budget system
- S_{OCN} Salinity of ocean adjacent to budget system
- S_G Salinity of ground water
- τ Water residence time of the system

Text Box 3.4. The algebra of the LOICZ methodology

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One-compartment, well-mixed system

Water and salt budgets
For a simple one-compartment estuarine system (Fig. 3.4.1), the change in mass of water (V) and salt (S) over some representative period (e.g., one year) is equal to the sum of the average water or salt fluxes into and out of the system during the period:

$$\Delta V = \overline{V_Q} + \overline{V_O} + \overline{V_G} + \overline{V_P} + \overline{V_E} + \overline{V_R} \quad (1)$$

$$\Delta VS_{SYS} = \overline{V_Q S_Q} + \overline{V_O S_O} + \overline{V_G S_G} + \overline{V_R S_R} + \overline{V_X(S_{OCN} - S_{SYS})} \quad (2)$$

Following LOICZ convention, inflows to the system are taken to be positive and outflows negative. Subscripts refer to:

- Q river flux, runoff, or non-point sources from the local drainage basin,
- O point sources directly discharging into the system,
- G groundwater sources,
- P direct precipitation onto the system,
- E evaporation from the system (negative in sign),
- R residual freshwater flow between the system and the adjacent open sea (negative for "positive" estuaries, positive for negative estuaries),

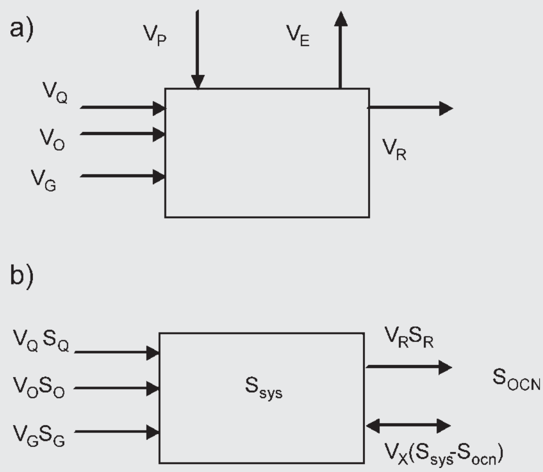

Fig. TB3.4.1. Schematic of (**a**) freshwater fluxes in a single-box model and (**b**) corresponding salinity fluxes, from which the V_X term can be calculated

3.2.1 Current Information Availability

The international LOICZ synthesis of global nutrient flux information has not been a field-based research effort, even though field studies have been stimulated and subsequently undertaken within the context of the project. Rather, the program has been a concerted, globally-directed effort to locate and use existing (or secondary) data. This has been done through literature searches, web posting of ongoing efforts, development of analytical tools and holding workshops designed to enlist the collaboration of the wider scientific community in the contribution of biogeochemical budget information in an internally consistent framework of data analysis (see Chap. 1, Sect. 1.5).

3.2.1.1 *LOICZ Budget Calculation Methodology*

The LOICZ methodology uses a few fundamental assumptions, including that of mass balance, to infer estimates of the community metabolism of coastal systems. The inputs to and the calculated results of these estimates provide the flux estimates. The general approach is discussed at *http://data.ecology.su.se/mnode/methods.htm*, and evolved from an earlier LOICZ publication (Gordon et al. 1996). The approach begins with construction of a simple, steady-state mass balance of water and salt. Together, these quantify the flows of freshwater and seawater that passively transport nutrients from terrestrial, atmospheric and oceanic sources. The products of these flows and mean dissolved concentrations of each of these sources constitute the nutrient fluxes necessary to construct steady-state nutrient mass balances for the system. In the absence of internal sources or sinks, these nutrient inflows and outflows should balance (conserva-

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- X exchange flow between the system and the adjacent open sea (positive by definition),
- OCN average value for the adjacent local ocean,
- SYS average value for the system.

Note that if flow-weighted average salinities are assumed, Eq. 2 can be written:

$$\Delta V S_{SYS} = \overline{V_Q}\,\overline{S_Q} + \overline{V_O}\,\overline{S_O} + \overline{V_G}\,\overline{S_G} + \overline{V_R}\,\overline{S_R} + \overline{V_X}\,\overline{S_{OCN} - S_{SYS}} \qquad (3)$$

At steady-state the left-hand sides of Eqs. 1 and 2 are zero, and they can be rearranged to solve for V_R (system residual flow) and V_X (system mixing volume):

$$\overline{V_R} = -\left(\overline{V_Q} + \overline{V_O} + \overline{V_G} + \overline{V_P} + \overline{V_E}\right) \qquad (4)$$

$$\overline{V_X} = \frac{\overline{V_Q}\,\overline{S_Q} + \overline{V_O}\,\overline{S_O} + \overline{V_G}\,\overline{S_G} + \overline{V_R}\,\overline{S_R}}{\overline{S_{SYS} - S_{OCN}}} \qquad (5)$$

In most cases, V_X reduces to:

$$\overline{V_X} = \frac{\overline{V_R}\,\overline{S_R}}{\overline{S_{SYS} - S_{OCN}}} \qquad (6)$$

Henceforth, we drop the overbars, remembering that the flux terms are average values over the period of interest. Note that the residence time of water in the system can be written:

$$\tau = \frac{V}{V_X + |V_R|}$$

which is always shorter than the freshwater fill-time,

$$\tau_f = \frac{V}{|V_R|}$$

Nutrient budgets
A mass balance for nutrients in a one-compartment system, assuming a fixed system volume, flow-weighted average nutrient concentrations, $Y_i(t)$ and internal sources or sinks ΔY is:

$$V(Y_{SYSF} - Y_{SYSI}) = V_Q Y_Q + V_O Y_O + V_G Y_G + V_P Y_P + V_R Y_R + V_X (Y_{OCN} - Y_{SYS}) + \Delta Y \qquad (7)$$

where the subscripts indicate the fluxes corresponding to those for water and salt, and where F and I denote final and initial concentrations, respectively. Under the assumption of steady-state, this can be rearranged to solve for the internal source/sink term, ΔY:

$$\Delta Y = + V_X Y_{SYS} - V_R Y_R - V_Q Y_Q - V_O Y_O - V_G Y_G - V_P Y_P - V_X Y_{OCN} \qquad (8)$$

For phosphorus (ΔDIP), the source/sink term is interpreted as the amount of phosphorus uptake or release associated with net ecosystem production. For nitrogen (ΔDIN), the source or sink is attributable to both NEM and the net effect of nitrogen fixation and denitrification.

Stratified systems

Water and salt budgets
For a simple stratified system with estuarine flow, two layers must be considered, along with their characteristic flows (Fig. 3.4.2). In classic estuarine circulation, water flows from the upper layer to the sea (V_{Surf}) and from the sea (at depth) into the lower layer (V_{Deep}), with an advective flux from the lower to upper layer equal to the inflow, which maintains mass balance of water. A vertical mixing flux (V_z) maintains salinity balance. As a result, at steady state, both V_{Deep} and V_z can be estimated from the salinity structure and the residual flow of the system:

Water balance, surface layer:

$$V_{Surf} = -(V_Q + V_O + V_G + V_P + V_E + V_{Deep}) \qquad (9)$$

Salt balance, surface layer

$$0 = V_{Surf} S_{Surf} + V_{Deep} S_{Deep} + V_Z (S_{Deep} - S_{Surf}) \qquad (10)$$

Salt balance, deep layer

$$0 = V_{Deep} S_{Deep\_Ocean} - V_{Deep} S_{Deep} - V_Z (S_{Deep} - S_{Surf}) \qquad (11)$$

Thus:

$$V_Z = \frac{V_{Deep}(S_{Deep\_Ocean} - S_{Deep})}{S_{Deep} - S_{Surf}} \qquad (12)$$

$$V_{Deep} = \frac{V_R S_{Surf}}{S_{Surf} - S_{Deep\_Ocean}} \qquad (13)$$

Nutrient budgets
For more complex systems, because concentrations within the system are not homogeneous, the nutrient budget calculations must be performed for each box and layer. For example, for the surface layer of a one-compartment stratified system, the ΔDIP value for the surface layer is given by:

$$\Delta DIP_{surf} = + V_Z(\mathrm{DIP}_{surf} - \mathrm{DIP}_{Deep}) - V_{Deep}\mathrm{DIP}_{Deep} - V_{surf}\mathrm{DIP}_{surf} - V_Q \mathrm{DIP}_Q - V_O \mathrm{DIP}_O - V_P \mathrm{DIP}_P - V_G \mathrm{DIP}_G \qquad (14)$$

and for the deep layer by:

$$\Delta \mathrm{DIP}_{deep} = V_{Deep}(\mathrm{DIP}_{Deep} - \mathrm{DIP}_{Deep\_Ocean}) - V_Z(\mathrm{DIP}_{surf} - \mathrm{DIP}_{Deep}) \qquad (15)$$

assuming that all terrestrial and atmospheric sources flow directly to the surface layer.

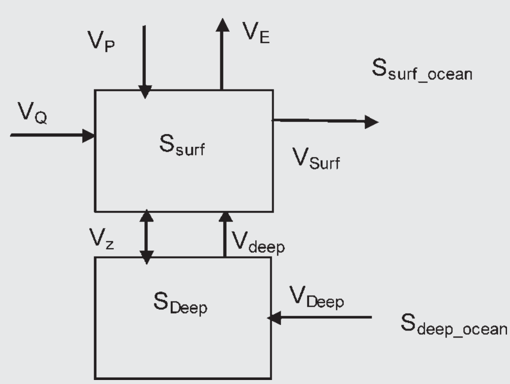

Fig. TB3.4.2. Two-layer box model showing water and salinity fluxes for a stratified system with estuarine circulation

tion of mass). Departures from this balance indicate the presence of a net source or sink (i.e., non-conservative flux). Non-conservative fluxes of DIP are attributed to net ecosystem metabolism (NEM or [*p* – *r*]), in the absence of evidence of other competing processes. Non-conservative fluxes of DIN are attributed to the net balance of nitrogen fixation minus denitrification [nfix – denit] within the system, after accounting for the flux of nitrogen associated with NEM. Text Box 3.3 refers to key abbreviations applied within the LOICZ nutrient budgeting process; Text Box 3.4 reviews these calculations for a one-compartment system, and briefly discusses the extension to multi-compartment systems.

The budgets provide estimates of non-conservative fluxes for DIP and DIN (and, potentially, other materials), with the estimates being constrained only by data quality and ecosystem suitability for budgeting. Stoichiometric relationships are assumed between P, N and C. These relationships provide insight into the net biogeochemical reactions that are occurring, with the quality of that insight reflecting how well the ecosystem function matches those assumed stoichiometric assumptions.

Text Box 3.5. Why not estimate carbon flux directly?

S.V. Smith

A major question within LOICZ has been to determine the degree to which the coastal zone produces or consumes organic carbon, yet LOICZ budgeting has been directed at estimating phosphorus and nitrogen fluxes, and not carbon. Why? There are two answers to this question.

In the first place, nutrient data for both river inflows and the marine environment are far more widely available than carbon data. Restricting budgets to sites with carbon data would greatly reduce the number of possible budgets. Inasmuch as the desire was to use a near-uniform budgeting approach, the comparisons were restricted to the phosphorus-based estimates of [*p* – *r*] While there are a few individual budget sites globally with direct carbon budgets, these few sites have not been used in the comparisons here.

The second issue is analytical quality of data, relative to data demand. This is best explained by example. The dissolved inorganic carbon (DIC) content of seawater is close to 2 mmol l^{-1}, and good analytical precision of DIC measurements is about 0.01 mmol l^{-1}. While higher precision can be achieved, data at even this resolution are rare in coastal datasets. Nutrient concentrations in surface seawater are proportionally far more variable than DIC, but DIP and DIN concentrations are typically of the order of 0.001 mmol l^{-1} (1 µmol l^{-1}), with typical precision of better than 0.00005 mmol l^{-1}.

A change in DIP of 0.0001 mmol l^{-1} could be readily measured. This change due to uptake of DIP into organic matter would lead to a DIC uptake of about 0.01 mmol l^{-1} – below the level of analytical resolution for most available coastal data. While this is only an example, it makes the point that changes in DIP concentrations due to organic reactions are generally more readily resolved than changes in DIC.

3.2.1.2 *The LOICZ Research Strategy*

3.2.1.2.1 *Choice of Sites and Consideration of Data*

Budgets have been developed in several ways: (*a*) in collaborative workshops that brought regional scientists together with the express purpose of organising previously-collected data along LOICZ budget guidelines (Gordon et al. 1996), (*b*) as "contributed budgets" from researchers working independently and using the budget guidelines, and (*c*) from studies of coastal systems obtained from the literature, from which the data could be reworked to conform to LOICZ budget guidelines.

Effectively, three criteria have been used to determine sites for which a biogeochemical budget can be developed:

- Is there a reasonable expectation of getting the data required to construct a budget?
- Is there a contact person for the site with access to the required data (i.e., a researcher with the interest and means of constructing a budget)?
- Does the budget help obtain general, worldwide coverage?

3.2.1.2.2 *Choice of Variables*

It is easily argued that estimations of fluxes of dissolved inorganic carbon, particularly non-conservative fluxes, are better made using the stoichiometrically-linked variables DIN and DIP. The relatively large amount of DIC in the coastal zone, compared with DIN and DIP, suggests that the DIC pool is relatively insensitive to effects of ecosystem metabolism, and thus the inverse problem of estimating metabolism from measured concentrations and their associated fluxes is much better addressed using DIP. Consequently, unless special care has been taken in the sampling and analysis of DIC, LOICZ budgets use DIP and Redfield stoichiometry to estimate NEM (see Text Box 3.5).

Variables required to construct mass balances are steady-state values of fluxes of water, salt and nutrients, or equivalently, long-term averages of water fluxes and associated area- or flux-weighted concentrations (to calculate nutrient fluxes). Table 3.1 contains a list of required variables for a typical one-compartment, one-layer budget.

3.2.1.2.3 *System Complexity and Data Issues*

Spatial complexity. System complexity, here considered to be any characteristic of a system that requires description beyond steady, homogeneous, single compartments, can complicate data requirements(Webster et al. 2000). Stratified estuaries require estimates of concentrations in both layers, and care is required in defining the boundary between layers. Spatially non-homogeneous systems, such as those of variable depth, extended longitudinal gradients, or containing significant sub-basins or tribu-

Table 3.1.
Data required for and derived from a one-compartment one-layer LOICZ budget

Required variables
Physical characterisation of the system: mean depth, surface area, volume
Water budget: annual runoff (V_Q), annual point source flow (V_O), annual groundwater flow (V_G), annual direct precipitation (V_P), annual evaporation from the system (V_E)
Salt budget[a]: S_Q, S_O, S_O, S_P, S_{sys}, S_{ocn}
DIP budget[a]: DIP_Q, DIP_O, DIP_G, DIP_P, DIP_{sys}, DIP_{ocn}
DIN budget[a]: DIN_Q, DIN_O, DIN_G, DIN_P, DIN_{sys}, DIN_{ocn}
Derived variables
Estuarine mixing volume, V_X
Estuarine water residence time, τ
"Non-conservative fluxes", ΔDIP, ΔDIN
Net ecosystem metabolism (NEM) = primary production minus respiration, $[p - r]$
Net nitrogen fixation minus denitrification, [nfix – denit]

[a] Salinity, DIN and DIP concentrations are assumed to represent an appropriate flux-average, system average or oceanic average as necessary.

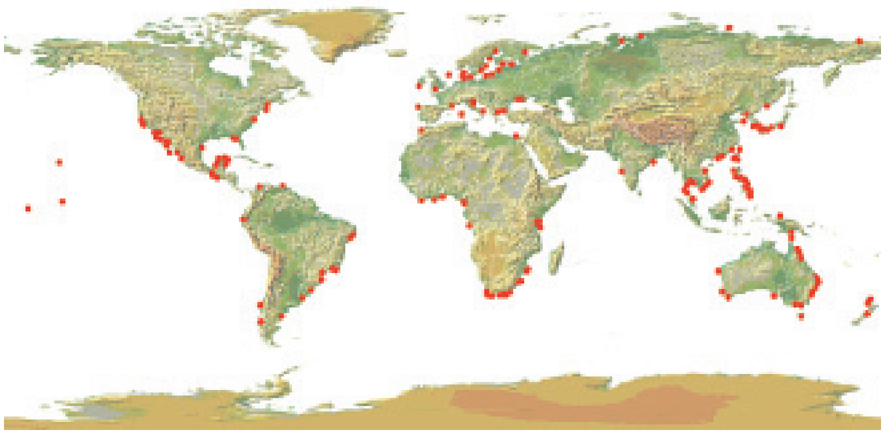

Fig. 3.2.
Budget sites. Global distribution (April 2002)

taries, sometimes require treatment as multiple compartments, each of which requires concentration data and flux estimates. Often, boundaries between these compartments are clearly suggested by system geometry.

Temporal complexity. Seasonally-varying systems can be treated as conventional systems, if data sufficient for constructing seasonally flow-weighted average concentrations are available. Otherwise, it may be more meaningful to construct budgets for single seasons, noting that dramatically different behaviour may be manifested in, for example, the dry season compared with the wet season of monsoonal coastal systems. Finally, while we acknowledge the significance of episodic loads and flushing in some systems (e.g., Furnas 2003), these events remain largely beyond the scope of the LOICZ approach due to limitation of data.

Operationally, our approach assumes that non-conservative fluxes during short-term, high-flow episodes are the same as these fluxes during the longer, low-flow periods. Two rationales for this assumption can be offered. First, high-flow events are likely to be so dominated by hydrographic fluxes that any non-conservative flux would be difficult to detect. Second, as long as these periods are short and infrequent, quantitatively large deviations from the assumption of "normal" non-conservative fluxes would be needed to seriously bias the estimated average fluxes.

3.2.1.2.4 *Additional System Information*

Other information, while not required for the data analysis, is helpful. If primary production for the system is available, then net ecosystem metabolism (NEM) can be compared with gross system metabolism. Similarly, benthic nutrient fluxes (usually releases) can be compared with the magnitude of NEM. If individual measurements of denitrification or nitrogen fixation are available, these can be compared with the estimate of [nfix – denit]. Many characteristics of the associated catchment basin may be relevant in understanding the controls and changes on system metabolism (e.g., population density, land use, economic development, physiography).

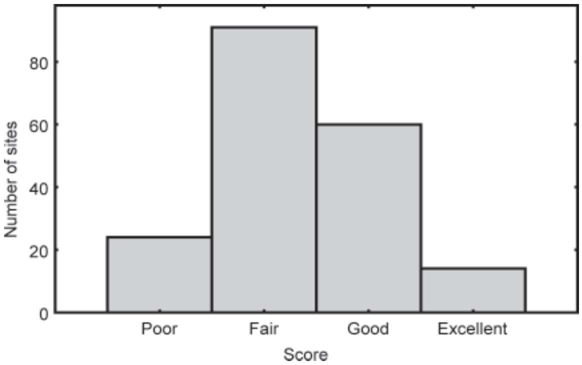

Fig. 3.3. Budget Sites. Frequency distribution of *ad hoc* quality assessment (relative score: 0=poor; 1 = fair; 2 = good; 3 = excellent)

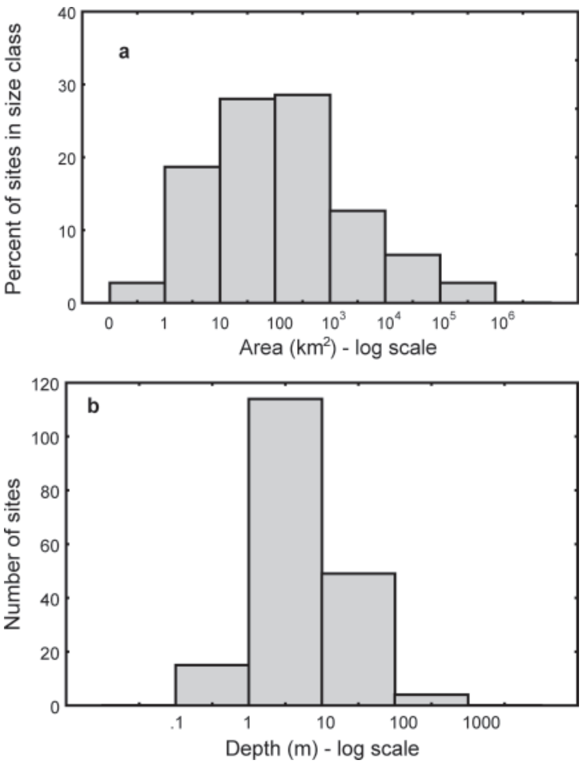

Fig. 3.4. Budget sites. Frequency distribution of (**a**) system area and (**b**) average depth

3.2.2 Fluxes and Variability of Fluxes

3.2.2.1 *Global Distribution of Budget Information*

Collection of budget information is ongoing. Approximately 200 sites had been budgeted as of April 2002 (Fig. 3.2), the cut-off date for information used in this assessment. Of these sites, 75–85% are regarded as reliable enough for consideration in statistical analyses of a budget dataset (Fig. 3.3, Text Box 3.6). The dataset can be characterised simply in terms of frequency distributions of its various collected or derived variables.

Text Box 3.6. Expert judgment of budget quality

S.V. Smith

How good are the individual budgets? From the beginning of the LOICZ project, it was clear that some evaluation of budget quality was needed. Of course, formal statistical techniques exist for considering analytical variability for each dataset and both spatial and temporal environmental variability. The most desirable situation would have been to be able to apply such a formal statistical analysis. Unfortunately, for most of the sites the data are not available to undertake such a formal analysis. Thought was given to making "expert judgments" of both the analytical and environmental variability for each site, and then undertaking a formal analysis. In the end, it was decided that the whole evaluation of budget quality was probably best done with expert judgment.

Criteria that went into this judgment included:

- the amount of data available, both in terms of spatial distribution of data representative at a single time and how representative the data seemed to be of temporal variation;
- the likely environmental quality of the data; and
- how the results measure up in terms of the guidelines (see Text Box 3.7).

Finally, systems with residence times near or below 1 day were not considered reliable, on the basis that they had insufficient time to develop a net non-conservative signal. The scores assigned were as follows:

0. Budget was not considered to be reliable (i.e., poor).
1. Budget was considered marginally reliable, but without any basis for total dismissal (i.e., fair).
2. Budget was probably satisfactory but may not have captured temporal variation effectively (i.e., good).
3. Budget appeared highly reliable (i.e., excellent).

While the coastal zone is generally considered as a relatively narrow ribbon extending to ~200 m depth (e.g., Pernetta and Milliman 1995), there is considerable variation in the area and depth of individual coastal ecosystems within the zone. System area of the sites that have been budgeted during the LOICZ project (Fig. 3.4a) is distributed approximately log-normally (i.e., normally distributed on a log scale) over 7 orders of magnitude, ranging from the 0.5 km^2 Lough Hyne, Ireland, to the 900 000 km^2 East China Sea. Average system depth (Fig. 3.4b) is also distributed approximately log-normally over ~3 orders of magnitude, from ~0.4 m in S'Ena Arrubia, Italy to > 500 m in Sogod Bay, Philippines. Relatively small coastal features such as fjords and trenches may have great depth, while shelf seas typically are < 100 m.

System salinity represents the salinity of the individual budget sites and oceanic salinity is the salinity immediately seaward of the sites. Both system and oceanic salinity distributions (Fig. 3.5a) are uni-modal but strongly skewed. The mode of salinity appears to be close to that of typical open-ocean seawater (~35 psu), with some higher salinities largely reflecting systems in which evaporation exceeds precipitation. The low-salinity tail of the frequency distribution includes many systems (e.g., the Baltic Sea and its subsystems) in which the "oceanic"

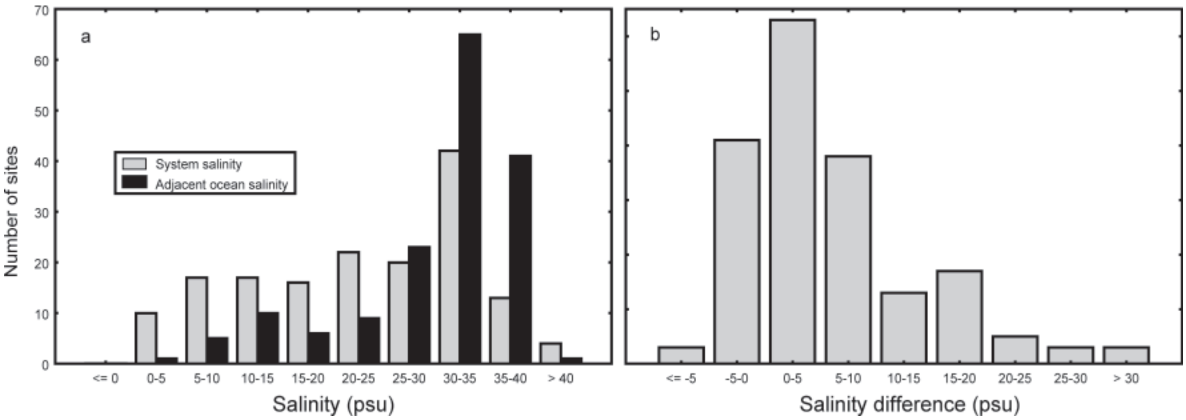

Fig. 3.5. Budget sites. Frequency distribution of (**a**) system and local oceanic salinities and (**b**) oceanic-system salinities

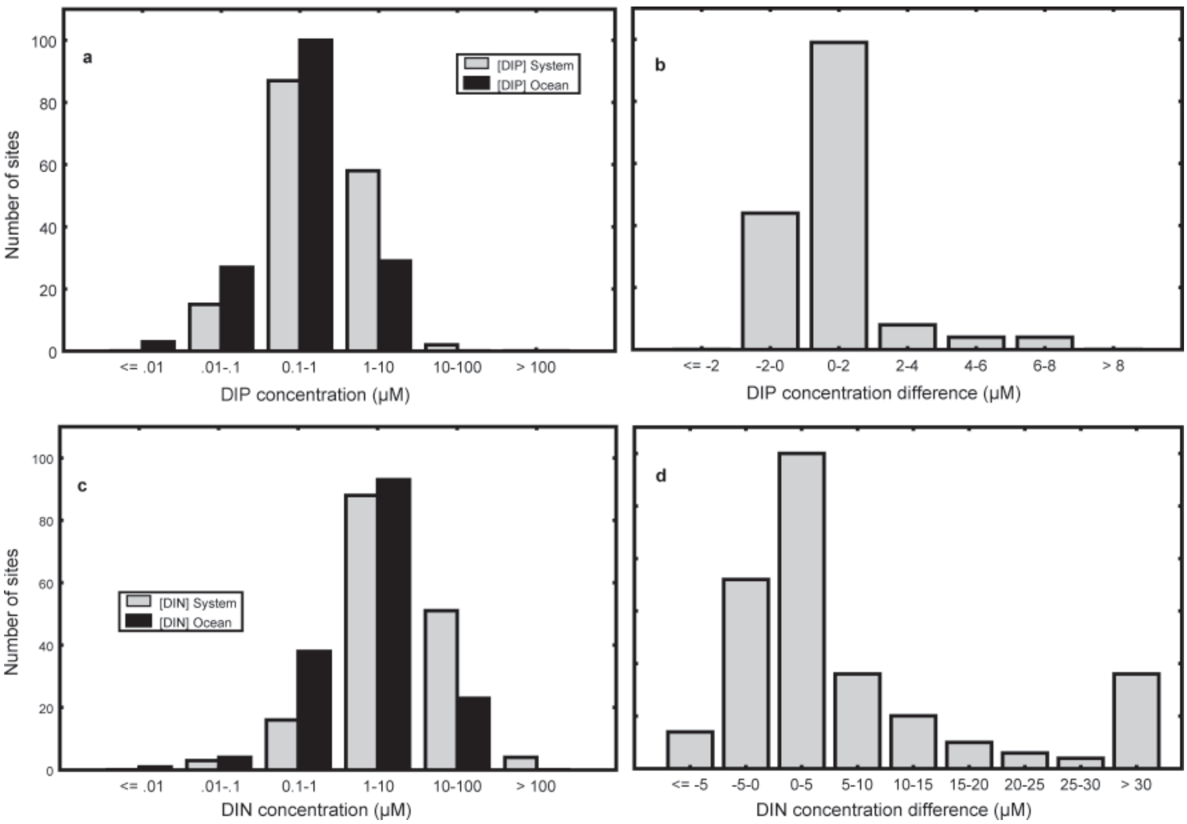

Fig. 3.6. Budget sites. Frequency distribution of (**a**) system and local oceanic DIP concentrations, (**b**) system-ocean DIP differences, (**c**) system and local oceanic DIN concentrations and (**d**) system-ocean DIN differences

source is not full strength seawater. Salinity difference between the local ocean end-member and the system provides a measure of the degree of freshwater dilution within the system. The distribution of ocean minus system salinity differences (used to calculate V_X) (Fig. 3.5b) is also skewed. Most systems exhibit relatively low gradients (between 0 and 5 psu); some are negative, reflecting hypersaline lagoons, while the remainder span the full range between 0 and 35 psu. The maximum values reflect the full seawater minus freshwater extreme.

The distributions of DIP and DIN concentrations are also skewed on a linear scale, but as for area and depth, they reveal an approximately log-normal distribution (Fig. 3.6a and c). The corresponding system-ocean nutrient concentration gradients are skewed in the opposite direction from salinity gradients, reflecting the dominance of terrestrial over oceanic dissolved nutrient sources (Fig. 3.6b and d). This seems especially pronounced in the case of DIN distribution, which shows a secondary node at the positive end of the system-ocean gradient.

3.2.2.2 *Water Fluxes*

The volume of water passing through the budgeted systems spans 6 orders of magnitude, and the distribution of these flows is approximately log-normal. Freshwater flows (V_Q) to the systems from riverine sources and other terrestrial runoff (Fig. 3.7a) span from < 10^{-3} km^3 yr^{-1} to > 10^3 km^3 yr^{-1}. Residual flow (V_R) between these systems and the ocean (generally negative, indicating outflows) spans a similar range (Fig. 3.7b), although a secondary mode of positive residual flows occurs for negative estuaries as seawater intrudes to replace net evaporation. The distribution of exchange flow (V_X) between these systems and the ocean spans a slightly greater range than V_Q (Fig. 3.7c).

3.2.2.3 *Loads and Exchanges of DIP and DIN*

The distribution of terrestrial + atmospheric DIP and DIN loads to the systems (Fig. 3.8) is also approximately log-normal, but with a secondary mode at the low end of the distribution corresponding to that observed in the distribution of V_Q. Note that atmospheric load is usually small compared with terrestrial load, but that exceptions exist, notably for systems of large areal extent relative to their catchment size (see Text Box 3.1). Fluxes of DIP and DIN associated with V_R also have two modes in their distributions, but in this case they correspond to net fluxes to and from the system. The dominant (negative) mode reflects the usual transport of system nutrients to the sea. The positive mode (inward) corresponds to the positive mode of V_X associated with negative estuaries. The bimodal distribution of the nutrient transport associated with V_X is solely due to the bimodal nature of this flow. Nutrient concentrations in the system greater than those of the ocean result in a negative nutrient flux (outflow) associated with V_X, and a nutrient concentration "deficit" results in an inward nutrient flux.

3.2.2.4 *Other Information Derived from the Budgets*

A key variable derived from basic morphometry and water budget analysis is the estimate of system water exchange time (see Sect. 3.2.1.1 and Text Box 3.4). This variable has obvious significance in the interpretation of nutrient dynamics. Its distribution over the budgeted sites (Fig. 3.9) reflects the log-normal distribution of volume and water flows.

Finally, the question of budget quality has been addressed simply by *ad hoc*, expert assessment (Text Box 3.6), and is partially based on guidelines for budget quality (Text Box 3.7). Each budget is assigned a quality rating (0–3) based on review of the data used to develop it and the plausibility of the magnitudes of its resulting fluxes. While most of the budgets receive a rating of fair or better, a significant fraction of the 200 site budgets are not regarded as useful from the standpoint of developing reliable statistics on fluxes and metabolic performance of the systems (Fig. 3.3).

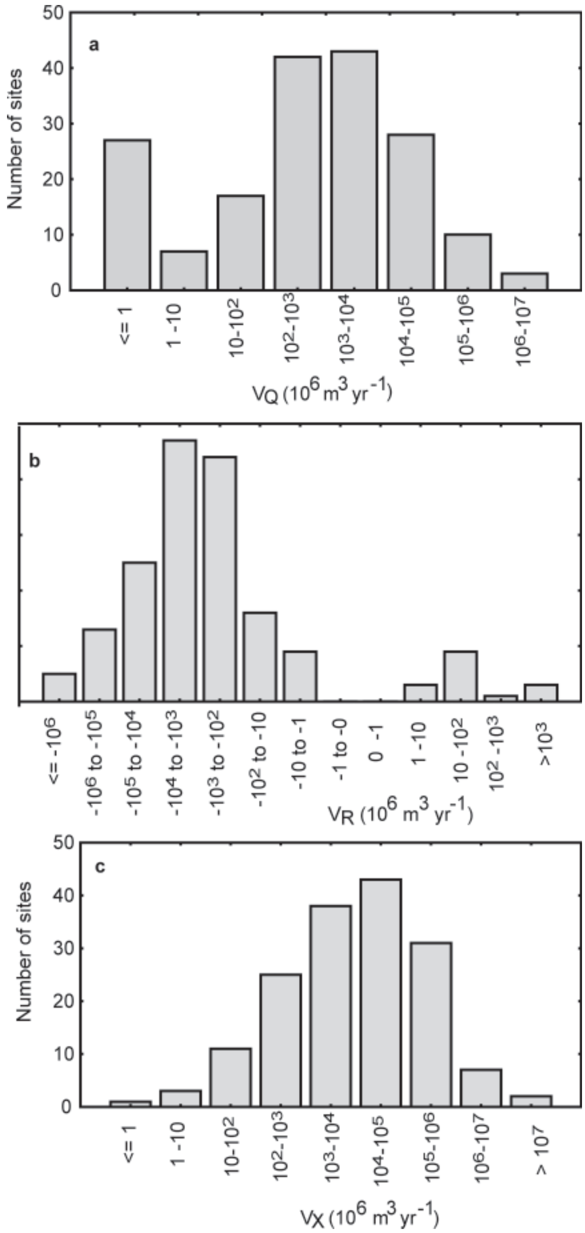

Fig. 3.7. Budget sites. Frequency distribution of (**a**) freshwater riverine, V_Q and runoff flows, (**b**) residual flows, V_R (note: negative sign represents an outflow, positive sign represents an inflow; positive and negative flows on the histogram are binned in log increments) and (**c**) exchange flows, V_X (positive by definition; in stratified systems this is V_D)

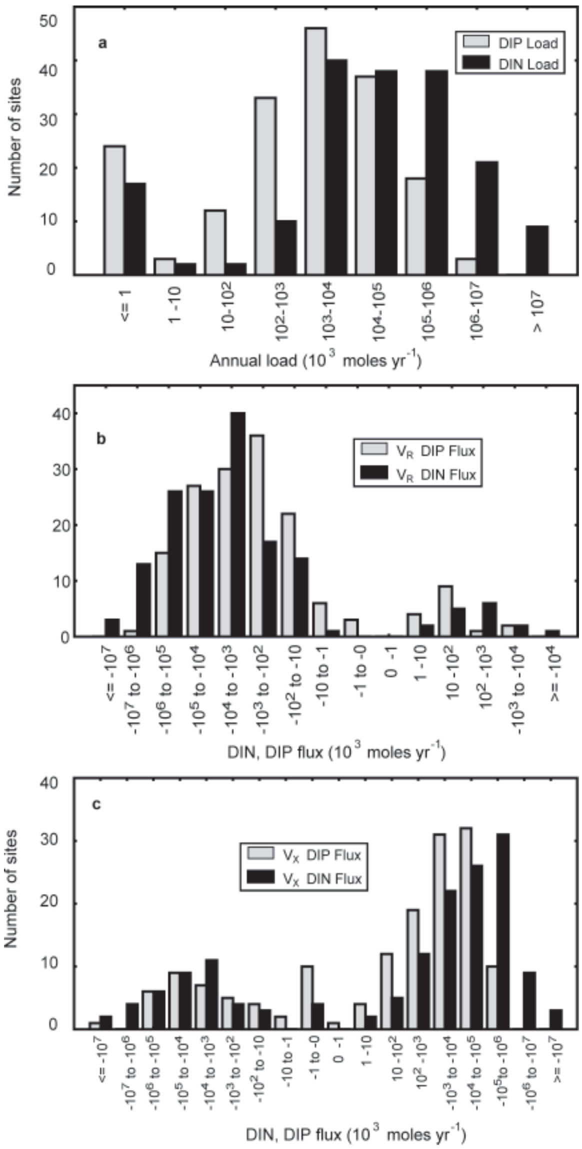

Fig. 3.8. Budget sites. Frequency distribution of (**a**) terrestrial + atmospheric DIN and DIP loads, (**b**) DIN and DIP fluxes associated with residual flows (see note for Fig. 3.7b regarding scale) and (**c**) DIN and DIP fluxes associated with exchange flows (see note for Fig. 3.7c regarding scale)

3.2.3 Non-conservative Fluxes: Their Distributions, Relationships to Other Variables and Biogeochemical Interpretation

The data gathered for the nutrient budget dataset described above include the terrestrial/atmospheric loadings, advective water flow and mixing, and permit the estimation of associated nutrient fluxes. Under the assumption of steady-state, they additionally permit estimation of the terms that describe internal uptake or release of these dissolved nutrients. In the jargon of oceanography, these internal uptake and release fluxes are indicative of non-conservative fluxes. In principle, the LOICZ budgeting procedure does not require the assumption of steady-state (Gordon et al. 1996). In practice, most datasets used during LOICZ were too sparse to be used in any manner other than with this assumption. Apparent non-conservative fluxes arise because reacting materials have sources or sinks other than advection, mixing and dilution or concentration via freshwater gains or losses. Hence, these reactive materials are not conserved relative to water and salt. Note that the calculations of these fluxes give the *net* values, and that these net fluxes are those most relevant to the role of any Earth system compartment relative to its neighbours.

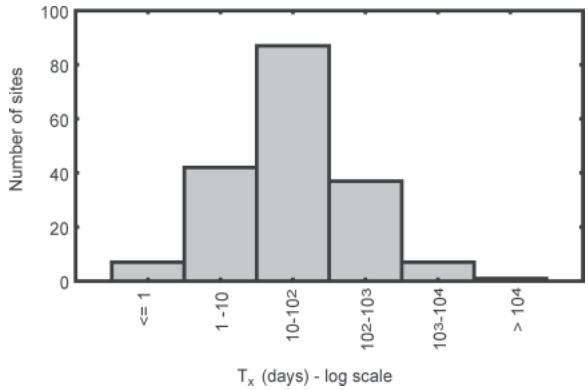

Fig. 3.9. Budget sites. Frequency distribution of exchange times

The non-conservative flux of DIP (ΔDIP according to LOICZ budget notation) is used as an approximation of net uptake of phosphorus into organic matter during primary production or net release from organic matter by respiration. The DIP flux is scaled to an estimated carbon flux via a scaling ratio (typically a molar C : P ratio of 106 : 1, representing the Redfield Ratio (Redfield 1958, Redfield et al. 1963). While it would be desirable to have direct measurements of carbon uptake into organic matter (Text Box 3.6), such data are not available for most locations. High precision is required for a good dissolved inorganic carbon (DIC) budget; such high precision data are rarely available, and certainly not available for most of the budget sites used here. Further, gas flux may dominate a DIC budget and be difficult to reconstruct from available data. Finally, processes such as calcium carbonate reactions and sulfate reduction complicate interpretation of DIC budgets. Therefore, as an alternative, the LOICZ approach uses ΔDIP as a proxy for net organic carbon flux.

One shortcoming of this proxy is that systems with high amounts of suspended mineral material (e.g., from rivers) may show evidence of DIP adsorption onto the particulate materials or desorption from them (Froelich 1988, Nixon et al. 1996). Further, systems with strong gradients in redox potential in the water column, such as

Text Box 3.7. Guidelines for constructing nutrient budgets of coastal systems

D.P. Swaney and S.V. Smith

These guidelines provide a basis for assessing whether or not information about a coastal ecosystem is reasonable in terms of general knowledge about natural science. Numerical values falling within these guidelines may be incorrect, but they are not immediately suspect. However, the further outside the guideline limits that the numbers fall, the more likely it is that an error exists in the values. These might involve erroneous calculations, erroneous assumptions or faulty data.

General knowledge and experience about the natural environment can inform the process of developing budgets. Some bounding of values may be obtained using simple scientific principles (such as the conservation of mass) and the overall comparison with many prior observations.

Hydrology

The total freshwater outflow to a coastal region (the sum of $V_Q + V_G + V_O$) is constrained by the net precipitation (rain + snowfall – evapo-transpiration) over the watershed (catchment) area of the coastal region. Therefore, over a sufficiently long time period (longer than the residence time of water in the catchment), riverine outflow plus groundwater flow to the sea should approximately equal the net precipitation over the catchment.

Exceptions to this rule occur in some areas, for example where groundwater is being "mined", i.e., extracted at a rate greater than it is being replenished by recharge, so the groundwater level is declining. While the mined water could be finding its way to the sea after use, a more likely possibility in arid environments is that it is being lost to evapo-transpiration. Except in the comparatively infrequent cases in which groundwater is a large term in the site budget, this is likely not to have a quantitatively significant effect on the water budget. Another possible violation of the rule is due to "inter-basin transfers" of water (water piped or channelled in from outside the drainage basin). For example, the New York City reservoir system lies partially outside the drainage area of the Hudson River (in the Delaware River basin). New York City discharges a large percentage of its sewage wastewater into the lower Hudson River estuary. The effect is an inter-basin transfer of water from the Delaware to the outflow of the Hudson River. An extreme transfer example, of course, is the diversion of the Colorado River flow to the city of Los Angeles and other destinations. A subtler effect is the alteration of the watershed hydrograph due to detention and evaporation of streamflow by reservoirs over the year or individual storm events.

Conventional estimates of evapo-transpiration may underestimate the loss of water associated with human activities, so caution should be exercised with these estimates for developed areas with large expanses of impervious surfaces, or other areas in which water is used extensively by the human inhabitants.

In any case, an upper limit on average freshwater flow to the sea is the product of average annual precipitation minus evapotranspiration (both in m) and catchment area (m^2). In most cases the flow will be dominated by surface runoff, loosely termed river flow. In environments with little or no surface flows to the sea, this figure should approximate the groundwater (subsurface) flows, especially in karstic bedrock conditions.

Maps of the global distribution of precipitation over the oceans are available from the IRI/LDEO Climate Data Library. Many maps of climatic and ecological variables over the continents may be found at the UNEP GRID websites (*http://www.grid.unep.ch/index.html* or *http://www-cger.nies.go.jp/grid-e/index.html*), including annual average precipitation and potential evapotranspiration (PET). Actual evaporation may be significantly lower than PET in desert areas because the lack of available water constrains the rate of evaporation. The GRID evapo-transpiration link contains a brief discussion of some methods to estimate evapo-transpiration from PET. For more information on precipitation and evaporation, examine the LOICZ Precipitation and Evaporation webpage (*http://www.loicz.org*).

Water and salt exchange with the sea

The term V_X used in LOICZ calculations represents a volume of water that effectively moves back and forth between the sea and the coastal system of interest, transporting salt with seawater concentration into the system from the ocean, and transporting salt at the system concentration back to the sea. Under the assumption of steady-state, this salt transport must be exactly equal and opposite to the transport of salt, at its concentration in the system, carried by V_R (i.e., the flow of water to or from the system to balance the freshwater budget). In fact, we use this relationship to estimate the value of V_X, and this suggests the magnitude of V_X even before calculation. First, while V_R may be positive (i.e., into the system, when evaporation or withdrawals from the system exceed sources) or negative (when freshwater flows exceed freshwater losses), V_X is always positive (by definition). Instances in which V_X may appear negative due to insufficient or inaccurate data sometime occur in hypersaline lagoons (in which salinity of the system should exceed that of the sea) subject to high evaporative losses of water. If the salinity difference between the system and the ocean appears to be positive and V_R also appears to be negative, then the ratio of $V_R : V_X$ is negative, yielding an estimate of V_X that is negative in sign. However, if the data are good, salinity will be elevated when V_R is positive and the resultant value for V_X will be positive. Bad data can result in inconsistent values for the salinity difference *and* V_R in either direction thereby resulting in (an incorrect) negative V_X.

Assuming that the estimate of V_X is positive, and V_R is negative (i.e., out of the system), what is a reasonable value? First, if annual averages are used and the system salinity is uncorrelated with freshwater flow, the salt flux associated with V_R is the product of system average salinity and V_R. The less saline the system, the greater V_R is relative to V_X. V_X is algebraically constrained to be numerically smaller than the magnitude of V_R if the system salinity is less than half of the oceanic salinity, and greater if the system salinity is greater than half-oceanic.

If seasonal data are available for salinity and V_R, then one can calculate their covariance, which is typically negative (during high freshwater flow periods, salinity drops, and vice versa). Because the salinity flux associated with V_R is the sum of this covariance and the product of average V_R and average system salinity, then this estimate of salinity flux is typically smaller than the previous estimate. Corresponding values of V_X should also be smaller.

From the standpoint of physical oceanography, V_X depends on several terms, including those associated with tidal exchange, density-driven currents, wind-driven currents, and frontal eddies. Gordon et al. (1996) provide formulas for estimating each of these four terms. Most of the time, only a single term is significant. For estuaries, with rare exception, V_X should be less than the tidal exchange volume, because tidal exchange does not operate with 100% efficiency and is usually the dominant contributor to V_X.

Oceanic salinity and nutrient data

Typical annual average values of salinity, nitrate (NO_3), phosphate (PO_4) and dissolved silicon (Si) for the global ocean at the sea surface and 1 000 m depth are available from the superb website hosted by the Lamont-Doherty laboratory of Columbia University (IRI/LDEO Climate Data Library). The website also provides monthly datasets and values for various depths in the ocean; these data can be transformed and downloaded as tables or figures. Values for particular locations may also be examined, but caution should be exercised in their interpretation due to the coarse level of resolution of the dataset.

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Examination of the maps in the Climate Data Library suggest that significant variability exists in the "local ocean" even on an annual average basis (e.g., salinity values in the Baltic Sea, the "local ocean" for several important coastal ecosystems is typically around 7–8 psu, much lower than the 35 psu regarded as typical for the open ocean). At the surface, average annual nitrate concentrations at the sea surface can range from approximately zero (middle Atlantic and Pacific Oceans) to 25–30 µM (in the upwelling zone at 60 degrees South latitude). Generally, phosphate follows similar patterns, ranging from zero to around 2 µM (consistent with the Redfield ratio). Silicon ranges from zero to around 70 µM (with high values again in the > 60° N – 60° S latitude band). Along continental shelves, locally elevated regions exist due to the influence of coastal upwelling zones and riverine plumes. At depths well below the photic zone, inorganic nutrient concentrations typically increase because the biological sink associated with primary production is eliminated, while remineralisation of organic matter falling from the surface layer continues. Most of the sub-polar ocean registers average annual concentrations more typical of those seen at the surface in upwelling areas (NO_3 25–45 µM, PO_4 1.5–3.5 µM, Si 50–150 µM). The range of salinity narrows to a few psu because the influences of surface evaporation, precipitation and runoff are eliminated.

For budgeting purposes, an estimate of the mean salinity and nutrient concentrations over the depth of the sea likely to be exchanged with shallow coastal areas is most meaningful. When calculating budgets, values based on careful local measurements are always preferable to tabulated data from compendia. This is particularly true in the inner portion of the coastal zone because of local variations in the amount and composition of freshwater inflow. These compiled values are based on open shelf values and do not represent well this inshore variation.

Coastal ecosystem metabolism

Metabolism elements are laid out in an order that reflects likely knowledge about the system, first for carbon metabolism and then for nitrogen metabolism.

1. Primary Production (p) – in plankton-based systems, long-term (seasonal) primary productivity is typically 100–1 000 g C $m^{-2} yr^{-1}$ (rounded daily rates of ~0.3–3 g C $m^{-2} d^{-1}$). While p can be somewhat lower or higher, values outside this range should be looked at with caution. For comparison with the biogeochemical calculations, these are expressed in molar rates: ~8–80 mol C $m^{-2} yr^{-1}$, 25–250 mmol $m^{-2} d^{-1}$. Systems dominated by benthic organisms (algae, seagrasses, mangroves, corals) may have primary production rates 2–3 times the upper limit for plankton.
2. Net Ecosystem Metabolism ($[p - r]$ or NEM) – the biogeochemical budgets, via ΔDIP, provide an estimate of net ecosystem metabolism, which is the difference between primary production (p) and respiration (r). That is, NEM = $[p - r]$. Ecosystems respire much of the organic matter that they produce and may (if there is an external source of organic matter) respire more than they produce. Values for p are frequently available, while r is much less frequently known but can be generally estimated. Typically p and r are within about 10% of one another. Assuming that p is known, this implies that the quantity $[p - r] = \pm 0.1p$. There can be exceptions to this, if the system receives extreme loads of either inorganic sewage nutrients or labile organic matter. However, for any system with $[p - r]$ outside the range $\pm 0.25p$, there is a strong possibility that either $[p - r]$ or (p) is in error.
3. Respiration (r) – rules 1 and 2 imply that r usually has about the same rate as p.
4. Nitrogen fixation (nfix) – this process is ordinarily slow in marine systems (< 1 mmol $m^{-2} d^{-1}$, < 400 mmol $m^{-2} yr^{-1}$). Most marine systems have no observable nitrogen fixation. Some coral reef, mangrove and tropical seagrass communities may exhibit rates 20 or more times this upper limit. As a general rule, though, few systems will have nitrogen fixation faster than this rate.
5. Denitrification (denit) – this process is apparently ubiquitous in systems with a significant rate of benthic metabolism and may occur in totally planktonic systems. The main requirement seems to be relatively rapid respiration, with benthic respiration being more efficient than planktonic respiration at promoting rapid denitrification. Typical rates in benthic systems would be around 0.5–2 mmol $m^{-2} d^{-1}$ (200–700 mmol $m^{-2} yr^{-1}$), but systems with high benthic respiration (driven by either high primary production or high loading with labile organic matter such as sewage) may have denitrification rates > 10 mmol $m^{-2} d^{-1}$ (or about 4 mol $m^{-2} yr^{-1}$).
6. Nitrogen fixation minus denitrification [nfix – denit] – This term expressing net nitrogen metabolism not directly associated with carbon metabolism involves the difference between nfix, as defined by item 4 above, and denit, defined by item 5 above. Unlike the situation with $[p - r]$ (1–3 above), [nfix – denit] are not necessarily strongly coupled. The implication is that the likely range of values for this process lies between maximum nitrogen fixation (~20 mmol $m^{-2} d^{-1}$, 8 mol $m^{-2} yr^{-1}$) and (minus) maximum denitrification (–10 mmol $m^{-2} d^{-1}$, –4 mol $m^{-2} yr^{-1}$). It follows from the discussion above, that a more typical range would be +1 to –2 mmol $m^{-2} d^{-1}$ (+0.4 to –1 mol $m^{-2} yr^{-1}$).

the Scheldt Estuary, can show an important contribution of non-biological processes (such as iron oxyhydroxide precipitation/dissolution) to non-conservative fluxes of DIP. It should be noted that this DIP sorption/desorption problem is most likely to be an issue in river-dominated systems, with large amounts of inorganic sediment, but it is not a major issue in most open-shelf settings. A second issue, also largely restricted to inshore systems, is the choice of an appropriate C : P scaling ratio. For example, benthic algae, seagrasses and mangroves all have carbon : nutrient ratios very different from the Redfield Ratio (Atkinson and Smith 1983). In general, terrigenous organic matter associated with vegetation has high C : nutrient ratios, while organic matter associated with organic waste is low in C : nutrient ratios (Vitousek et al. 1988, San Diego-McGlone et al. 2000). On the open shelf, dominated by planktonic systems, phytoplankton may legitimately be assumed to be the dominant form of reacting organic matter.

The relative influence of terrestrial/atmospheric loads and oceanic fluxes varies enormously across systems. On the terrestrial side, the level of influence depends upon the relative size of the associated drainage basin and level of human development, among other factors. On the oceanic side, the relative intensity of exchange (physical processes) is important as well as the quality (e.g., primary production and/or nutrient concentrations) of the oceanic end-member. Because these balances are sensi-

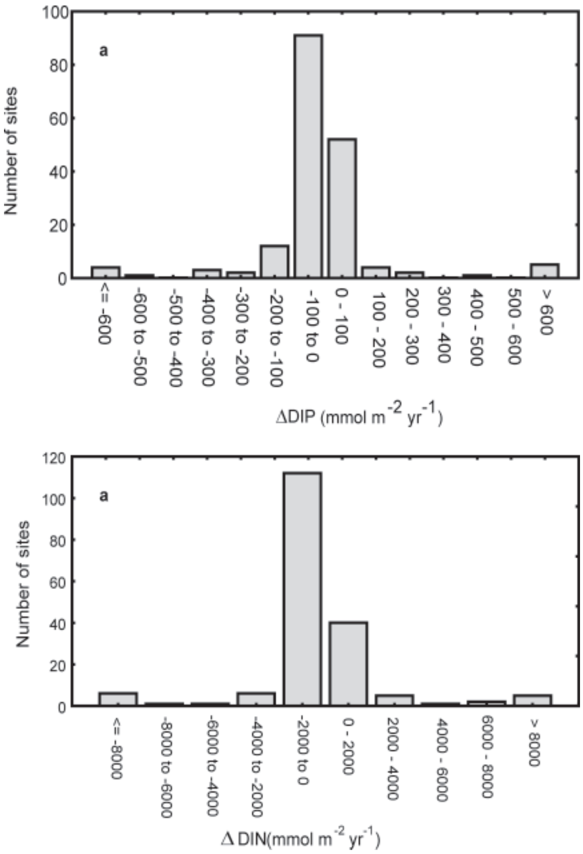

Fig. 3.10. Budget sites. Frequency distributions of (**a**) ΔDIP and (**b**) ΔDIN

tive to system size, as measured directly by area, depth or volume, or indirectly by residence time, we expect relationships between these measures to emerge by analysis of the defining equations. We hope that by studying the departures from these expected relationships observed in the actual data, insight may be gained into the relationships between the non-conservative fluxes and size of the system. We wish to establish relationships not only between the magnitude of the non-conservative fluxes and the driving variables, but also between the sign of the flux and the driving variables.

3.2.3.1 *Distributions of ΔDIP and ΔDIN*

The frequency distributions of the non-conservative fluxes of P and N (Figs. 3.10a, b) reveal a strong peak centred near zero, but with a bias to the negative side, indicating that, on average, a few more sites function as net internal sinks of both nitrogen and phosphorus than as sources. Following conventional LOICZ interpretation, this suggests a slight bias both toward autotrophy and toward a net denitrification over nitrogen fixation. It is important to note, however, that area and volume of the sites are not taken into account in this analysis, so that the actual balance of these processes for the overall coastal zone may not be accurately reflected by this interpretation.

3.2.3.2 *Some Relationships between Variables Controlled by LOICZ Methodology*

There are several relationships between variables imposed by the defining equations for non-conservative flux estimates (Text Box 3.8). While it is possible to derive many of such relationships from the LOICZ methodology, we examine two obvious candidates here: (*i*) limitations from relationships between non-conservative fluxes and the degree of terrestrial/oceanic influence, and (*ii*) the relationships between these fluxes and the system's water residence time (exchange time). Details of these approximations, including a discussion of terrestrial and oceanic dominance, are shown in Text Box 3.8.

3.2.3.2.1 *Non-conservative Fluxes and Terrestrial/Oceanic Dominance*

For systems dominated by ocean exchange, we can conclude from the imposed relationships that:

- The sign of ΔDIP (and thus the signal of its autotrophic/heterotrophic status) will be determined by the sign of the system-ocean concentration gradient.
- In the absence of a strong correlation between V_X and the system-ocean concentration gradient, a log-log plot of ΔDIP versus V_X should have a slope of +1 i.e.,

$$\log \Delta\text{DIP} \cong \log(V_X) + \log(\text{DIP}_{\text{sys}} - \text{DIP}_{\text{ocn}})$$

- If there is a significant correlation between V_X and the system-ocean concentration gradient (or more properly, between their log values), then this should be expressed in the slope of the log-log plot.

Conversely, for systems dominated by terrestrial loads, we can conclude from the imposed relationships that:

- The sign of ΔDIP will be determined by the sign of the concentration gradient between the terrestrial load and the residual flow.
- In the absence of strong correlations between V_R and the concentration gradient in the first term, a log-log plot of ΔDIP vs V_R should have a slope of +1.
- If there are significant correlations between V_R and the concentrations, then this should be expressed in the slope of the log-log plot.

3.2.3.2.2 *Non-conservative Fluxes and Exchange Time*

If we eliminate V_X from the budget expressions and express the relationship with ΔDIP in terms of water resi-

Text Box 3.8. Imposed relationships between LOICZ budget variables

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The budget methodology provides an estimate of non-conservative fluxes in terms of the driving variables. The "algebra" of these relationships (Text Box 3.4) can suggest the factors that dominate the behaviour of these estimates under various limiting conditions, thereby providing clues in the search for patterns.

Non-conservative fluxes and terrestrial/oceanic dominance

Consider dissolved inorganic phosphorus (DIP) as an example. Defining DIP_{Load} as the flow-weighted average concentration of DIP from all terrestrial and atmospheric sources (losses of DIP through water evaporation are assumed to be negligible, as $DIP_E = 0$), then:

$$DIP_{Load} \equiv \frac{-1}{V_R}(V_Q DIP_Q + V_O DIP_O + V_P DIP_P + V_G DIP_G) = \frac{\sum V_i DIP_i}{\sum V_i}, \quad i \in \{Q, O, P, G\} \tag{1}$$

Substituting, we obtain the simple result:

$$\Delta DIP = V_R\left(DIP_{Load} - DIP_R\right) + V_X(DIP_{sys} - DIP_{ocn}) \tag{2}$$

or, in terms of the terrestrial/atmospheric flux of DIP:

$$\Delta DIP = \left(FLUX_{DIPLoad} - V_R DIP_R\right) + V_X(DIP_{sys} - DIP_{ocn}) \tag{3}$$

In the above expression, we see that the estimate of non-conservative DIP flux is expressed as the sum of two terms, representing gradients of nutrient fluxes. The first term is a product of the system residual flow (V_R) and an effective gradient of DIP concentrations between the terrestrial loads and the residual nutrient flux (Eq. 2), and the second, the product of the DIP system-ocean concentration gradient, and the system mixing volume (V_X). The structure of this relationship suggests a natural "partitioning" of the variables in which to look for patterns.

If the first term is negligibly small compared to the second term (i.e., ΔDIP is *ocean-exchange dominated*), then

$$\Delta DIP \cong +V_X(DIP_{sys} - DIP_{ocn})$$

Alternatively, if the first term is large compared to the second term(i.e., *terrestrial-load dominated*), then

$$\Delta DIP \cong (FLUX_{DIPLoad} - V_R DIP_R)$$

These simplifications can be interpreted in terms of controls on autotrophy and heterotrophy (see text).

Non-conservative fluxes and exchange time

We can also eliminate V_X from the above expressions to express the relationship in terms of the system water residence time (τ):

$$\Delta DIP = V_R\left(DIP_{Load} - DIP_R\right) + \left[\frac{V_{Sys}}{\tau} - |V_R|\right](DIP_{sys} - DIP_{ocn}) \tag{4}$$

For positive estuaries ($S_{sys} < S_{ocn}$, $V_R < 0$):

$$\Delta DIP = V_R(DIP_{Load} - DIP_R + DIP_{sys} - DIP_{ocn}) + \frac{V_{Sys}}{\tau}(DIP_{sys} - DIP_{ocn}) \tag{5}$$

For negative estuaries ($S_{sys} > S_{ocn}$, $V_R > 0$):

$$\Delta DIP = V_R(DIP_{Load} - DIP_R - DIP_{sys} + DIP_{ocn}) + \frac{V_{Sys}}{\tau}(DIP_{sys} - DIP_{ocn}) \tag{6}$$

Here, the first term is the product of V_R and a sum of the DIP concentrations of the load, system, residual flow and ocean. These concentrations represent the difference between the gradients of concentration between the load and the residual flow, and the system and the ocean. As such, they are a "gradient of two gradients" of concentration, somewhat analogous to the second-spatial derivative of concentration seen in models of diffusive exchange. Thus, the first term should be sensitive to differences in the concentration gradient between the load and the system, and the system and the ocean, such as might occur in spatially extensive systems. The second term is the product of the DIP system-ocean concentration gradient, and the ratio of system volume to exchange time.

Here, if the *first term is small* compared to the second term, then

$$\Delta DIP \cong +\frac{V_{Sys}}{\tau}(DIP_{sys} - DIP_{ocn})$$

suggesting a significant negative relationship with exchange time. Alternatively,

$$\Delta DIP = V_R\left((DIP_{Load} - DIP_R) \pm (DIP_{sys} - DIP_{ocn})\right)$$

suggesting that the balance of gradients between terrestrial and oceanic boundaries is dominant.

dence time (τ), we can approximate limiting behaviour with respect to τ, i.e., the smaller the value for τ, the smaller the change in DIP concentration associated with any particular non-conservative change in DIP (represented as ΔDIP). If residual flow is relatively small, or the concentration gradient between terrestrial sources and the coastal system is not much different than that between the system and the local ocean, then:

- The sign of ΔDIP (and thus, the signal of its autotrophic/heterotrophic status) will be determined by the sign of the system-ocean concentration gradient.
- In the absence of strong correlations between τ and the other variables of the second term, a log-log plot of ΔDIP versus τ should have a slope of −1.
- If there are significant correlations between τ and the other variables of the second term (or more properly, between their log values), then this should be expressed in the slope of the log-log plot.

Conversely, the balance of concentration gradients should dominate and:

- The sign of ΔDIP will be determined by the sign of the "gradient" of the concentration gradients associated with terrestrial load/residual flux and system/ocean concentrations.

- In the absence of strong correlations between V_R and the concentrations in the first term, a log-log plot of ΔDIP versus V_R should have a slope of +1.
- If there are significant correlations between V_R and the concentrations, then this should be expressed in the slope of the log-log plot.

3.2.3.3 *Additional Relationships between Variables*

Here, we examine a few relationships between the budget variables suggested by the above analysis. In doing so, we have log-transformed the data presented in the figures because (*a*) the great range in the magnitude of the variables suggests the use of the log-transformation to stabilise variance when performing statistical analysis and (*b*) we may be able to test predictions of some coefficients of linear relationships observed in log-transformed data, at least for some subsets of the data (see Text Box 3.9).

3.2.3.3.1 *Water Exchange Time and System Area*

In broad terms, water exchange is driven by the combination of advective inflow and outflow, and mixing. For embayments ranging from a small inlet to a large enclosed sea such as the Baltic, the model works well and the advection (in and out) is defined by the freshwater balance. Mixing must balance the advective flux of salt. For the most part our data represent such an embayment structure. Budgets would not be expected to work well in a classical open shelf (unless the shelf is considered to be infinite in length and the transports to be cross-shelf transports). Nevertheless, we suggest that biogeochemical processes (the primary interest of this research) work similarly on open shelves as in more well-defined systems such as the southern North Sea, the Irish Sea and the East China Sea. We have attempted budgets of narrow upwelling shelves of both South America and South Africa with minimal success (e.g., Hall et al. 1996).

For the systems we have budgeted, Fig. 3.11 shows a noisy but clear relationship between budgeted area and

Text Box 3.9. Regression techniques for estimating functional relationships between variables

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The most popular method of fitting a line to a set of data is simple linear regression, in which the slope and y-intercept of the line are determined by minimising the squared deviations of the *y*-data from the line. Multiple regression is generally used if there are two or more dependent variables. It is important to recognise that simple linear regression can introduce bias in the slope estimate if the *x*-data are also subject to measurement error (see Sokal and Rohlf 1995). If both the *x* and *y* (the independent and dependent variables) are subject to the same types of errors, the data are often better analyzed using a "Model II" type regression which uses the deviations of both *x* and *y* from the line of best fit (Figs. TB3.9.1 and TB3.9.2). Ricker (1973) recommends a specific type of Model II regression, called Geometric Mean (GM) or Reduced Major Axis (RMA) regression, for such cases (Ricker 1973, Sokal and Rohlf 1995, Laws 1997). We have used the GM regression wherever feasible to examine linear relationships between the log-transformed variables, using a simple Excel™ spreadsheet add-in developed by Sawada (*http://www.uottawa.ca/academic/arts/geographie/lpcweb/newlook/data_and_downloads/download/sawsoft/modelii/modelii.htm*) and modified by Swaney to estimate corresponding approximate confidence intervals (Ricker 1973). The modified add-in is downloadable from the LOICZ website (*http://data.ecology.su.se*). For regressions involving more than one independent variable, we use conventional multiple regression, though future efforts may involve more sophisticated techniques, including principal components analysis, and principal components regression (see Dunteman 1989). More sophisticated statistical classification capability is available through the LOICZView, discussed in Chap. 1.

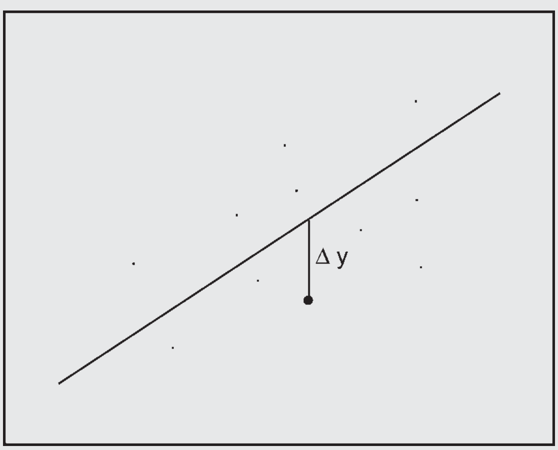

Fig. TB3.9.1. Vertical (Δ*y*) deviation of a data point from the best fit line, the sum of which is minimised in simple linear regression

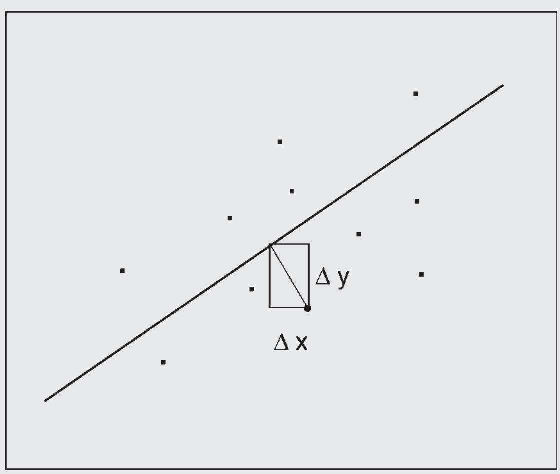

Fig. TB3.9.2. Rectangle associated with the normal deviation of a data point from the best fit line ($\Delta x^2 + \Delta y^2$), the sum of which is minimised in Model II regression. The line bisecting the rectangle is at 90° to the best fit line water exchange time. For systems smaller than about 100 km^2, there is no strong pattern but a range in exchange times between about 1 and 100 days. For systems larger than 100 km^2 there appears to be a clear trend of increasing exchange time with size. Systems larger than a few thousand km^2 typically have exchange times in excess of a year, e.g., the North Sea (area ~300 000 km^2, exchange time 370 days), the East China Sea (area ~900 000 km^2, exchange time 490 days).

3.2.3.3.2 *Internal Processes and Exchange Time*

Water exchange time is a measure of renewal time. Systems with a long exchange time retain materials long enough to react internally; systems with a short exchange time are simple conduits through which water flows. The budgeted systems range in exchange time from < 1 day to many years.

The figures illustrate non-conservative fluxes of both DIP and DIN (Figs. 3.12a–d), as well as the derived estimates of $[p - r]$ and [nfix – denit] (Figs. 3.13a–d) as functions of water exchange time (τ_X). The patterns that emerge are very noisy, but not inconsistent with the arguments based on the mass balance equations expressed above. All of these non-conservative variables show a negative log-log relationship with τ_X, and a slope not too different from –1. Assuming that this indicates that the first term in Eqs. 5–6 of Text Box 3.8 is relatively small, then it follows that the sign of ΔDIP or ΔDIN should be given by that of the ocean-system nutrient gradient. For ΔDIP, it follows that the sign of this gradient should be a dominant factor in determining autotrophy versus heterotrophy.

This hypothesis about control over metabolism was examined further by dividing the budget sites into two categories: those with a system-ocean nutrient concentration difference > 0, and those with a concentration difference ≤ 0, considering both DIP and DIN concentrations. Statistical *t*-tests were applied to the mean values of ΔDIP and ΔDIN for each category to determine if these were significantly different from each other (both regular and log-transformed magnitudes with sign preserved were tested). Irrespective of the log-transforma-

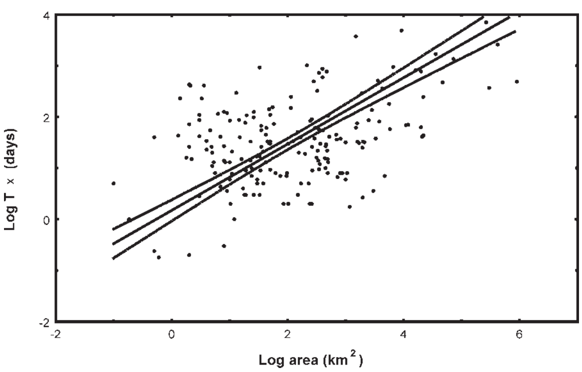

Fig. 3.11. Budget sites. Exchange time versus system area (Model II regression line with 95% confidence: $y = 0.17 + 0.65x$, $r = 0.46$, $n = 184$)

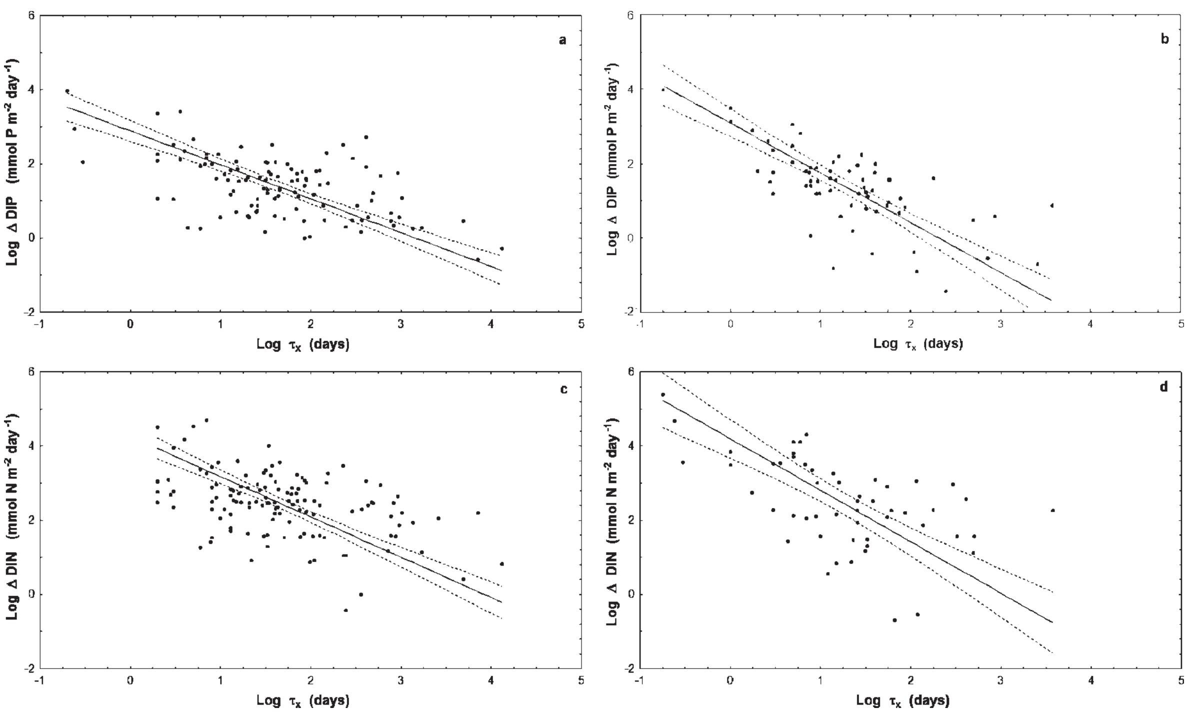

Fig. 3.12. Budget Sites. ΔDIP and ΔDIN as functions of system exchange time (Log-log plots; Model II regression line with 95% confidence). **a** ΔDIP < 0 ($y = 2.89 - 0.91x$, $r = -0.54$, $n = 107$); **b** ΔDIP > 0 ($y = 3.09 - 1.34x$, $r = -0.68$, $n = 65$); **c** ΔDIN < 0 ($y = 4.26 - 109x$, $r = -0.45$, $n = 124$); **d** ΔDIN > 0 ($y = 4.19 - 1.39x$, $r = -0.53$, $n = 51$)

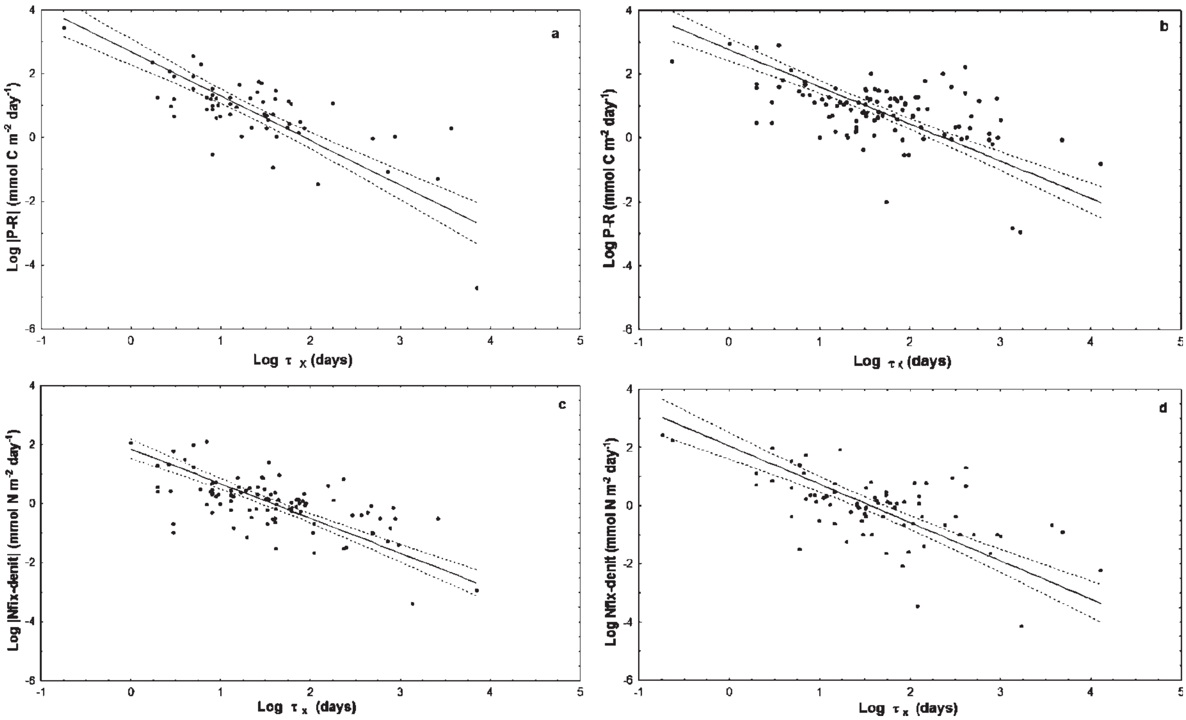

Fig. 3.13. Budget Sites. Apparent net ecosystem production [$p - r$] and apparent nitrogen fixation minus denitrification [nfix – denit] as functions of system exchange time (Log-log plots; Model II regression line with 95% confidence). **a** [$p - r$] < 0 ($y = 2.68 - 1.39x$, $r = -0.73$, $n = 59$); **b** [$p - r$] > 0 ($y = 2.74 - 1.15x$, $r = -0.52$, $n = 104$); **c** [nfix – denit] < 0 ($y = 1.85 - 1.18x$, $r = -0.64$, $n = 96$); **d** [nfix – denit] > 0 ($y = 2.05 - 1.32x$, $r = -0.60$, $n = 75$)

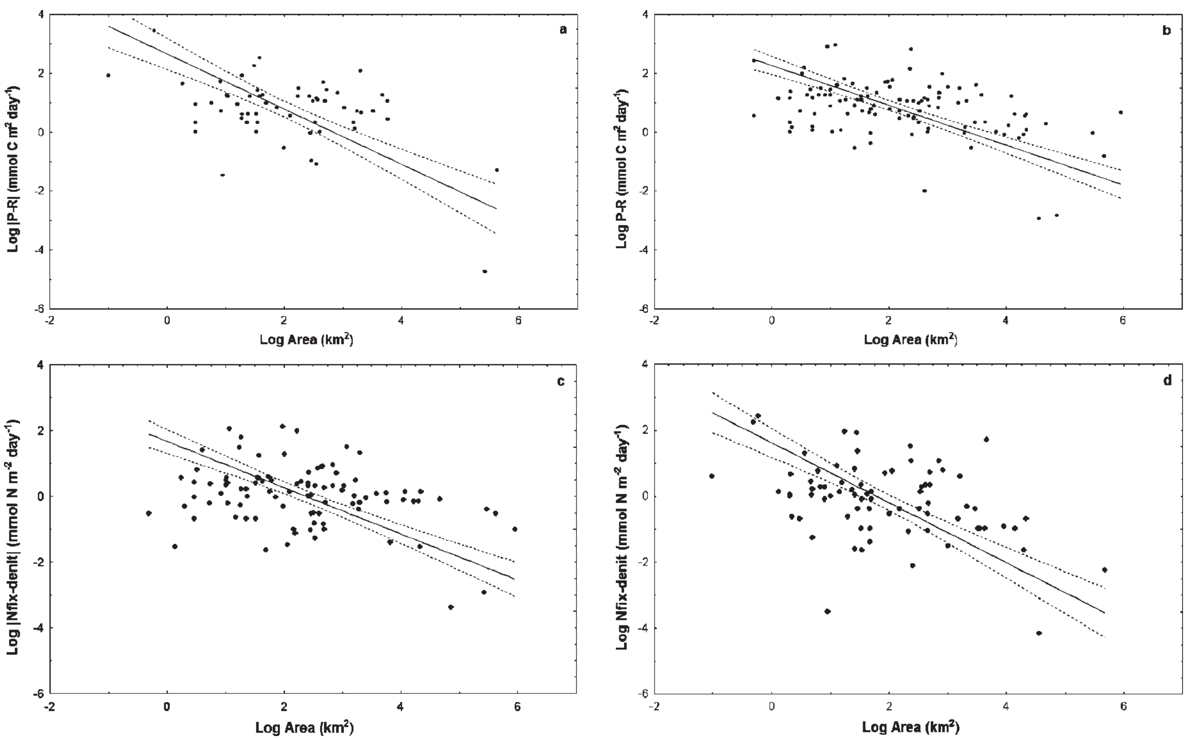

Fig. 3.14. Budget sites. Apparent net ecosystem metabolism [$p - r$] and apparent nitrogen fixation minus denitrification [nfix – denit] as functions of system area (log-log plots; Model II regression line with 95% confidence). **a** [$p - r$] < 0 ($y = 2.65 - 0.94x$, $r = -0.46$, $n = 58$); **b** [$p - r$] > 0 ($y = 2.26 - 0.68x$, $r = -0.42$, $n = 105$); **c** [nfix – denit] < 0 ($y = 1.67 - 0.70x$, $r = -0.31$, $n = 97$); **d** [nfix – denit] > 0 ($y = 1.62 - 0.91x$, $r = -0.40$, $n = 76$)

tion, ΔDIP was found to exhibit significantly different values depending upon the sign of either the DIP or DIN nutrient gradient, and ΔDIN was not. In other words, ΔDIP (and accepting the LOICZ assumptions, net ecosystem metabolism) appears to be sensitive to the sign of the system-ocean nutrient gradient, but ΔDIN does not. A possible interpretation is that for ΔDIN, the oceanic-system gradient may not be as dominant a variable; terrestrial sources of DIN may play a significant role.

Regardless of the complexities of the interactions of nutrient loads, exchange and residence time, most of the observed non-conservative behaviour (either as net sources or sinks) for these systems occurs at exchange times < 100 days and system areas of < 1 000 km^2 (Figs. 3.13, 3.14). One interpretation of this result is that smaller coastal systems (as opposed to larger, shelf seas) are the dominant engines of coastal zone metabolism. Whether the cumulative effects of the nutrient processing of many small high-output systems dominate those of relatively few large but less intense systems remains to be seen.

3.3 Classification of Coastal Fluxes

3.3.1 Budget Sites and Coastal Areas: Sizes, Scales and Representation

The types and sources of the data used, conceptual approaches and tools are discussed in Chap. 1. Here we consider the classification approaches applied to develop patterns of coastal fluxes in the global coastal zone in terms of categories, processes and the variables available for use.

Two major data constraints have shaped the approaches and outcomes and are central to the discussions that follow. First, the global database used for coastal zone classification (typology) is based on a gridded system of half-degree (0.5°) latitude and longitude boxes. Although this resolution is dictated by the scale of many of the globally available datasets and the need to make the databases available over the internet, it is too coarse to resolve many of the important coastal zone features and smaller budget sites. This imposes significant limitations on the upscaling processes and short-term potential, and points to obvious areas of potential improvement and extension (see Recommendations). Another aspect of this choice of gridding is that the relationship between distance in kilometers and degrees of longitude is a non-linear function of latitude (see Text Box 1.7, Chap. 1), so the grid cells are not equal in area, and biases could be introduced by some cell-based comparisons or calculations.

The second constraint, which interacts strongly with the first, is that the coastlines of the world are mostly dominated by small, local drainage basins, whereas most of the knowledge about the characteristics of riverine input to the coastal zone is generated from relatively few, better-studied large and medium-sized river systems (Milliman and Syvitski 1992). While the total discharge and nutrient flux *to the ocean* is dominated by large rivers, the direct effects of high volume inputs (i.e., large rivers) *on the coastal zone* are very localised. The greatest length of coastline, the largest volume of coastal water (Text Box 1.1, Chap. 1), and quite possibly the overall nature of biogeochemical fluxes, strongly reflect smaller and more locally-derived inputs of rivers, groundwater and other freshwater sources. Thus, the most important features of the coastal zone probably include those systems that are least accurately described, both in general and by the half-degree data resolution used for typology.

In order to consider the potential for upscaling to regional and global contexts or generalising results based on the budget and typology datasets, we consider both the nature of the variables available and the physicochemical forcing functions and inputs to the coastal zone from both land and ocean. Particularly on the terrestrial input side, the distinction between anthropogenic influences and natural inputs is critical to understanding both present and possible future dynamics. In considering both the land-ocean and human-natural dichotomies, two further critical questions arise: (*1*) how well and how effectively can we define and classify "small" coastal basins, and predict their functions, in a data environment with resolution limited to 0.5°; (*2*) how well does the LOICZ budget dataset represent the world's coastline?

3.3.2 Land versus Ocean Dominance of Biogeochemical Processes: Dynamic Factors in Coastal Classification

The relative dominance of the biogeochemical budget variables by land and ocean influences is discussed and illustrated in Sect. 3.2.2 and Text Box 3.8. In order to upscale these observations, they must be expressed in terms of, or correlated with, more generally available environmental variables with well-characterised coastal zone distributions. Physical forcing (fluxes and exchange times of water) will determine the relative dominance of land and ocean with respect to supplying nutrient inputs; the nature of those inputs will be determined by the concentrations of nutrients in the source waters.

Three major factors that determine overall physical forcing are:

- Hydrologic (terrestrial) forcing – runoff, primarily in the form of river discharge, but with potential contributions from groundwater discharge and diffuse surface runoff. This physical forcing may be a conduit for a variety of chemical components of both human and natural origin.
- Ocean forcing – waves, tides and currents.

- Coastal openness or exposure – the geomorphology of the coastal system, in terms of depth, orientation and coastal complexity, a major factor in how these driving forces determine the critically important residence time of the system that in turn modifies the rates and extent of the biogeochemical reactions (Bartley et al. 2001).

3.3.2.1 *Oceanic Forcing*

Physical forcing of the system water exchange time – the turnover rate of the biogeochemical reactor – is determined by water flux. From the marine side, this reflects the combined effects of currents. For very large systems or open shelf settings, regional oceanic currents may be important as physical drivers, just as upwelling zones may be important to the supply of oceanic nutrients (Nixon et al. 1996, Michaels et al. 1996). For small and intermediate-sized budget systems, effects of tidal and wind-driven currents are likely to be particularly important to local water exchange and mixing. The typology database does not contain information on larger-scale oceanic system currents at present. For most of the duration of the LOICZ project, available global data on wave height and tidal range have been limited to rather coarsely classified datasets with relatively sparse coverage. However, recent acquisition of much more detailed marine wind data (da Silva et al. 1994) and tide model outputs (Stewart 2000) have permitted classification of the smaller-scale forcings with greater confidence. While these provide an incremental shift in the typology database capacity, it should be noted that the scale and resolution of the additional tidal and wind data characterise open coastal conditions. Their application as proxies for water processes in small or semi-enclosed embayments is less certain.

Figure 3.15 shows LOICZView clustering classifications of two marine energy proxies, a tidal flushing index (maximum amplitude multiplied by a form factor representing diurnal/semidiurnal frequency) and the square of the average wind speed (as an index of wind stress). Also shown is the average depth of the coastal cells, which strongly conditions the transmission of water and energy. For the energy variables, the colour index ranges from red at high values (higher winds, higher tides, greater flushing) to blue for calmer conditions. For depth, red indicates shallow water, while blue is deeper. Using six or seven categories, this classification approach demonstrates the spatial continuity of the marine forcing variables and illustrates the potential for combining the variable classifications into a more general multivariate exchange or energy index.

Marine forcing variables tend to have rather smooth spatial distributions at scales of tens of kilometers and above in the offshore environment (ocean and open shelf), in part due to data resolution and in part due to apparent spatial heterogeneity of the land. This pattern holds for the distributions of precipitation and evaporation and other climate-controlled variables. These parameters can be described and analysed well at the half-degree level. However, application to specific budget settings becomes more problematic because of the effects of local coastal structure that can strongly modify the forcing functions and especially their interactions.

3.3.2.2 *System Size, Complexity and Exposure*

The physical configuration of a coastal system is the critical link between the terrestrial and the marine forcings.

For classification and upscaling, the essential issue is the relationship of system size to the half-degree typology database grid, and to the resolution of the component geomorphic variables in the database. There are strong analogies between coastal system size and catchment basin size; systems or basins with areas in the 1 000–10 000 km^2 range are likely to be described reasonably well by the characteristics of the corresponding grid cells, while smaller systems are less likely to be well-represented by half-degree variables unless they are particularly open and well-connected with the offshore environment. Figure 3.4 illustrates the distribution of system size (areas) of budget sites; almost 75% of the systems analysed are <1 000 km^2 in area, and only about 15% are in the typologically optimal 1 000–10 000 km^2 range.

System configuration – shape, complexity, exposure – has three major components readily identifiable in terms of typology:

- Depth – the depth of a system and its immediate surroundings exerts strong control over the dissipation and distribution of tidal and (especially) wave energy, and on the amount of light reaching the benthic ecosystems.
- Coastal complexity – convoluted or compartmentalised systems are likely to be both heterogeneous and relatively protected from the effects of the marine physical forcing functions.
- Orientation and relationships – the relationships of wind and current direction to coastline orientation determine both the degree of "exposure" of a system and the magnitude of its oceanic exchanges. Offshore environmental factors such as bottom slope or the presence/absence of shoals and barriers also strongly mediate interactions between systems and the more broadly distributed forcing functions.

Although the distribution of budget sites characterised to date is concentrated well below the scale of the current typology grid system, the key geomorphic variables have underlying resolutions much more appropri-

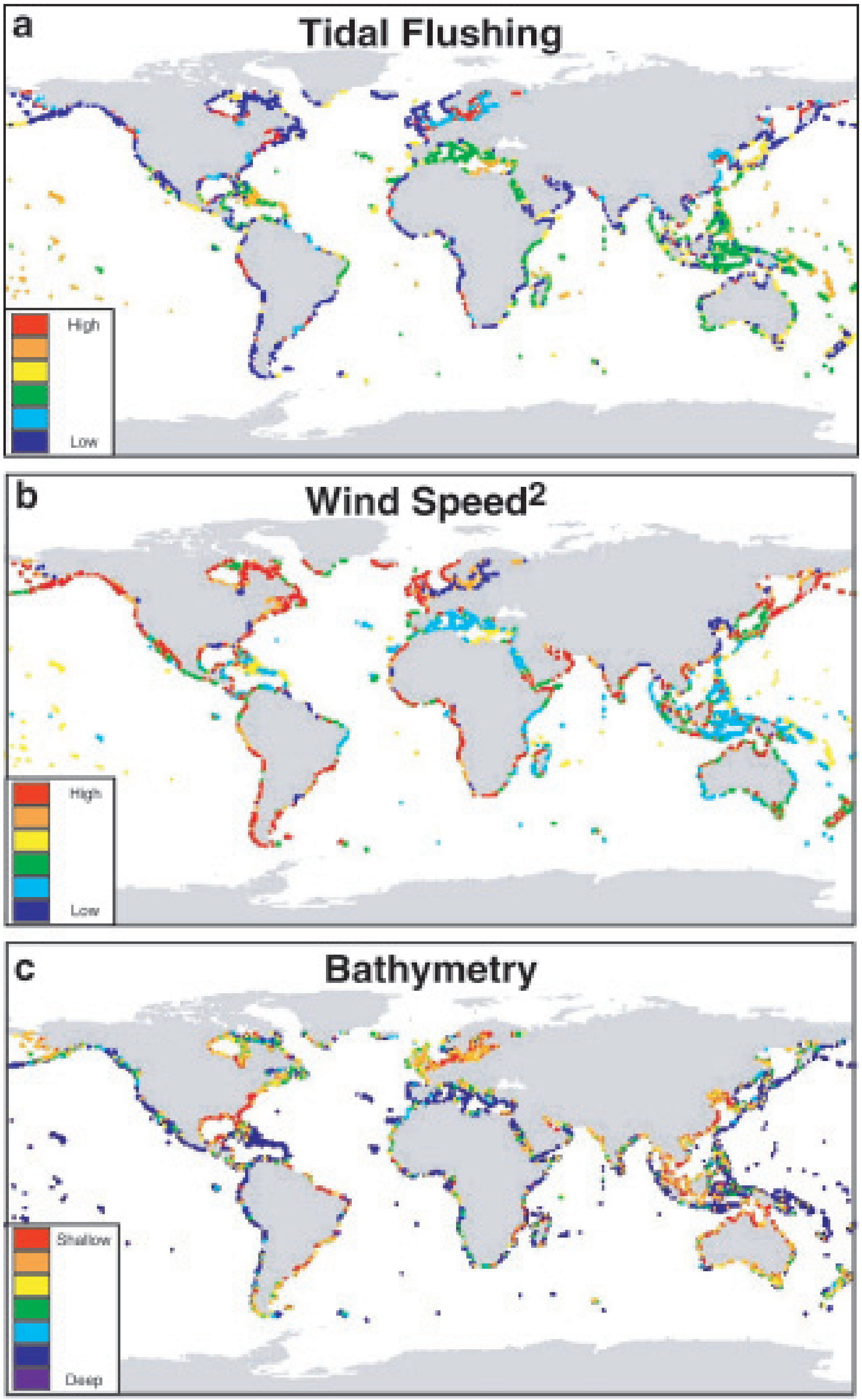

Fig. 3.15.
Classification of proxy variables for ocean forcing.
a LOICZView clustering of a tidal flushing index for coastal and adjacent Ocean I cells. Intensity of potential tidal flushing increases from *blue* (lowest) through *red* (highest).
b LOICZView clustering of wind speed squared for coastal and adjacent Ocean I cells. Mean wind speed (and hence wave-induced mixing and wind-driven currents, represented by velocity squared) increases from *blue* (lowest) through *red* (highest).
c Clustered distribution of mean depth of coastal cells. *Blue cells* are deepest, *red* are shallowest

ate to the necessary characterisation. The World Vector Shoreline data has both directionality and sub-kilometer scale resolution, and the ETOPO2 bathymetry database has pixel sizes of 2' (4 km or less, depending on latitude). Additionally, the wind data in use have vector as well as scalar components, although these have not been incorporated into the database.

The present half-degree database system includes sub-grid scale information about the component variables. Coastline length and total land and water areas within the cells are examples of data that provide information about characteristics within the cells. The typology database also contains statistics on depth distributions of the 2' pixels within the half-degree cells (mean, maxi-

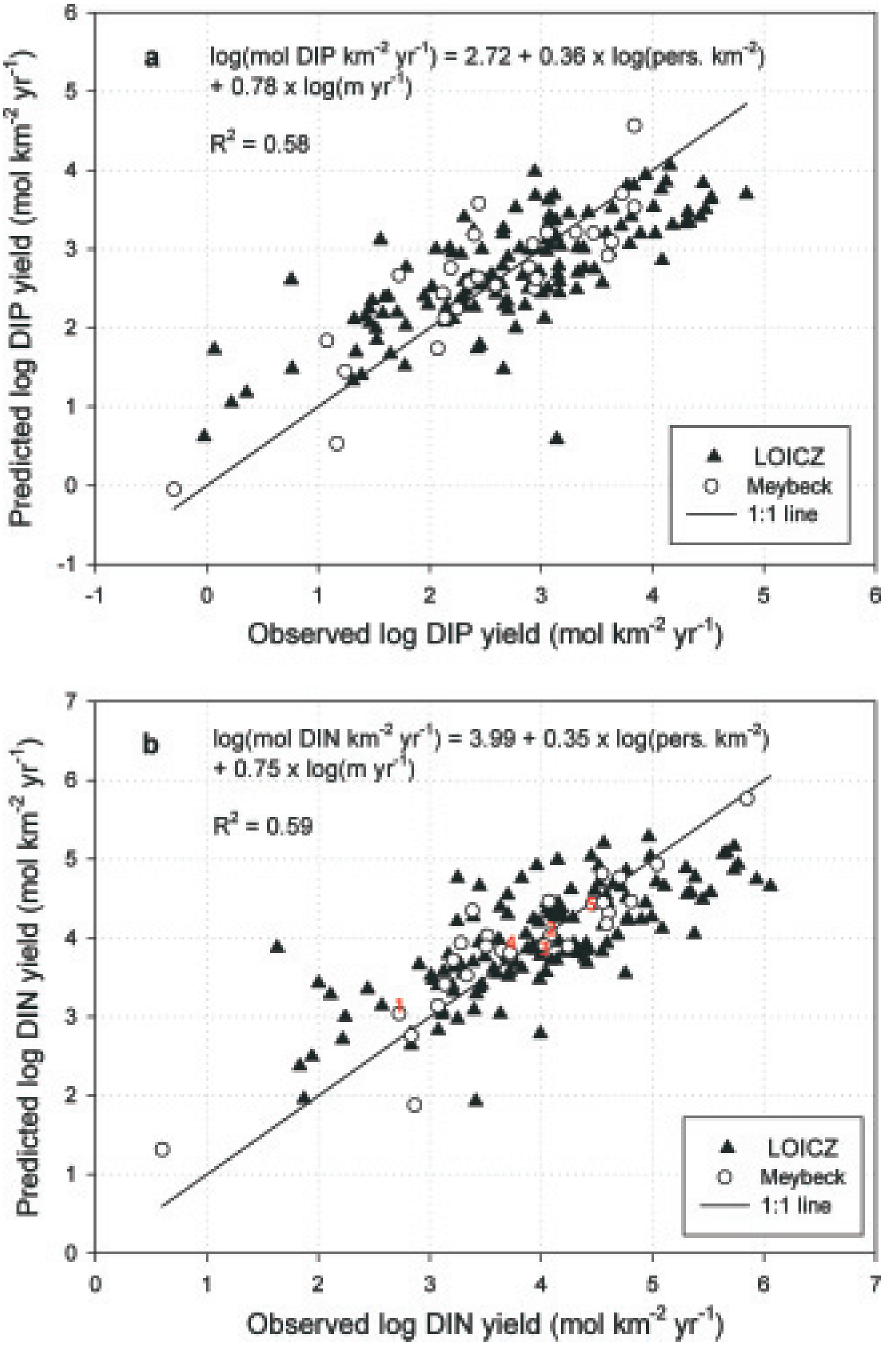

Fig. 3.16.
Nutrient loading – loads to coastal systems. Observed versus predicted values for (**a**) DIP and (**b**) DIN loading (from Smith et al. 2003). *Triangles* represent LOICZ budget sites; *circles* represent Meybeck (1982) basins. The five largest basins are identified by number: *1* Amazon; *2* Congo; *3* Rio de la Plata; *4* Amur; *5* Changjiang

mum, minimum, standard deviation); these provide within-cell estimates of features such as slope and heterogeneity. However, limitations of the datasets need to be considered; the absolute accuracy of the ETOPO2 pixel depths is much less than the nominal 1 m depth resolution provided.

Overall, the complexity parameters are among those that are currently problematic but that offer opportunities for rapid progress in coastal zone classification and typology applications (Bartley et al. 2001, see Text Box 1.1, Chap. 1).

3.3.2.3 *Hydrologic (Terrestrial) Forcing*

The hydrologic forcing variables from the budget datasets that contribute to the total freshwater flow are V_Q (stream discharge), V_G (groundwater discharge), V_P (precipitation), V_E (evaporation), and V_O (point discharges) (see Text Box 3.4 for definitions). In most situations V_Q is volumetrically dominant. The typology database lacks variables that can estimate or correspond to V_G and V_O; V_P and V_E are represented by corresponding environmental datasets, but have not been applied to typologies developed to date. The typology variable equivalent to the important V_Q variable is basin runoff (RO); the RO data are derived from water balance models and might more accurately be termed "potential runoff". For many applications we use the catchment area (A)-normalised values of these volumes, V_Q/A or RO/A, in units of m yr^{-1}.

The typology catchment basin variables were augmented with refined basin data for the catchments associated with most of the localised budget sites, developed by using GIS techniques and the Hydro1K (USGS 2001) dataset, to produce catchment basin polygons. These are identified as the km-scale basins and were used to determine the basin area and to sample other areally-distributed variables (Buddemeier et al. 2002, Smith et al. 2003). Of particular relevance to the discussions that follow are runoff-related variables, human population and population density. In most cases, km-scale basins could be directly identified with a corresponding half-degree basin or cell. The values of the variables sampled at the basin scale were not only used for analysis of the budget variable relationships (see Sect. 3.3.3), but also for examining issues of basin scale and the degree to which the present biogeochemical budget sites may represent either the global distribution of sites or their functional processes (Text Box 3.12; Sect. 3.3.5).

3.3.3 Natural and Anthropogenic Factors: Pristine to Highly Altered

3.3.3.1 *Combined Controls on Nutrient Loads and Anthropogenic Factors*

Climatically-driven forcing functions, such as runoff, interact with land cover, land use and geomorphology to modulate inputs to the coastal zone that result from a mixture of natural processes and varying degrees and types of anthropogenic modifications.

For the km-scale budget site basins, Smith et al. (2003) have observed a logarithmic relationship between DIP and DIN loads, and the population density and area-normalised discharge (Fig. 3.16; see also Buddemeier et al. 2002). This robust finding substantially extends and is consistent with many studies (e.g., Meybeck and Ragu 1997) and provides a useful starting point both for further refinement of the relationship in terms of climate and land use, and for consideration of upscaling the terrestrial inputs to the ocean on the basis of readily available terrestrial data.

Influences of human activities within river basins are encapsulated by both the population density and runoff terms. Land use modifies the potential runoff calculated from the water balance (the typology runoff variable) to produce the actual observed runoff or discharge (e.g., V_Q), which is one of the challenges involved in relating RO and V_Q, and in the upscaling efforts discussed below. The use of population density as the primary human dimension forcing function glosses over the explanatory potential of various more refined variables (e.g., extent and types of agriculture, economic development levels, industrial and urban activities). Obviously, the scatter of points shown in Fig. 3.16 provides a basis for further analysis of those variations in terms of the influences of other factors on N and P loads to coastal ecosystems. Preliminary analyses by Sandhei (2003) have shown that agricultural land use and nutrient input variables have some potential to refine the equations, particularly for developed countries (also see Text Box 3.10). The equations derived in Fig. 3.16 provide a potential approach to generalising or upscaling some important components of coastal biogeochemical fluxes. Indeed, Smith et al. (2003) used the relationships in combination with geospatial cluster analysis to generate estimates of the global loads and their distributions. The ubiquity of human influences and the fact that they influence both of the independent variables in the load regression equations to some degree means that estimation of the pristine or natural fluxes is particularly challenging.

3.3.3.2 *Environmental Settings and Characteristics of Pristine Coastline Types*

Identification of sectors of natural (pristine, or free from major human alterations) coastline function provides the basis for:

- estimates of pre-anthropogenic fluxes for global regions and for the Earth system as a whole;
- estimates of the degree of change in material fluxes already experienced;
- making predictions about future changes, when coupled with information on the effects of human populations on fluxes; and
- understanding the natural mechanisms regulating biogeochemical cycles.

Global delivery to the ocean of DIP and DIN as a result of human activities is estimated to have increased threefold between the 1970s and 1990s (Smith et al. 2003, see Table 3.2). Earlier estimates by Meybeck (1982) were based on extrapolation by expert judgment from 30 major river basins. The global loading estimates by Smith and colleagues were derived statistically from the regression models for catchment basin loading to the ocean (see Fig. 3.16), based on the data from 165 budget sites discussed in this chapter and utilising the LOICZ typology approach. The estimated increase in human-derived DIP and DIN to the coastal ocean over the last two decades is commensurate with the dramatic increase in global population, agricultural production and atmospheric

Text Box 3.10. Anthropogenic drivers for nitrogen and phosphorus in Southeast Asia

M. L. San Diego-McGlone and V. C. Dupra

The Asia-Pacific region has a longer coastline than any other region of the world. The strategic position of these coastal areas in terms of trade and extraction of resources has resulted in a continuing expansion of the coastal human population, due to both growth and migration from inland areas. While about 50% of the world's population lives within 100 km of the coastline, and about 65% (4 billion) within 200 km of the coast, by 2025 this number should approach 6 billion, roughly today's entire world population (*http://www.prb.org/*). Southeast Asia currently has the highest percentage of coastal dwellers in the world, with some 70% (350 million) of the population living within 50 km of the coast, so human impacts within this region may foreshadow those of the global coastal zone of the future.

The massive increase in coastal population of the region, and its accompanying economic activity, has brought with it significant changes in the flux of materials from land to coastal waters. The sources of nitrogen and phosphorus may be broken down into a handful of anthropogenic activities. These activities include agriculture, human waste disposal and aquaculture. Their importance for some situations in Southeast Asia is reviewed below.

Agricultural activities, including crop and livestock production, are a primary source of nutrients to the coastal zone. Crop production contributes to N and P effluents primarily through the transport of sediments. Intensive agriculture involves significant soil erosion, and eventual sediment transport to coastal waters. Two-thirds of the world's sediment transport to oceans is in Southeast Asia (GEMS 1996). This may be due to active tectonics, heavy rainfall, steep slopes and disturbed soils that are easily eroded. Levels of suspended solids in Asian rivers have almost quadrupled since the late 1970s (ADB 1997, GEMS 1996). This problem of soil erosion is exacerbated by the increasing use of fertilisers; for the Asia-Pacific region, fertiliser consumption increased 340% from 1975–95 (ADB 1997). Livestock production also contributes to N and P effluents through the production of animal wastes. A portion of animal wastes is applied to fields as fertiliser, and finds its way to coastal waters through transport of sediments and dissolved nutrients in streamflow. The substantial portion of animal wastes not used as fertiliser may be simply flushed away to nearby water sources, making its way to coastal waters.

Human waste (sewage and solid waste) is a leading contributor to nitrogen and phosphorus effluents entering coastal waters. The growth in human waste production mirrors the growth in population and improvements in nutrition. Waste residuals will continue to be a growing problem, as most Southeast Asian countries have inadequate treatment facilities. In South and Southeast Asia, only 10% of sewage is treated (ADB 1997). Currently, only 3% of Metro-Manila (Philippines) households are connected to a central sewer that discharges directly to Manila Bay and, as of 1998, no major coastal city in Indonesia had a sewage treatment facility in place.

Coastal aquaculture takes two primary forms. Fishponds are built along coastal lands, often replacing mangrove systems that are important for their residual assimilation capacity. After harvest, fishpond waters are typically flushed directly into adjoining coastal waters. Fish pens and fish cages are located directly within coastal waters; feeds and wastes are deposited directly into the water. The introduction of excessive nutrients to coastal waters is reflected in the frequent occurrence of red tide algal blooms and fish kills along the coasts of many countries.

The impact of anthropogenic activities on coastal waters is seen not only in increased nutrient discharges but also in reduced assimilation capacity of the systems below natural levels. For example, in Southeast Asia, mangroves (documented as natural filters and sediment traps) have been reduced to about 45% of the estimated cover of the early 1900s (Talaue-McManus 2000). At present rates, the region will lose its mangrove forests by about 2030 (Talaue-McManus 2000). With less assimilation and added discharges from aquaculture ponds converted from mangrove swamps, anthropogenic impact to receiving waters has increased substantially.

The responses to nutrient loading in coastal waters were examined in 30 coastal ecosystems in Southeast Asia, particularly in China, Indonesia, Malaysia, Philippines, Taiwan, Thailand and Vietnam. In one study (Case A, below), the contribution of major economic activities to DIP and DIN load was quantified and assimilation capacity compared in four coastal bays located in Vietnam, Thailand, Philippines and Malaysia (Talaue-McManus et al. 2001). In another study (Case B, below), the physical attributes of 30 coastal bays in all seven Southeast Asian countries were correlated with DIN and DIP loads to derive possible proxies for DIN and DIP loads, useful when site data are not available (Dupra 2003). The contribution of the rivers, ocean and other sources (groundwater, atmosphere, sewage) to the nutrient (DIN and DIP) loading were discriminated for the 30 coastal sites in a third study (Case C, below, Dupra 2003).

- *Case A*. Four coastal watersheds in Southeast Asia were examined: the Red River Delta in Vietnam (mangrove-dominated), Bandon Bay in Thailand (mangrove-dominated), Lingayen Gulf in the Philippines (extensive reef system), and Merbok Estuary in Malaysia (mangrove-dominated). Agriculture contributed 20–80% of the total DIN (21% for Bandon Bay, 37% for Merbok Estuary, 64% for Lingayen Gulf, 77% for Red River Delta) and 20–80% of the total DIP (21% for Bandon Bay, 45% for Merbok Bay and Lingayen Gulf, 76% for Red River Delta) from the watershed. Household waste provided 15% of the total DIN and DIP to Bandon Bay and 33% of the total DIN and 52% of the total DIP to Lingayen Gulf. To assess assimilation in these bays, an index ratio was estimated between generated nutrient waste and total nutrient loading (Talaue-McManus et al. 2001) to compare anthropogenic influence on nutrient (DIN and DIP) loading. An index of 1 indicates highest anthropogenic impact to receiving waters, >1 implies high assimilative capacity, and <1 high loading and high impact from natural sources. The Red River Delta showed highest buffering capacity followed by the Merbok Estuary. Lingayen Gulf received the most impact from human-generated waste, while Bandon Bay was the least impacted.
- *Case B*. Among the physical attributes of the 30 coastal ecosystems, the variables that correlate well with DIN and DIP river loading are river discharge ($r^2 = 0.85$ for DIN load and $r^2 = 0.97$ for DIP load), catchment population ($r^2 = 0.85$ for DIN load and $r^2 = 0.77$ for DIP load) and catchment area ($r^2 = 0.72$ for DIN load and $r^2 = 0.49$ for DIP load). Simple and multiple regression equations that describe DIN and DIP loading in the 30 coastal ecosystems as functions of river runoff and/or population in the catchment are presented in Table TB3.10.1. The regression equations imply that log-transformed DIN and DIP river loads per square kilometer of catchment area increase with log-transformed river runoff per square kilometer of catchment area and population density in the catchment. The derived regression models may then be used to estimate DIP and DIN river loads for a coastal bay given a value for river discharge and population density in the catchment.
- *Case C*. Estimated DIN and DIP fluxes that include river load, net oceanic flux and other fluxes (i.e., sewage, groundwater flux and atmospheric flux combined) in the 30 coastal ecosystems within Southeast Asia were evaluated to determine their relative contributions to net coastal ecosystem nutrient flux. River load and net oceanic flux dominated in most of the coastal ecosystems. Net oceanic flux is generally net transport to the adjacent ocean except for coastal ecosystems with high levels of DIN and DIP waters from the outside. Net export fluxes to the adjacent ocean were influenced by the catchments draining into them and may also be parameterised by runoff and population density in the catchment.

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Table TB3.10.1. Regression equations for log-transformed nutrient river loads (log [F_{DINQ}/A_B] and log [F_{DIPQ}/A_B]) versus log predicting variables (log [V_Q/A_B] and log [N/A_B]). (F_{DINQ} = DIN river flux and F_{DIPQ} = DIP river flux, A_B = basin area, V_Q = runoff, N = population)

Response variable	Regression equations	Number of sites	r^2
River load			
Log (F_{DINQ}/A_B)	3.64 + 0.29 log (N/A_B) + 0.66 log (VQ/A_B)	24	0.71
Log (F_{DINQ}/A_B)	2.83 + 0.62 log (N/A_B)	25	0.39
Log (F_{DINQ}/A_B)	4.38 + 0.81 log (VQ/A_B)	28	0.65
Log (F_{DIPQ}/A_B)	2.41 + 0.24 log (N/A_B) + 0.75 log (VQ/A_B)	24	0.80
Log (F_{DIPQ}/A_B)	1.31 + 0.62 log (N/A_B)	25	0.39
Log (F_{DIPQ}/A_B)	3.16 + 0.87 log (VQ/A_B)	28	0.76

Table 3.2. Nutrient loading. Global transport of DIP and DIN in the coastal zone, estimated from 1970s data (Meybeck 1982) and 1990s data (Smith et al. 2003)

	DIP load (10^9 mol yr^{-1})	DIN load (10^9 mol yr^{-1})
1970s data		
Natural or pristine load	13	320
Global load (natural + anthropogenic)	26	480
1990s data		
Natural or pristine load	21	400
Global load (natural + anthropogenic)	74	1 350

emissions noted elsewhere (WRI 2000). Despite the differences in datasets and extrapolation methods, each assessment arrived at similar values for natural loads of DIP and DIN to the global ocean. These natural load values are indicative of the order of magnitude for loading under pristine settings. To go beyond this kind of order-of-magnitude estimate, more data and more sophisticated analyses will be required.

Since we view the unaltered past from the perspective of a substantially altered present, we are unlikely ever to be confident that we have acquired data for a truly pristine condition. However, we can certainly identify areas of relatively minimal impact and we can rank different environments in terms of their probable degree of alteration. That at least permits us to narrow the possible range of pristine values and to focus our search on the most promising or representative candidates. We discuss this subject further in Sect. 3.4.

For the preliminary assessment presented here, we assume that the degree of anthropogenic alteration of land-based inputs to the coastal zone (see Text Box 3.11) is generally substantially greater than the alteration of the oceanic fluxes. To identify relatively natural systems, we begin therefore by deciding which terrestrial areas to disqualify. In the preceding section we discussed the dependence of DIN and DIP loads on population density (clearly indicative of alteration) and runoff. The runoff is a vector for both natural and human-modified fluxes, and further, is itself subject to human alteration of surface water hydrology. In order to arrive at some degree of separation of the relative effects of runoff and population, we can classify the dataset according to value ranges for both variables. Because most of the numerical values of runoff/area and population density fall within a four order of magnitude range, and because the load relationship is defined on the basis of $\log_{10}$ variables, categorisation of the terrestrial systems into four classes based on log values is a convenient and reasonable starting point.

3.3.4 Budget Sites as Representatives of the Global System

Text Box 3.12 illustrates the basis for the four-class log-scale classification system. We use that as a starting point from which to consider the global distribution of the nutrient loads and the factors controlling them, as well as how adequately the present distribution of budget sites samples the various environments. After identifying the most critical types of coastal systems to sample and understand, we turn to the question of relating the local, budget-site measurements and data to the similar but not identical global datasets that must be used for extrapolating or upscaling the local results.

3.3.4.1 *Global System and Budget Site Distributions*

Smith et al. (2003) used data from the budget sites and the catchment basins associated with them to derive a rela-

Text Box 3.11. Inorganic nutrient fluxes in the coastal ecosystems of Southeast Asia

V. C. Dupra and M. L. San Diego-McGlone

Dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) annual fluxes have been estimated for 30 coastal ecosystems in the Southeast Asia region using the mass balance approach developed by LOICZ (Dupra et al. 2000a, 2000b). Inorganic nutrients are delivered mainly by rivers in most of the coastal ecosystems. River load and net oceanic flux generally dominate nutrient fluxes and net oceanic flux is usually net export to the adjacent ocean. River load and net export to the adjacent ocean were balanced to determine net coastal ecosystem nutrient fluxes. The net coastal ecosystem DIN and DIP fluxes are potential net biological reactive nutrients (non-conservative fluxes) and may be interpreted stoichiometrically as apparent net ecosystem metabolism.

River DIN and DIP loads may be scaled as total load per year (aggregate of loads from the catchment) or as load per square kilometer of catchment per year (called yields). Figure TB3.11.1 presents log-transformed total loads for 30 coastal ecosystems (from Dupra 2003). The coastal ecosystems that have the highest total DIN loads are Pearl (China), Madaomen (China), Aimen (China), Tien (Vietnam) and Hau (Vietnam). The biggest watersheds drain into these ecosystems. Their DIN loads (antilog of the values in Fig. TB3.11.1) vary from about 2×10^9 moles yr^{-1} to 6×10^9 moles yr^{-1}. The other coastal systems received relatively smaller total DIN loads. Total DIP loads were highest for the Pearl, Hau and Tien rivers. Their loads fall between about 0.2×10^9 moles yr^{-1} and 0.4×10^9 moles yr^{-1}. Total DIP loads for Modaomen and Aimen are not elevated in proportion with DIN. Lingayen Gulf (Philippines) and Manila Bay (Philippines) have comparable DIP loads with Madaomen and Aimen, respectively. The other coastal systems have relatively low DIP river loads.

Figure TB3.11.2 illustrates log-transformed river nutrient loads scaled by catchment (load per square kilometer of catchment area per year) (from Dupra 2003). Hau (Vietnam) and Tanshui (Taiwan) have the highest DIN load per square kilometer. These systems have small catchment areas. The other coastal systems have < 100 kmol km^{-2} yr^{-1} DIN load. The Philippine systems (Sogod,

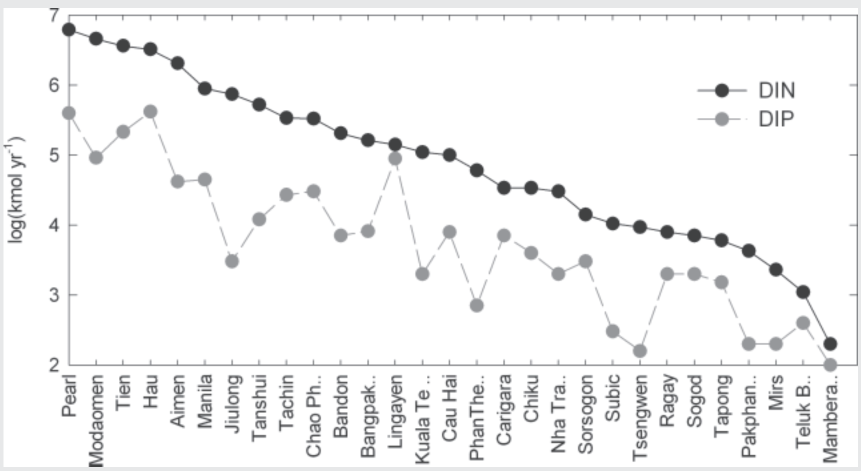

Fig. TB3.11.1. Log transformed dissolved inorganic nitrogen river load (F_{DINQ}) and dissolved inorganic phosphorus river load (F_{DIPQ}) for the coastal ecosystems in the Southeast Asia region. VanPhong Bay river load is 0 (log is undefined) and is excluded in the analysis

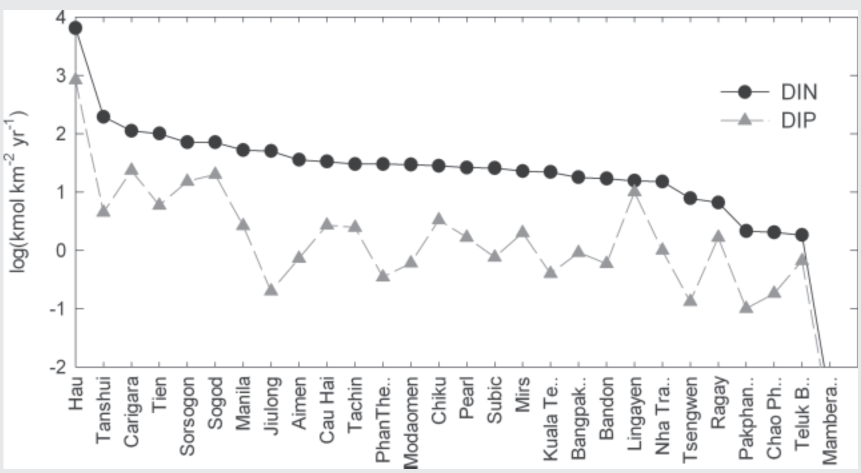

Fig. TB3.11.2. Dissolved inorganic nitrogen river load per catchment area (F_{DINQ}/A_B) and dissolved inorganic phosphorus river load per catchment area (F_{DIPQ}/A_B) for the coastal ecosystems in the Southeast Asia region. VanPhong Bay has 0 nutrient river load and Tapong Bay has 0 catchment area (log is undefined) and are excluded from the analysis

tionship between the yields of DIP and DIN and the area-normalised runoff and populations of the catchment basins. They then used geospatial clustering techniques to develop an estimate of the global coastal DIP and DIN loads, based on the distributions of the independent variables.

We assume that regardless of the uncertainties in the Smith et al. (2003) regression equations, the relationships are sufficiently representative of the processes and relationship to provide guidance about the relative importance of various factors and geographic regions to the

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Carigara, Sorsogon and Lingayen) have the highest DIP load per square kilometer (> 10); the other coastal systems have less than 5 kmol km^{-2} yr^{-1} DIP loads.

Negative net oceanic DIN and DIP fluxes in the budgeted coastal ecosystems represent net exports of nutrients from the system to the adjacent ocean. Budgeted coastal ecosystems with negative net oceanic nutrient flux were grouped and analyzed to determine relationships between net oceanic fluxes and river loads. Relationships of log-transformed river loads and net oceanic fluxes for both DIN and DIP are presented in Fig. TB3.11.3 as scatter plots (from Dupra 2003). The negative (i.e., outward) net oceanic fluxes were changed to positive before logarithmic transformation of the data. For both DIN and DIP fluxes, net oceanic flux is highly coupled to river load, $r^2 = 0.87$ and 0.81, respectively. The slopes of both lines differ considerably from 1. It seems that for both DIN and DIP, there is increasing export of the nutrients to the adjacent ocean with increase in river nutrient loads and the increase in the nutrient export is proportionally lower than the increase in nutrient load. For DIN flux, solution of the regression equation indicates that an increase of DIN river load from 1×10^6 mol yr^{-1} to 10×10^6 mol yr^{-1} would mean an increase of net oceanic export of DIN from 2×10^6 mol yr^{-1} to 18×10^6 mol yr^{-1}. In the case of DIP flux, changing river DIP load from 0.1×10^6 mol yr^{-1} to 1×10^6 mol yr^{-1} would result in an equivalent change in net oceanic export from 0.2×10^6 mol yr^{-1} to 1.8×10^6 mol yr^{-1}. Net oceanic flux to the adjacent ocean was approximately twice as much as the nutrient river load. Seemingly the dissolved inorganic nutrients from the river support only half of what is being transported to the ocean. However, the strong relationships between the river load and net oceanic export suggest that either the river would support an internal source of the net oceanic export or the river flux carries organic materials that are oxidised to release the required dissolved inorganic nutrients within the estuary.

River nutrient loads and net export oceanic flux in log DIN km^{-2} yr^{-1} and log DIN km^{-2} yr^{-1} for the 30 coastal ecosystems may be described as linear functions of runoff per square kilometer of catchment per year and catchment population density. The regression equations that describe river nutrient loadings in the 30 coastal ecosystems may be applied to the coastline of the Southeast Asia region using regional data on runoff and population density in the catchment to derive patterns of nutrient loading.

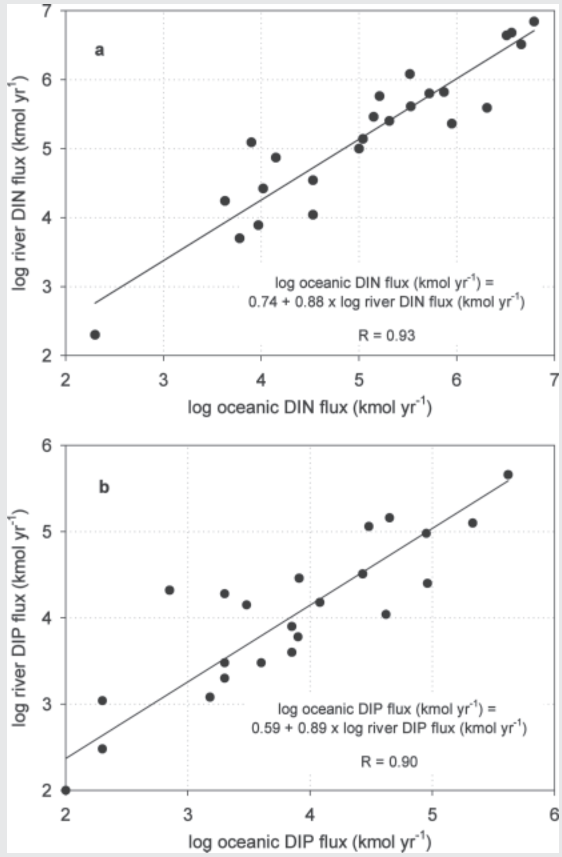


Fig. TB3.11.3. Scatter plots of log-log nutrient river load (F_{DIPQ}) versus net oceanic flux (F_{DIPOcn}) for Southeast Asia budgeted coastal ecosystems with net export (from the system to the adjacent ocean) oceanic nutrient flux. The convention of negative sign for net export in the budgets was reversed for log transformation

magnitudes and distributions of coastal biogeochemical fluxes. Independent variables and basin area can both be conveniently classified into four order-of-magnitude classes (see Text Box 3.13). For initial analysis we have employed a four-by-four matrix with log runoff/area classes of < –2, –2 to –1, –1 to 0, and > 0 and with log population density classes of < 0, 0 to 1, 1 to 2 and > 2.

Because the form and coefficients of the DIN and DIP regression equations derived by Smith et al. (2003) are very similar, there are no significant differences between the relative distributions of the two nutrients, and in this discussion we simply average the DIN and DIP results and present total nutrient load. Applying the equations to the global runoff, area and population data from the LOICZ database, we obtain the normalised yield and calculated distribution of the loads (Fig. 3.17).

The normalised yield, which is positively correlated with both variables, predictably shows a smooth increase from low to high values on both axes. The realised load, however, is primarily a function of the area of land within each class, and secondarily a function of the details of the normalised runoff and population values within the classes. The distribution of the total nutrient load therefore differs strikingly from the yield distributions, as seen in Fig. 3.17b and the associated table.

Two of the matrix cells account for 61% of the global load, another two for an additional 23%, four more add an additional 14%, while the other half of the 16 matrix cells contribute only a few percent. Over 90% of the total load comes from the six cells formed by the intersection of the two highest runoff classes and the three highest population density classes. The uncoloured and unshaded numbers in the table of Fig. 3.17 identify the locations that seem most likely to provide natural background (pristine) load values relevant to the enhanced loads derived from the higher population locations in the same runoff categories.

Text Box 3.12. Classification of river basins and budget site nutrient loads

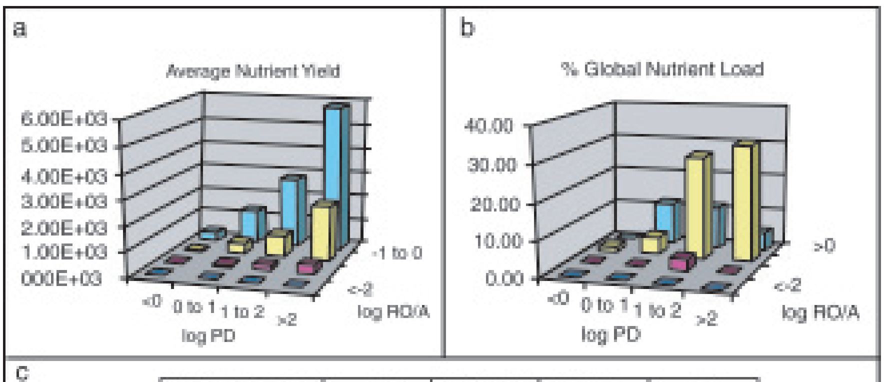
R. W. Buddemeier and S. V. Smith

How well do the LOICZ budget sites represent, or sample, the river basins of the world coastal zone? To answer that question with respect to the size distribution of the basins, we considered 8 016 typology database coastal cells contained within the global 60° S – 66° N latitude band. We compared these with budget site datasets based on both the typology database values and the values derived from the kilometer-scale basin analysis. The exclusion of the high latitude cells was based on the fact that very few budgets are within this latitudinal range, and on the considerations given in Text Box 1.7, Chap. 1.

Of the basins for which budget-sites are available, 30% have no corresponding half-degree sub-basin area in the typology database; this means that they have land areas too small to have been resolved by the University of New Hampshire flow model that generated the sub-basin areas. For this analysis these basins were assigned the land area of the typology cell in which they occur. This generates a typology basin area dataset with values that overestimate the actual basin areas substantially, but that are of the correct order of magnitude for the log-scale distribution analyses presented below.

Figure TB3.12.1 illustrates the distributions of areas and the critical population density and runoff/area variables across log-scaled size classes for the global database and both the typology and km-scale datasets for the budget site basins. Of the global coastal cells, 85% contain half-degree basins with area < 10 000 km^2. Many of these reflect the assigned cell area (2 000–2 500 km^2) rather than a true basin area; this underestimates the actual number of small basins, since cells may contain more than one basin and discharge point. For the half-degree budget basin dataset the corresponding percentage is ~45, but when the km-scale basin areas are used, this percentage rises to ~55. The current LOICZ collection of budgets therefore over-samples the larger area basins and under-samples the smallest coastal systems. Similar patterns are observed in the cases of population density and runoff/area, but here the general distribution patterns (summarised by the shape of the cumulative percentage plot) are reasonably similar. Most of the classes of budget site values have enough members to support at least rudimentary within-group statistical analysis.

From the standpoint of estimating global loads, the distribution of the budget basins is reasonable, since the higher values of both population density and runoff are likely to dominate the total fluxes. However, for evaluating pristine fluxes, the distributions are poor – the lowest values of population density, which are seriously under-sampled, are most likely to provide access to a near-natural signal. These observations do not determine or address the issues of terrestrial forcing directly. Consideration of basin size will probably be a critical factor in regional flux determinations, since for sub-global determinations the coastal zone dominance by small systems will have to be explicitly considered. Given the resolution limits imposed by the half-degree data system and differences between the typology and km-scale datasets, these distributions help set the stage for defining the types of variables that can be used, and systems and issues that may be successfully addressed, by upscaling on the basis of basin-level characteristics.



logRO/logPD	<0	0 to 1	1 to 2	>2
>0	0.3	11.8	11.1	5.2
-1 to 0	1.4	5.1	28.7	31.8
-2 to -1	0.1	0.3	3.3	0.8
<-2	0	0	0.1	0

Fig. 3.17. Nutrient loading. Global distribution of nutrient yields (**a**, *left*) and loads (**b**, *right*) calculated using 7 016 coastal basin cells between 60° S and 66° N, the typology dataset, and the regression equations derived by Smith et al. (2003). Note that table cells are oriented to correspond to cells in the bar chart if the chart base were raised to the vertical. *Grey background* indicates negligible contribution to the global load, and the *unshaded cells* are those with high potential for identifying natural background (pristine) fluxes. Other *cell colours* are indexed to the colours in the bar charts above the table

Figure 3.18 compares the distributions of land area, approximate catchment number, runoff/area (RO/*A*), and population density in the 4 × 4 matrix, and also plots the distribution of the present inventory of budget sites on the same basis. This provides a basis for evaluating both the utility of the present dataset and the needs for additional data. The first pair of plots contrasts the total land area (including the inland drainage basins that discharge through the coastal cells) associated with the coastal typology cells in each of the 16 classes. One unit accounts for about 25% of the total land area, but when the numbers of systems (coastal typology cells or, very approximately, coastal catchments) is considered, the distribution is much more even. This is a graphic illustration of the fact that most budgeted coastal systems are relatively small in total area. We believe that small ecosystems numerically dominate the world coastline.

The second pair of plots illustrates the distribution of the totals of runoff and population. Runoff follows the pattern of area across the RO/*A* gradient. The population plot points up the human dimension impact – one matrix unit with only about 10% of the land area con-

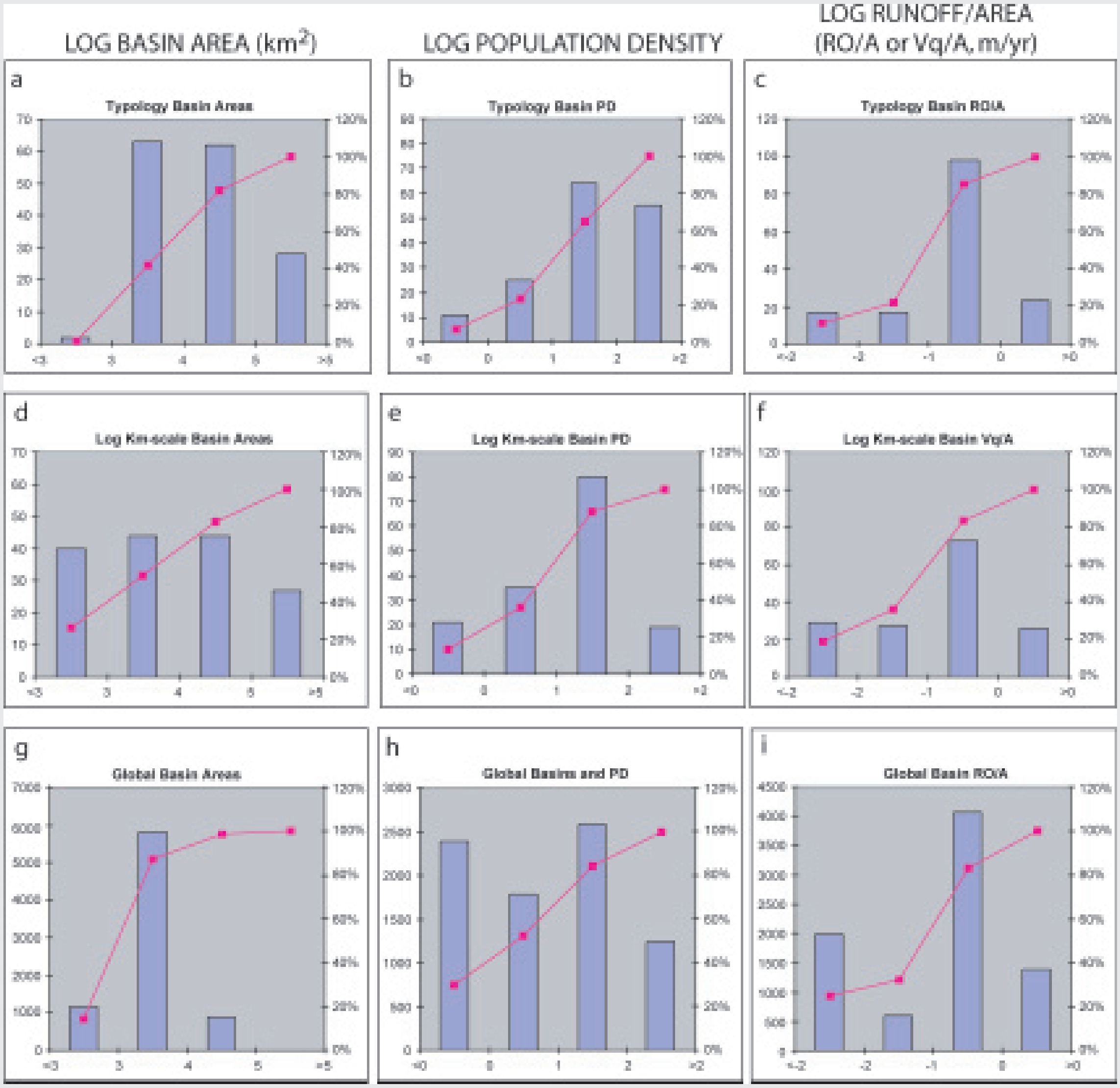


Fig. TB3.12.1. Frequency distributions of $\log_{10}$ values of three drainage basin variables (area, km^2, *left column*; population density, people km^{-2}, *center column*; runoff discharge, $m\,yr^{-1}$, *right column*). *Left axes* (*bars*) are numbers of basins; *right axes* (*line and dots*) are percent of total sample. Panels **g**, **h** and **i** (Global Basin) depict the distribution of the typology database values in 8016 coastal cells between 60°S and 66°N. Panels **a**, **b** and **c** (Typology Basin) display the distributions of the same variables as sampled by 155 LOICZ biogeochemical budget sites, and the panels **d**, **e** and **f** (Km-scale Basins) display the corresponding distributions determined by use of the refined basin areas and the budget surface water discharge data. Note that the relative proportions of the two lowest classes of basin area are distorted in the typology displays by the 0.5° grid system, which forces an area cut-off in the 10^3–10^4 km^2 region. There are almost certainly more basins in the $<10^3$ km^2 class than in the next larger class.

tains over 50% of the population and accounts for 30% of the total load (as shown in Fig. 3.17). The final pair of charts in Fig. 3.18 shows the distributions of the LOICZ budget sites among the matrix units using two different calculation methods. Figure 3.18e uses the same typology values used in the global descriptions to classify the sites, whereas Fig. 3.18f is calculated on the basis of the budget V_Q/A values and areas determined for the km-scale basins.

Overall, comparison of either Figs. 3.18e or 3.18f with Fig. 3.17 suggests reasonably good representation of the two highest load classes, and at least some sampling of most of the other categories. This is admittedly a somewhat circular argument, since the load predictions were

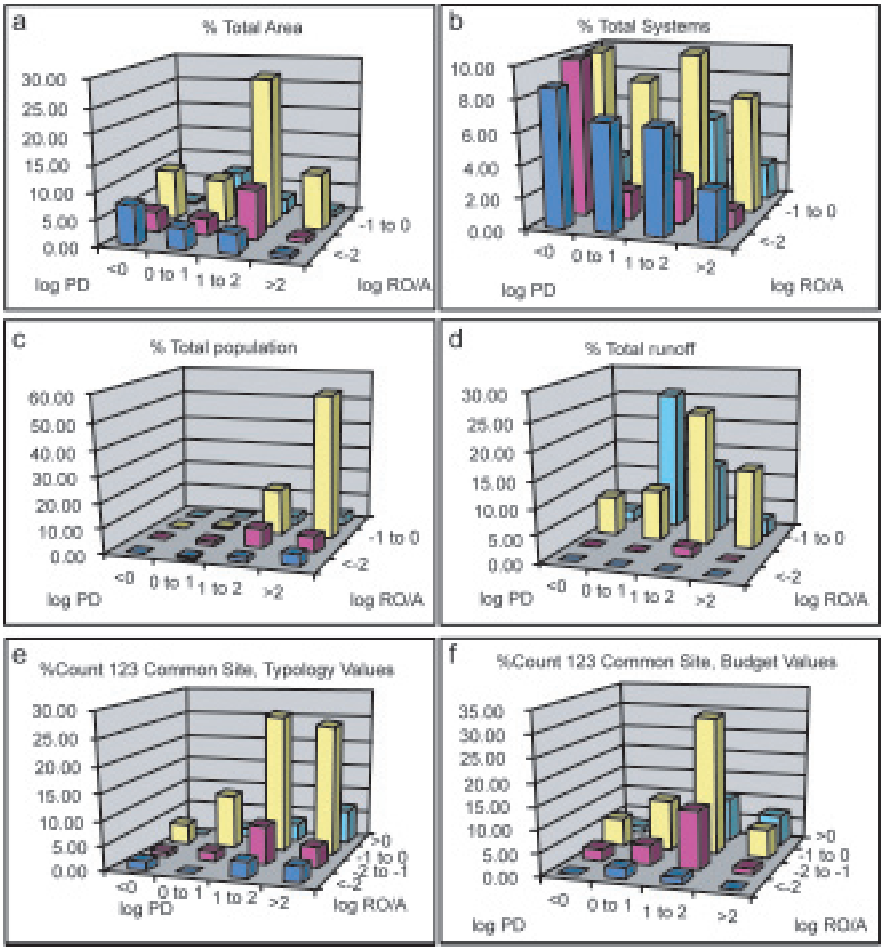


Fig. 3.18.
River basin runoff. Global 16-class distributions based on population density and runoff/area of coastal basin: **a** land area; **b** number of coastal cells/basins; **c** percentage of total population; **d** percentage of total runoff; **e** percentage of budget basins calculated with typology database values; **f** percentage of budget basins calculated with budget dataset variable values

derived from the budget distribution shown, but as the discussion by Smith et al. (2003) points out, the results are consistent with other estimates and models, and we have not found the scatter of the data points in Fig. 3.16 to be strongly related to the load values.

These initial classifications of the coastal zone in terms of delivered DIN and DIP have implications for both the interpretation of the results and the extension of the research. One important point is only indirectly illustrated here (see the comparison of system number and total area above) – the disparity between the dominance of larger systems in determining total load delivered to the ocean, and the dominance of smaller systems in characterising the largest proportion of the coastline. This is illustrated graphically in Chap. 5. The previous sections of this chapter have emphasised the variety of influences on how delivered load is actually processed within the coastal zone and the importance of the small-system, inner-shelf processes in overall coastal biogeochemical fluxes. Because of this, and because coastal processes are important locally apart from their contribution to the global budgets, the load distributions illustrated in Fig. 3.17 are not the only factors determining the significance of coastal systems.

Another issue is the question of baseline fluxes, or the pristine loads without human effects. Although areas with high and growing loads might reasonably have some priority for further study, predicting and mitigating changes due to increasing population and development requires some understanding of pre-impact conditions. In order to achieve this, greater attention to low population density analogues of the high-population, high-load regions is required. Text Box 3.13 illustrates some of the differences to be expected between pristine and perturbed sites. It also illustrates the confounding effects of runoff; since humans are terrestrial animals, the absence of terrestrial runoff will tend to shield coastal waters from human impacts. However, arid or strongly ocean-dominated sites are unlikely to produce baseline data from which we can deduce the pristine characteristics of wet but unaltered locations.

Finally, this initial classification approach leads to two conclusions that deserve emphasis:

1. Reconsideration and more detailed analysis of the initial order-of-magnitude classifications is in order. The high load, large area, high population regions deserve a more finely resolved analysis, as do the re-

Text Box 3.13. Perturbed and "pristine" systems

V. Camacho-Ibar and R. W. Buddemeier

Most LOICZ budgets developed within the Latin American region correspond to sites with some degree of anthropogenic impact, and this is particularly the case of systems associated with permanent rivers. This probably reflects both that few coastal ecosystems in this region remain unaffected by human activity, and that the scientific community in the region has focused its studies on local, accessible systems rather than on remote systems difficult to access (both in terms of logistics and the cost of sampling). These inaccessible sites are precisely the systems likely to be least subject to anthropogenic influence, such as some remote coastal lagoons in the arid region of NW Mexico (Gulf of California), which are as yet under negligible human pressure.

For this comparison, we contrast two "perturbed systems," Maricá-Guarapiná (MG), Brazil and Cienega Grande de Santa Marta (CGSM), Colombia, with Bahía San Luis Gonzaga (SLG), Baja California, Mexico which is a system with essentially no human impact.

Maricá-Guarapiná and Cienega Grande de Santa Marta represent qualitatively different types of perturbations. MG is heavily loaded with sewage and has undergone some hydrologic modification, while CGSM suffers primarily from severe alterations of its hydrologic regime by road construction, water diversion and other forms of development that have altered its ecosystem components.

The Maricá-Guarapina (MG) system (Couto et al. 2000, *http://data.ecology.su.se/MNODE/South%20America/MG/mgpi.htm*) comprises three small choked coastal lagoons and a wetland connected by narrow channels, on the east coast of Rio de Janeiro state. Present anthropogenic influence is mainly sewage inputs, but in the 1950s the system suffered several hydrologic impacts including artificial change of the oceanic opening from the middle to the eastern extreme, and since then landfill in the link channels has restricted water circulation.

The Cienaga Grande de Santa Marta (CGSM) system (Rivera-Monroy et al. 2002, h*ttp://data.ecology.su.se/MNODE/South%20America/cienegagrande/cienagagrande.htm*) is a lagoon-delta ecosystem that forms the exterior delta of the Magdalena River, the largest river in Colombia. This system can be classified as a type I setting (river-dominated, arid, with low tidal amplitude) containing fringe, basin and riverine mangroves (Thom 1982). The CGSM has been impacted by the construction of a coastal highway and a road levee along the Magdalena River. The resulting alteration of the natural flow of marine and freshwaters in combination with freshwater diversion has caused hypersalinisation of mangrove soils leading to die-off of almost 27 000 ha of mangrove forest in a 36-year period (Botero 1990, Cardona and Botero 1998). In 1993, a rehabilitation project was initiated to re-establish the hydrology in some areas of the CGSM and restore both the hydrologic regime and the mangrove forests (Twilley et al. 1999).

The Bahía San Luis Gonzaga (SLG) system (Delgadillo-Hinojosa and Segovia Zavala 1997, *http://data.ecology.su.se/MNODE/mexicanlagoons/slg.htm*) in Baja California is a small, rapidly exchanging bay covering an area of about 3 km^2 in an arid region. In addition to low annual rainfall ($P < 4$ mm; $E \gg P$), population in the drainage basin is very low (~30 people) and scattered, with no significant industry, agriculture or sewage discharge. It is naturally productive (GPP 130–190 mmol C m^{-2} d^{-1}) but is net heterotrophic on an annual basis. Table TB3.13.1 summarizes some of the important characteristics of the three systems.

The characteristics of the three systems are consistent with the general coastal characteristics discussed in Sect. 3.4. and in the sections dealing with marine, terrestrial and human dominance. The arguably pristine system in this case is strongly ocean-dominated, having neither significant terrestrial nor human inputs, and is net heterotrophic. The more perturbed systems have shifted toward autotrophy, apparently as a result of reducing ocean exchange via physical alteration of channels and (in the case of MG) greatly increasing nutrient loads.

These observations further reflect the messages of Figs. 3.18 and 3.21 – there are many candidate pristine sites on the numerous arid coastlines of the world, but these generally are dominated by ocean forcing, and will only weakly represent the salient differences between inner coast and shelf or ocean metabolisms. More important for assessment purposes is the identification of relatively unperturbed systems with a substantial amount of terrestrial – but not human – influence; these types of system represent coastal input to the global cycles characteristic of pre-development conditions, and in which the human-driven changes have been and will continue to be the greatest.

Table TB3.13.1 Comparison of perturbed and unperturbed Latin American coastal systems. Systems included: Marica Guarapini, Brazil (MG), Cienaga Grande de Santa Maria, Colombia (CGSM), Bahia San Luis Gonzaga, Baja California, Mexico (SLG)

	Perturbed		Unperturbed
System	**MG**	**CGSM**	**SLG**
Stresses	Sewage loading, hydrologic modification	Hydrologic modification	none
Responses	Eutrophication	Ecosystem loss (mangrove die-off)	–
Vq (10^6 m^3 yr^{-1})	~95	100	0
Forcing	Runoff and nutrient load	Runoff/exchange	Exchange/upwelling
ΔDIP (1 000 mol yr^{-1})	–610	Slightly negative	Intra/interannually variable
ΔDIN (1 000 mol yr^{-1})	–6	Slightly negative	Intra/interannually variable
[*nfix* – *denit*] (mmol N m^{-2} d^{-1})	0.28	0.4	Seasonally +/–
[*p* – *r*] (mmol C m^{-2} d^{-1})	1.8	2	Seasonally +/–
NEM	Autotrophic	Autotrophic	heterotrophic

gions in which runoff is the major contributor to load. All of the significant sub-categories will need to be examined in terms of climatic and socio-economic factors for the next stages of classification and analysis. Some of the initial considerations are illustrated in the discussion of future loads in Sect. 3.3.6, but further data will be required for these efforts. However, the initial LOICZ studies have developed the targeting mechanisms and rationales to make further work more efficient and informative.

2. The disparities between the budget variable values and the comparable typology datasets (illustrated in Figs. 3.18e and 3.18f) need to be resolved. Ultimately, upscaling must be based on regionally or globally available datasets. However, to date, the successful development of relationships (Fig. 3.16) has been based on the biogeochemical budget variables. The following section presents a more detailed comparison of the two categories of variables for the budget sites.

3.3.4.2 *Comparison of Budget Variables*

An obvious potential problem in scaling is the breakdown of quantitative correspondence between typology variables and budget-system variables for the large number of budget systems (sites and associated catchment basins) that are poorly represented by half-degree cells. Basin area provides the most straightforward demonstration of this problem, but any extensive variable (i.e., one whose value is proportional to the size of the system) will present similar problems. The basin size at which the half-degree typology basin descriptors may become a relatively poor predictor of the GIS-refined km-scale basins is shown in Fig. 3.19.

The results in Fig. 3.19 indicate that the areal correspondence breaks down in the basin area range of 1 000 to 10 000 km^2 (log = 3–4), values approximately equivalent to the area of a few low-latitude typology grid cells. This is neither subjectively unreasonable, nor particularly unexpected for a gridded typology system in which the smallest defined unit is 2 500 km^2. A value of about 3.3 on the $\log_{10}$ km-scale basin area axis (~2 000 km^2)

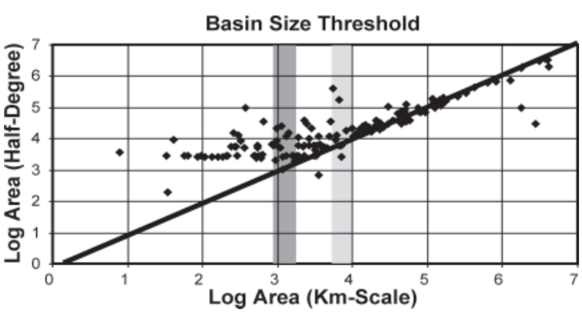


Fig. 3.19. River basin runoff. Scaling relationships of the two datasets. The log plot of the half-degree basin area against the km-scale basin area was obtained by detailed GIS analysis. The solid line is the 1 : 1 correspondence line. The two shaded lines show the region just below 10^4 km^2 where the relatively tight relationship starts to break down, and the region below about $10^{3.3}$ km^2 (approximately the area of a single mid- and low-latitude half-degree or typology cell) where any correspondence is lost. The dataset consists of 155 reasonably localised basins with data for both typology and km-scale basin areas

corresponds to the area of a single typology cell. Within the typology system, the cell area is used for budget basins when no half-degree basin is identified in the database. At this value, the correspondence between half-degree and km-scale basins breaks down almost completely.

However, area-normalised variables (e.g., runoff normalised to catchment area or population density) can serve as a basis for process analysis and prediction (e.g., Fig. 3.16) using some of the critical forcing variables, and they also provide a basis for upscaling that avoids the problems of extensive variables. If the small coastal basins (areas < 10 000 km^2) are generally subject to reasonably consistent *local* hydrologic forcing (i.e., on the scale of a few grid cells), area normalisation of variables that do not have steep gradients or discontinuities on that same scale should permit upscaling with little distortion of results.

For coastal cells in the typology database that contain the discharge point of a half-degree basin < 10 000 km^2 and have both basin and cell runoff values, there is no significant difference between the area-normalised runoff values for half-degree basin and the discharge-point cell. This confirms that the modelled runoff variable in the database exhibits only minor spatial variation at the scale of a few grid cells. Predictably, the km-scale basin runoff determined from the same cell-based typology runoff data also does not differ significantly from cell and half-degree basin values. The more critical question is how these globally available variables relate to the budget system variables and especially to V_Q, the river discharge.

The results of using normalised variables to compare the km-scale budget basins and the corresponding half-degree typology basins are presented in Figs. 3.20a–c for three different types of variable comparisons. Figure 3.20a compares the two normalised basin runoff estimates using different, but arguably comparable, runoff parameters – typology runoff for the half-degree basins, and V_Q for the km-scale budget basins. Figure 3.20b illustrates the effects of area-normalisation only, showing the comparison between the half-degree normalised typology runoff and the same runoff data used to calculate the value for the corresponding km-scale basin area. Figure 3.20c shows the km-scale and half-degree basin comparisons of population density based on sampling the same higher-resolution original dataset (the native LandScan population coverage used to populate the database) using both the half-degree and the km-scale basin areas.

Runoff comparisons between the two datasets (RO and V_Q) for small and large basins show large systematic differences (Fig. 3.20a), with the smaller basins data subset less well correlated than the larger basins. The slope of the regression line is such that the half-degree basin values over-predict the km-scale values for the lowest runoff basins, under-predict the highest values of V_Q, and show a noisy but reasonable relationship in the runoff range of about 0.1 to 1 m yr^{-1}. Under these circumstances, effective upscaling will probably require either a focus on the basin types that are most reliably predicted, or an improved understanding of nature and types of basins showing systematically different responses in the two variables and how these differences might be reduced or calibrated.

The data of Fig. 3.20b suggest that the problems in comparing V_Q and RO values lie primarily with the differences between the runoff variables rather than with the areal scaling. When the same runoff dataset is used for normalisation by both sets of basin areas, the resulting comparison is close to 1 : 1 overall, with good correlation coefficients. The small basins deviate from this pattern because of the influence of four very low runoff/area values that force a slope < 1; without these, the correspondence is substantially better.

In the case of the larger (> 10^4 km^2) basins, for population density (Fig. 3.20c) the correlation is very high and the relationship very close to 1 : 1. For the small basins, the correlation is not quite as good, but the slope is not substantially different. However, the half-degree basin values consistently under-predict population densities in the corresponding km-scale basins. This is understandable, since population density can vary significantly over scales of tens of kilometers, and there is probably a general tendency for populations to be higher in close proximity to streams and rivers.

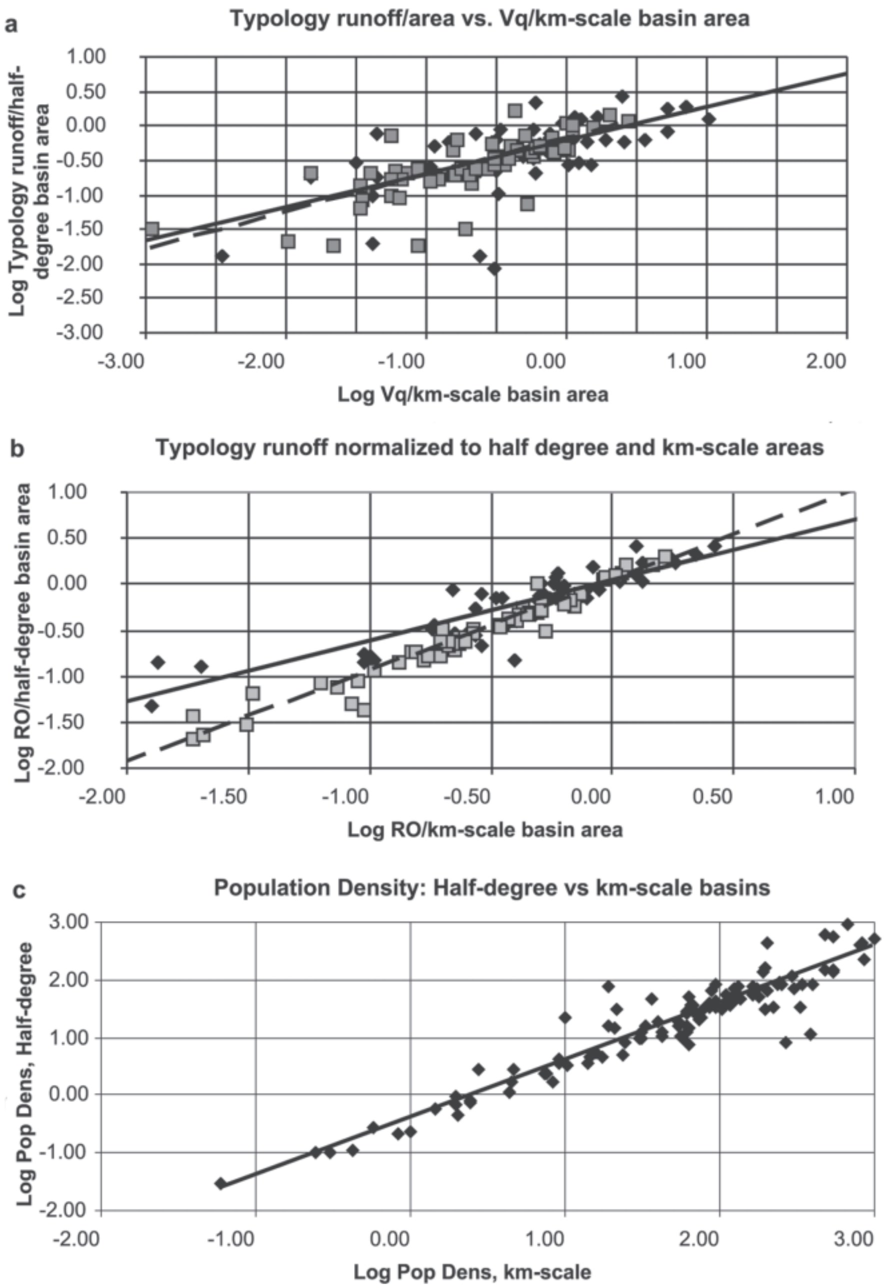


Fig. 3.20. River basin runoff. Normalised variables comparisons. **a** Comparison of area-normalised typology (half-degree) runoff and V_Q (km-scale) values. Regression for the total dataset is $y = 0.51x - 0.24$, $R^2 = 0.48$, $n = 115$. For the small basins (< 10^4 km^2; *diamonds, solid line*) the regression is $y = 0.48x - 0.25$, $R^2 = 0.40$, $n = 57$, and for the large basins (> 10^4 km^2; *squares, dashed line*) $y = 0.54x - 0.21$, $R^2 = 0.56$, $n = 58$. Basins with zero values for either runoff variable have been omitted, as have a few extreme outliers. **b** Comparison of typology (half-degree) runoff values normalised to the half-degree and the km-scale basin areas. Regression for the total dataset is $y = 0.98x + 0.07$, $R^2 = 0.90$, $n = 115$. For the small basins (< 10^4 km^2; *diamonds, solid line*) the regression is $y = 0.66x + 0.02$, $R^2 = 0.80$, $n = 57$, and for the large basins (> 10^4 km^2; *squares, dashed line*) $y = 0.99x + 0.03$, $R^2 = 0.95$, $n = 58$. Discarding the values below −1.5 brings the small basin regression line very close to 1 : 1, but with a somewhat smaller correlation coefficient. **c** Comparison of population density (log persons km^{-2}) of basins determined from the edited half-degree and km-scale data sets ($y = 0.99x - 0.40$, $R^2 = 0.89$, $n = 108$). The correlation is good, and no significant variations are observed if the dataset is divided into small basins (area < 10^4 km^2; $y = 1.01x - 0.38$, $R^2 = 0.84$) and large basins (area > 10^4 km^2; $y = 0.98x - 0.42$, $R^2 = 0.98$)

3.3.5 Typology for Flux Extrapolation

3.3.5.1 *Coastal Classifications as Flux Predictors*

Extrapolation of flux estimates from known sites or typical coastlines to unmeasured but similar regions is a fundamental component of the upscaling approach (see Text Box 1.6, Chap. 1). The ability to associate appropriate coastal classes with flux values is an essential step, the initial components of which are presented in Sect. 3.3.3. The project has had significant success in some areas, while the problems encountered in others have helped to identify the additional data and tools needed to fully implement the upscaling effort.

The most clear-cut success has come in the classification of river basins in terms of their probable DIP and DIN load based on globally available data (Smith et al. 2003). The correlation relationships are best if specific V_Q values for each budget site are used for runoff; global climatology runoff values can be substituted, but further work is needed to improve the correspondence and substitutability (see Fig. 3.20a). This relationship, derived over a wide range of basin sizes and types, can almost certainly be extended to basins in general and to those coastal regions not identified as part of specific catchments in global-scale elevation models.

The prediction of DIP and DIN loads can be further improved; preliminary studies have already suggested that for some regions, additional economic and land-use variables can significantly improve on the predictions developed with population density as the single proxy for human influence (Sandhei 2003). Further, the success in developing this classification system provides some assurance that effective classification schemes related to the critical non-conservative fluxes in the budget systems can be developed.

In the case of the non-conservative fluxes, it was pointed out in Sect. 3.2.3.2 that water residence time and some of the related variables are important in explaining the sign and magnitude of ΔDIP and ΔDIN, and in Sect. 3.2.3.3.2 that "… *smaller coastal systems (as opposed to large, shelf seas) are the dominant engines of coastal zone metabolism* …" Although the typology database has values for relevant variables, and the general conceptual basis for understanding controls on water residence time is well-established (see Sect. 3.3.2), efforts to develop a satisfactory regression or cluster-based classification system for these variables have so far been unsuccessful. We believe that this is a special case on the marine side of the need for finer resolution datasets noted in the catchment basin flux studies. Many of the budget systems are small compared with a half-degree cell, and these small systems may be disproportionately important in terms of their effects on overall non-conservative fluxes. Inability to resolve the oceanic forcing variables at a scale that can relate to small system function is probably one of the major challenges to be overcome in developing a full typologic approach to global flux estimates in the coastal zone.

We foresee two concurrent approaches to this problem. One is to develop better indices of coastal complexity and exchange from the existing (and steadily improving) global-scale datasets. As noted above, the bathymetry data, the coastline itself and some of the satellite-derived datasets, such as productivity and water clarity, can show features substantially smaller than a half-degree. In addition, vector representations of coastline and (for example) wind orientation could be used to substantially refine estimates of exposure and potential exchange. In addition to such complexity indices, improved estimates of cross-shelf transport and open-boundary exchange could be developed by using combinations of chemical and physical data to define gradients rather than localised values. Even if the final products are formulated at the half-degree scale, appropriate combinations of these variables as proxies for sub-gridscale features could substantially improve the dataset for application to dynamic variable prediction.

The other approach that will be needed is analogous to the development of the km-scale basin analyses. The marine equivalent of the watershed will need to be defined at a resolution that will permit more accurate association with the typology variables than is possible with the present set of observations. As with the basins assessments, we expect that Geographic Information System analysis and mapping of the systems and variable distributions will be a major step forward in linking system-level observations to generalised coastal zone characteristics. As information technology develops, it will be possible to incorporate higher resolution datasets within the coarser grid systems. This, in combination with GIS-defined budget systems, will greatly improve capabilities for examination of cross-scale relationships among the variables available for system and process characterisation and for upscaling.

3.3.6 Prospects for Future Fluxes and Their Assessment

3.3.6.1 *Climatic Controls and Geomorphic Evolution*

Climatic controls on fluxes may be assessed for both oceanic and terrestrial changes, for changes in the input fluxes (e.g., marine and terrestrial DIP and DIN) and for changes in the conditions of the coastal biogeochemical processes that influence the nature and rates of non-conservative fluxes within the system. On the marine side, changes in upwelling and wave or current strength may occur, but predictive abilities are limited and the rates of change seem relatively slow compared with the more dynamic terrestrial inputs. Changes in the physical structure of the coastal interface (e.g., erosion, sedimentation, subsidence, inundation) may affect the nature of the coastal system in significant ways. The most confidently predictable effect is a probable sea-level rise of 0.3–0.5 m by 2050 (Houghton et al. 2001). Coastal vulnerability and impact assessments have been carried out for human infrastructure and ecosystem function (e.g., Scavia et al. 2002) but the effects of sea-level rise on the overall biogeochemical functioning of the coastal zone have not yet been evaluated.

Changes in terrestrial input can be viewed in terms of the DIP and DIN load dependence on population density and runoff, discussed above. Runoff may be influenced by climate change through both precipitation and land cover, but both land cover and the hydrologic cycle (especially runoff) are subject to greater modification by humans in areas of significant population. Figure 3.17a shows that the DIP and DIN loads are relatively less sensitive to runoff than to population; the left hand row of bars (PD, population density, < 0) rises much more slowly with increasing runoff than the two higher runoff categories (toward the rear of the plot) rise with increasing population effects. Overall, the most probable short-term drivers of changes in coastal zone fluxes are human alterations of the environment (see also Text Box 3.11).

3.3.6.2 *Human-induced Change: Where and How Fast*

Humans may change coastal zone fluxes in many ways, including land-use changes, interception of runoff for consumption, waste disposal or contamination and direct actions to modify coastlines and nearshore morphology. At local and regional scales these effects are likely to outweigh the influence of climate change, with global-scale effects that are readily predictable. At present, our best predictive tool relies on the general correlations between yields, population density, runoff and the resulting loads.

Figure 3.21 brings together the geographic distributions of the $\log_{10}$ population density and runoff classifications discussed above with a clustered map of $\log_{10}$ nutrient yield for the small coastal basins (represented by the combined coastal and terrestrial cells of the typology database). These comparisons provide several insights into the process of comparison and load estimation, and into the initial results for the critical class of drainage systems that dominate most of the world coastline.

Figures 3.21a and 3.21b illustrate the observation made previously that a second-order analysis is needed to refine the classification system used for initial explorations. In the case of population density, the two middle classes seem in need of boundary adjustment; there are few areas in the 1–10 people km^{-2} category, while the 10–100 category is large, uninformative and groups some regions together that seem intuitively disparate (e.g., NW Australia and W Alaska with parts of the Mediterranean and the Caribbean regions). The two middle classes are also problematic in the runoff classification. The 0.01–0.1 m yr^{-1} class represents little area, while the 0.1–1 m yr^{-1} class is excessively coarse, especially in view of the fact that it represents many of the highly developed coastlines as well as areas that would be expected to be more nearly pristine.

Figure 3.21c depicts the relative distribution of nutrient yields, derived from Figs. 3.21a and b and the regressions in Fig. 3.16. Yields can be expected to change with growing population even if we assume that the natural potential runoff will be more stable. Changes in load will reflect the area-weighted changes in yield. If most of the high-population coastal areas (Fig. 3.21a) are approaching saturation level in terms of human inputs and system responses, then the coastal systems may be relatively stable, if highly altered. On the other hand, most of these areas are experiencing continued growth and development. This is likely to be associated with still greater nutrient fluxes in the less developed countries and in areas of high to moderate runoff.

By linking expected changes in coastal zone fluxes to population projections we can identify some general geographic patterns of change now and, as we further assess the controls over both inputs and system response, we will be able to refine those expectations. We may also use the same approach to identifying the possible baseline or pristine areas, as discussed in Sect. 3.3.4.1. Figure 3.21 indicates that there are ample low-population, low-runoff areas to consider, but the situation is less clear for the more important moderate- to high-runoff, low-population density sites. There are relatively few low- and mid-latitude unaltered sites with runoff in the higher categories, and they tend to be close to areas that have a higher yield. This poses significant challenges to reconstructing baselines and natural mechanisms in these areas and reinforces the need for the refined analysis discussed above.

3.4 Conclusions

The LOICZ biogeochemical budgeting effort produced accomplishments in several areas:

- Improved understanding of the controls on biogeochemical fluxes and reactions in coastal systems, including an updated estimate of dissolved inorganic nutrient (N, P) loading to the ocean and its estimated geographic distributions and responses to human population and runoff.

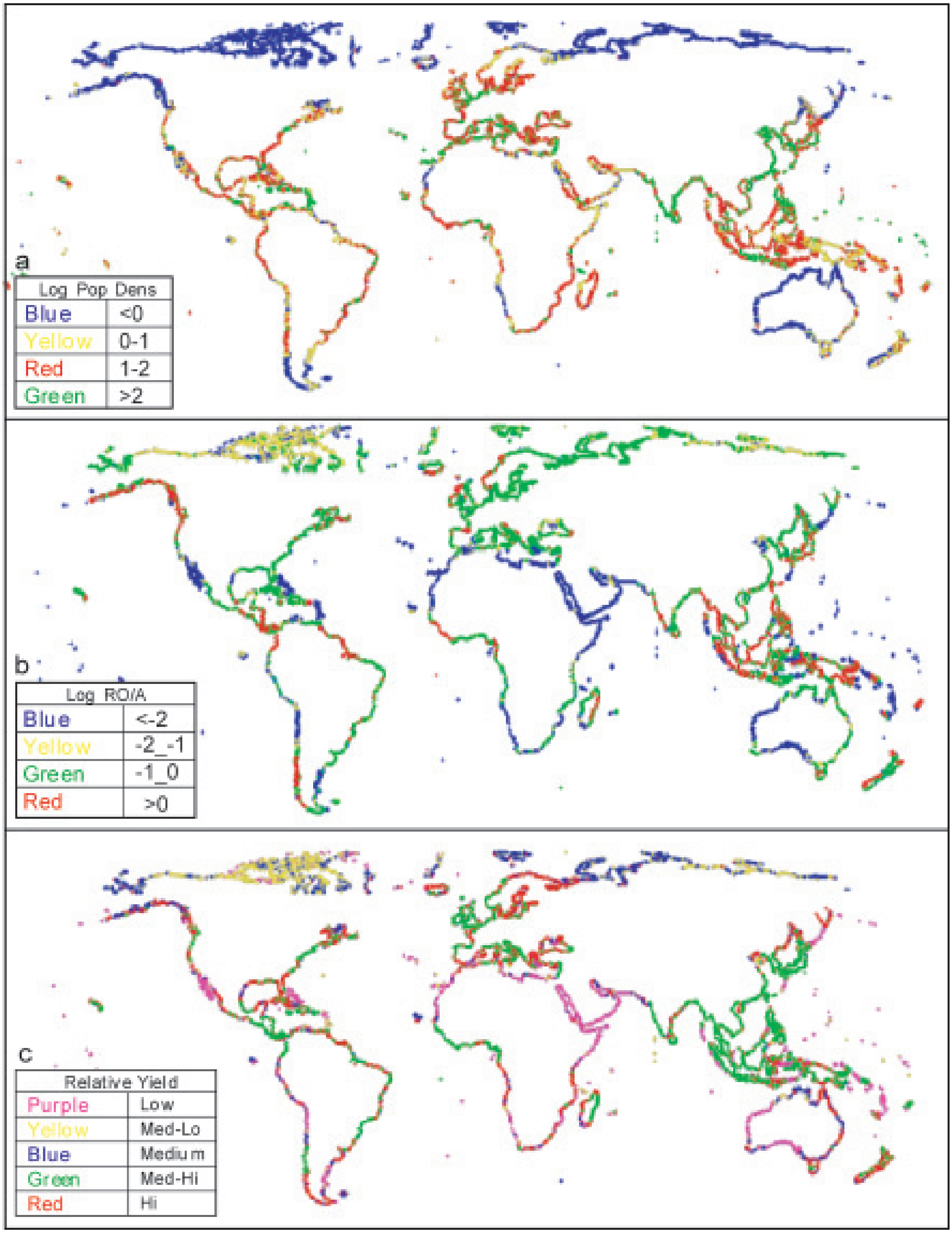


Fig. 3.21. Nutrient flux. Comparisons of present population density, runoff/area, and nutrient yields in small coastal basins (data used by Smith et al. 2003): **a** Four-class distribution of $\log_{10}$ population density (compare with PD axes in Figs. 3.17 and 3.18). **b** Four-class distribution of $\log_{10}$ runoff/area (compare with RO/A axes in Figs. 3.17 and 3.18). **c** Five clusters of DIP yield generated using the LOICZView tool. Cluster mean values are, from low to high: 0.1, 2.2, 28.2, 407 and 2138 moles $km^{-2}\,yr^{-1}$

- Conceptual understanding of the issues and potential approaches involved in cross-scale analyses and the effective upscaling of local observations, including identification of priority targets in terms of data needs, methods development, and geographic regions of particular interest.
- Infrastructure development, in the form of databases, tools and networks of scientists.

3.4.1 Biogeochemical Systems and Nutrient Loads

3.4.1.1 *Definition and Characterisation Issues*

Particulate materials tend to sediment near the sites of their delivery to the ocean, while reactive dissolved inorganic materials tend to react there. The strong negative log-log relationships seen between the absolute rates of the non-conservative fluxes (Figs. 3.13 and 3.14) and either system size or system exchange time argue that the most rapid rates of net material processing occur inshore, in small coastal systems linked to small coastal drainage basins. Since these small systems are typical of most of the length of the global coastline, integration of either the non-conservative fluxes of ΔDIP and ΔDIN or the derived fluxes of $[p-r]$ and [nfix – denit] suggests that these rapid, inshore, small-system fluxes dominate global shelf fluxes, i.e., system size matters.

The flux dominance by small systems suggests that the importance of terrestrial input to the shelf is largely felt at a local (inner-shelf) scale, especially in bays and estuaries (see Text Box 3.14). These smaller-scale features rapidly process and respond to both natural and human inputs and are thus particularly sensitive to human modification.

At global to regional scales, changed inorganic nutrient loading to the coastal zone may have little impact on the shelves as a whole. If we look at the loading for the ocean as a whole, we observe that cycling between the deep ocean and surface ocean (for both N and P) and between the surface ocean and the atmosphere (for N) are far larger than the nutrient load from land (Michaels et al. 1996). Assuming that some small but significant fraction of this internal cycling exchanges with the open shelves (Thomas et al. 2004), changes in the terrestrial load are probably not generally significant at the scale of the shelves.

This contrast – between acute local effects on systems important to and exploited by humans and greatly attenuated far-field signals at a global scale – highlights the rationale for the basic LOICZ approach and explains many of the remaining challenges. Top-down, global-scale models can neither resolve nor represent the intensity and diversity of coastal zone functions.

3.4.1.2 *Updates of Nutrient Loads*

LOICZ results have led to an update of the estimates of dissolved inorganic nutrient (N, P) loading to the ocean, through development of a regression equation describing the logarithm of nutrient yield as a function of the logarithms of population density and runoff per unit area. These results have led to estimates of geographic distributions of that loading and load response to human population and runoff. The new estimates are substantially higher than those of Meybeck (1982) and somewhat elevated above the estimates shown in Figs. 1.1b and c. We have also used comparison with both Meybeck's pre-pollution estimates and our own low-load estimates to approximate pre-human inorganic nutrient loads to the ocean (Table 3.2).

Direct updates of either dissolved organic nutrient or particulate nutrient loads have not been developed, but the following general evaluations apply. Globally, inorganic nutrient loads seem likely to have changed the most; this is consistent with Meybeck. One might expect that greatly elevated erosion would have increased particulate nutrient delivery to the ocean. Based on analysis of the US (Smith et al. 2001), this seems not to be the case for particulate material in general in continental settings. Apparently most particulate erosion occurring at some distance from the coast yields products that have thus far remained mostly on land, especially where retained by dams and reservoirs. This is likely to be true of most large land masses with a relatively low perimeter/area ratio. However, in areas where most of the runoff and erosion originates from relatively small coastal basins, and especially in areas undergoing development, there is evidence for increasing net delivery to the ocean as a result of increased erosion.

These conclusions about the importance of system size and the nature of the nutrient yield relationships are important. However, both the results achieved and the lack of additional specific conclusions point to needs for further data and methods development. One need directly related to system and load characterisations concerns the use of ΔDIP as a proxy for organic carbon metabolism. This clearly works in some – but not all – systems. In particular, other reaction pathways, notably sorption and desorption of DIP with respect to sediment particles, interfere with the proxy. This is a particular problem for systems with high mineral turbidity. Yet the data simply do not yet exist to develop a large number of budgets or inventories based on reliable carbon data (see Text Box 3.5). Either an alternative approach must be found or methods must be developed to refine the DIP budgets.

The other identifiable needs are most clearly related to questions of scaling and relationships across temporal and spatial scales, natural domains and scientific disciplines.

Text Box 3.14. Regional variation of nutrient dynamics in the Baltic Sea

Dennis Swaney

The Baltic Sea is the most studied brackish water body in the world (see Wulff et al. 2001). It comprises three major sub-basins: (*i*) the Baltic Proper, which includes the Gulf of Finland and all of the region south of the Bothnian Sea to the Danish Straits, (*ii*) the Bothnian Sea, which separates much of Finland from Sweden, and (*iii*) the Bothnian Bay, which extends northward above the Bothnian Sea (Fig. TB3.14.1). Baltic Sea nutrient loading dynamics exhibit considerable variability within these regions. The northern drainage basin of the Baltic Sea extends well above the Arctic Circle, and the waters flowing from major drainage systems, such as the Luleälv (LE) in northern Sweden, are relatively nutrient-poor. Most of the loads to the Baltic Sea come from the south, into the Baltic Proper (as defined here), draining Eastern Europe and Russia (Fig. TB3.14.1).

Five major coastal ecosystems within the Baltic basin collectively dominate the freshwater and nutrient loads to the Baltic Sea. The Szczecin Lagoon (SL), the Gulf of Gdansk (GoG), the Curonian Lagoon (CL), the Gulf of Riga (GoR) and the Neva Estuary (NE) span the south-eastern coast of the Baltic Sea, and their rivers drain lands of Russia and "countries-in-transition" with rapidly changing environmental impacts. The drainage basins of the systems are large, ranging from 10^5 to 2.9×10^5 km^2, their spatial dimensions vary significantly and their average water residence times vary from two months (SL) to longer than two years (GoR). These systems have been subject to large anthropogenic nutrient loads, averaging 45 000 t yr^{-1} N (CL) to 140 000 t yr^{-1} N (GoG), and 2 000 t yr^{-1} P (GoR) to 7 000 t yr^{-1} P (GoG) from riverine sources alone. Despite these large loads, which account for about two-thirds of the riverine nutrient input to the Baltic, analysis of steady-state nutrient budgets suggests that significant differences exist, in terms of the proportion of the system loads which flow to the sea.

Wulff et al. (2001) and *http://data.ecology.su.se/mnode/Europe/BalticRegion/Baltic2001/baltic_seabud.htm* consider the Baltic Proper as a stratified system, as it has a marked permanent halocline, whereas the smaller, less saline basins of the Bothnian Sea and Bothnian Bay are well-mixed (Fig. TB3.14.2). Major DIP and DIN fluxes through these basins are noted in Figs. TB3.14.3 and TB3.14.4. Of particular interest is the near balance of autotrophy (upper layer) and heterotrophy (lower layer) in the Baltic Proper, and the excess of apparent denitrification over nitrogen fixation overall, despite the excess of nitrogen fixation over denitrification in the surface layer.

Also of interest is the strong latitudinal gradient in loading within the region (Table TB3.14.1). The northern regions, (e.g., the Luleälv basin) which drain into the Bothnian systems, have relatively low population densities and attendant impacts and are subject to the extremes of the Arctic environment. Nutrient loads are low, and the Luleälv estuary is heterotrophic and net nitrogen-fixing (Table TB3.14.2). This scarcity of nutrients is reflected in the metabolism of the Bothnian Bay, which is autotrophic and shows a net of nitrogen fixation over denitrification.

In the densely populated and agricultural regions of the southern Baltic, which feed the Baltic Proper, nutrient loads are high. Most of these coastal subsystems are autotrophic and denitrification exceeds nitrogen fixation, reflecting the abundance of available nutrients.

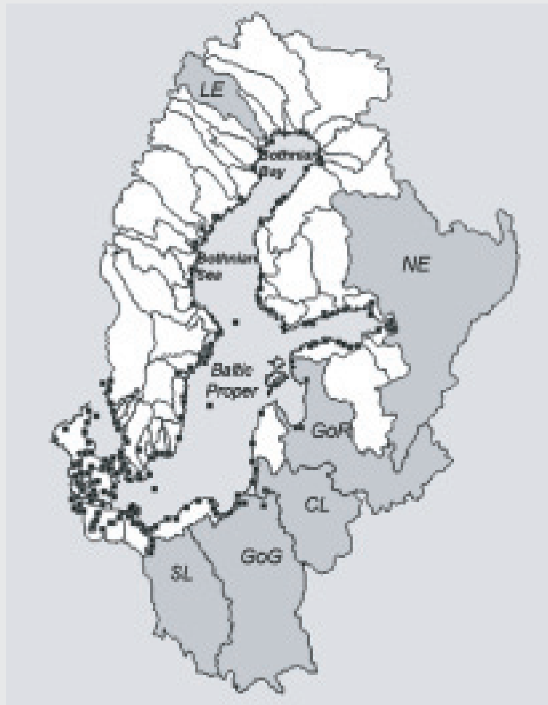


Fig. TB3.14.1. The Baltic Sea and its principal drainage basins. *Dots* indicate major point sources of nutrients

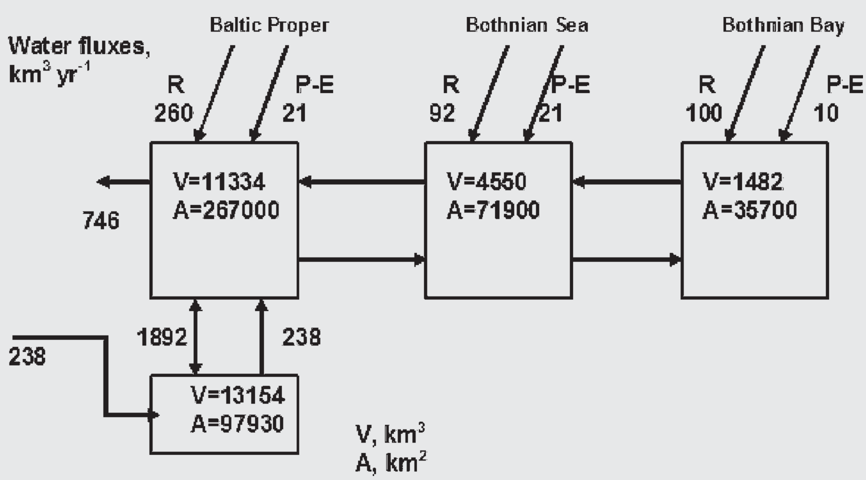


Fig. TB3.14.2. Water balance of the Baltic Sea (1975–90). Mean annual flows (km^3 yr^{-1}) and minimum and maximum flows for the period are shown as well as area (A, km^2) and volume (V, km^3) of each model box

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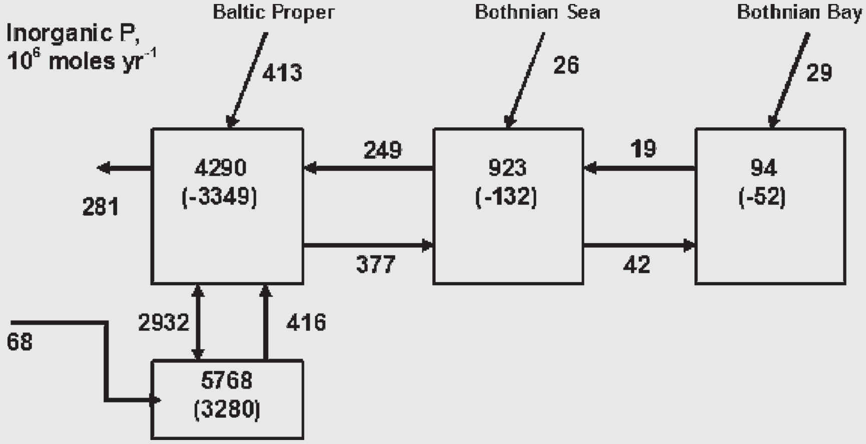

Fig. TB3.14.3. Inorganic phosphorus balance of the Baltic Sea (1975–90). Values inside boxes are the magnitudes of the P pool and the magnitudes of the estimated non-conservative flux of P (in parentheses)

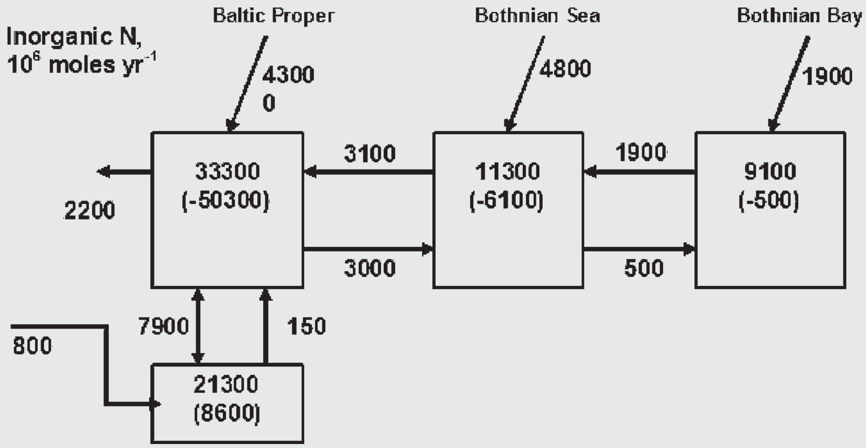

Fig. TB3.14.4. Inorganic nitrogen balance of the Baltic Sea (1975–90). Values inside boxes are the magnitudes of the N pool and the magnitudes of the estimated non-conservative flux of N (in parentheses)

Table TB3.14.1. Features and fluxes of some significant Baltic coastal systems

System	Surface area (km^2)	Drainage basin area (10^3 km^2)	Basin population density (ind. km^{-2})	Residence time (days)	*Vq* (km^3 yr^{-1})	DIP load (10^6 mole yr^{-1})	DIN load (10^6 mole yr^{-1})
Luleälven Estuary (LE)	50	–	–	12	9	1.2	65
Neva Estuary (NE)	1 430	282	26	82	30	119	4 300
Gulf of Riga (GoR)	16 330	134	34	36	825	70	5 800
Curonian Lagoon (CL)	1 580	100	50	23	75	25	735
Gulf of Gdansk (GoG)	3 250	194	123	38	15	183	6 300
Sczeczin Lagoon (SL)	690	119	129	22	45	63	3 300

3.4.2 Scale, Resolution and Generalisation

3.4.2.1 *Upscaling and Generalisation*

Successful extrapolation from the budget data to the global coastal zone requires three classes of globally available data in addition to the system-specific budget data and the techniques for linking them. Global datasets must permit characterisation of that portion of the land-atmosphere system delivering materials to a particular location (system or budget site) in the coastal zone, oceanic data for the specific system and oceanic data for the waters adjacent to and interacting with the system.

We have addressed the methodological issue of extrapolation from a relatively small number of budget

Text Box 3.14. *Continued*

Table TB3.14.2. Net ecosystem metabolism (NEM) of major Baltic Sea sub-basins and sub-systems

Basin/subsystem	ΔDIP (10^6 mole yr^{-1})	NEM (mmol C m^{-2} day^{-1})	ΔDIN (10^6 mole yr^{-1})	(nfix – denit) (mmol m^{-2} day^{-1})
Lulealven Estuary (LE)	1.6	–10	50	1.3
Neva Estuary (NE)	–51	10	–2400	–3
Gulf of Riga (GoR)	–36	0.6	–4750	–0.7
Curonian Lagoon (CL)	7	–1.4	–99	–0.6
Gulf of Gdansk (GoG)	–211	19	–5800	–2
Sczeczin Lagoon (SL)	–4	1.8	–2270	–9
Baltic proper (combined layers)	69	–0.007	–41700	–0.42
Bothnian Sea	–132	+0.53	–6100	–0.15
Bothnian Bay	–52	+0.42	–500	0.025
Total Baltic Sea	–115	+0.14	–48300	–0.32

sites to the global coastal zone primarily though use of powerful geo-statistical clustering tools initially developed for LOICZ applications (i.e., LOICZView [*http://www.palantir.swarthmore.edu/loicz*] and its successor application, DISCO [*http://narya.engin.swarthmore.edu/disco*]). The typology database developed for the project (Environmental Database link at *http://www.kgs.ku.edu/Hexacoral*) consists of data assembled at a grid scale of 0.5 degrees (areas > 2000 km^2) for much of the globe; see Text Box 1.7, Chap. 1). This grid scale is dictated largely by the available global spatial datasets, most of which are at scales of 1 degree or coarser, and must be interpolated or sampled to smaller scales. At least for smoothly varying variables, this poses no particular analytical challenge, but variables with small-scale variation and/or discontinuities at the coastline are problematic.

On land, because most features are both spatially fixed and readily visible, global resolution to 1 km is available for many variables, making it possible to resample those data at the scale of the budget system watersheds, or catchment basins, a more natural or functional scale than the half-degree (0.5') grid. This higher-resolution subset of data on the catchment basins related to the budget sites has been used to develop process-based regression models of material fluxes, which were then extrapolated to the generally coarser and more artificial catchments defined by the half-degree grid spacing.

For the budgeted systems, the primary physical forcing data and chemical results have been obtained at scales appropriate to the site, along with system dimensions. However, the lack of an objective, spatially explicit "functional unit" for budget systems equivalent to catchment basins, together with the lack of spatial detail in available oceanic data, have so far precluded an equivalent analysis for either the budget systems themselves or the ocean region exchanging with any particular system.

In the ocean, the more rapid dynamics of water movement, the limited ability to describe visible sub-surface features and the importance of largely invisible chemical characteristics of the water place serious limits on the potential for developing high-resolution static representations. It is therefore impossible to use the coarsely defined marine data as a basis from which to classify or extrapolate the characteristics of small coastal features. Some alternative approach must be found.

3.4.2.2 *Heterogeneity and Functional Classification*

It is obvious that with decreasing system size comes increasing inter-system heterogeneity. The ocean is a large system in which most metabolism is accomplished by plankton with relatively rapid biotic turnover rates. Smaller sizes of systems, for example in the coastal zone, are locally dominated by plankton, benthic algae, seagrasses, coral reefs and mangroves. These systems differ greatly from one another; turnover times at the ecosystem level may be much slower than for planktonic systems and the response to perturbations is very different. Generalising globally therefore demands that each major type of system be adequately represented in the sampling and data analysis.

Heterogeneity can be expressed in terms of temporal as well as spatial characteristics, since larger systems tend to have longer water exchange times. Any budget or inventory approach to assessing the function of aquatic ecosystems has two broad classes of material transfer to deal with – physical transfer and biotic cycling. As a generality, the physical transfers have a wide dynamic range at small scales. For example, water flow can vary from near stagnant (< 1 mm sec^{-1}) to several meters per second (a range of orders of magnitude). As scales get larger, the *net* physical transfers are smaller; transfers occurring in opposite directions tend to average each other out. At the small scales, biotic transfers tend to have a much lower dynamic range. Although these processes also tend to balance at larger scales, the ability to see the small net effects of the biotic processes improves at larger scales because the biogeochemical budgets integrate rates over time. Large systems tend to have very long exchange times (Fig. 3.11) so they also have long integration times, which effectively modulate the results of small differences in the short-term rates. The most robust budgets involve relatively large systems with relatively long exchange times (e.g., the Baltic system, Shark Bay (Western Australia), Spencer Gulf (South Australia), the North Sea), but these systems are also characterised by low net biogeochemical rates. Small, active systems with short water exchange times represent an important part of the global coastal zone, but these systems tend not to yield robust estimates of fluxes because their short integration times result in noisy and variable integrated differences. Improved methodologies for obtaining widespread, reliable biogeochemical flux information are needed.

3.4.2.3 *Relevance to the Global Carbon Cycle*

Smith and Hollibaugh (1993) estimated that there is about 7×10^{12} mol yr^{-1} of net carbon oxidation in the coastal zone and 16×10^{12} mol yr^{-1} in the open ocean. The LOICZ analysis does nothing to alter this essential picture. In effect, this picture was based on establishing a globally robust budget for the entire ocean, which does not resolve the details of where the oxidation occurs. The local budgets give more understanding of the details but cannot be reliably added up to a global result. However, two aspects of this analysis of carbon flux are important to understanding coastal zone contributions. First, compared with estimated coastal and open ocean net primary production estimates of 500×10^{12} and $3\,000 \times 10^{12}$ mol yr^{-1}, respectively, the coastal ocean appears more heterotrophic ($p/r = 0.97$) than the open ocean ($p/r = 0.998$). Second, the apparent slight net heterotrophy of the global (coastal + open) ocean ($p/r = 0.994$; $[p - r] = -23 \times 10^{12}$ mol yr^{-1}) is an important part of understanding oceanic function and linkage to the slightly autotrophic land. Functionally, this net heterotrophy is quantitatively insignificant in terms of its influence on the ocean's role as a sink for anthropogenically generated CO_2. The overall oceanic CO_2 uptake is about 10 times greater than the CO_2 release due to net oceanic heterotrophy. On the 150-year timescale over which humans have significantly perturbed the carbon cycle, the global oceanic CO_2 sink is dominated by inorganic processes – changing atmospheric partial pressure and the physical chemistry of seawater. On longer time-scales, the carbon sequestration roles of the ocean biological carbon pump (Karl et al. 2003) and the corresponding continental shelf pump (Chen et al. 2003) are influenced by both open ocean and coastal ocean biogeochemical processes.

3.4.3 Infrastructure and Methodology

LOICZ has made contributions to systematising and integrating coastal zone studies. These are alluded to in some of the conclusions listed above and in the recommendations that follow.

- Establishment, testing and dissemination of a standardised, widely applicable and easily used process for evaluating coastal system biogeochemical fluxes that permits intercomparison of the results of different studies and provides guidelines for measurements and surveys.
- Establishment of an internet-accessible environmental database that supports on-line manipulation and analysis as well as downloading of both budget site and global environmental data, and integrating those capabilities with other projects and consortia to ensure its sustainability and wider application.
- Development of on-line geospatial similarity analysis and visualisation tools (LOICZView, which has evolved to produce DISCO) that can be used with the LOICZ database or with independently supplied datasets.
- Pioneering the now widely-used approach of environmental typological analysis for functional classification and comparison of systems.
- Developing a world-wide network of scientists and environmental managers in both developing and developed countries who have common interests, problems, and the potential to benefit from the shared information and common methodologies of the larger community.

3.5 Recommendations

This section identifies priority areas for further research and assessment based on collective LOICZ experience, both specifically with regard to the biogeochemical budget effort and more generally in terms of its interactions with the other LOICZ activity areas. The first set of recommendations concerns conceptual and methodological developments desirable for extension of the fundamental LOICZ research and assessment activities in the area of coastal zone biogeochemical fluxes. Following this are more specific recommendations concerning LOICZ software tools and support.

3.5.1 Concepts and Methodology

The list below draws not only on the experience of the authors but also on the conceptual issues raised and substantive suggestions made by participants in LOICZ workshops, other collaborators and reviewers. We use three categories as a means of classifying scales of time and feasibility for the recommended activities:

1. Achievable with present data, technology and infrastructure, requiring only adequate funding and staffing.
2. Conceptually achievable with available or readily acquired data and tools, but requiring informational or institutional organisation and assembly and/or some development and testing as well as technical work.
3. "Blue sky" questions – needs that may or may not be feasible to meet and which would require significant new understanding, techniques or databases, but which are important and have the potential to transform our understanding.

Many of the recommended activities have aspects that belong in more than one category and are thus candidates for systematic, progressive exploration.

- *Category 1:*
  - Evaluate which additional (available or potentially available) data would be useful in improved budgets and system characterisations. Items for consideration could include more detailed information about the associated drainage basins, coastline, local coastal oceanography, dominant ecosystem and habitat type associated with each budgeted site. Test possible effects on sample systems.
  - Evaluate systematically the assumption of steady-state for various classes of coastal systems (e.g., incorporation of long-term trends, seasonal behaviour and episodic behaviour). For which regions of the world is it possible to go beyond steady-state? Where is it necessary?
  - Incorporate assessments of the uncertainty or error of budget terms into LOICZ methodology. The trade-off between the construction of a nutrient budget with high uncertainty in the values of its fluxes and its elimination for lack of information has been questioned. Specific consideration of this issue at the methodological stage would improve our ability to aggregate budgets for regional and global estimation and would suggest research needs in various regions.
- *Categories 1–2:*
  - Consider the effect of limitations on productivity other than P i.e., where does the assumption of a stoichiometric relationship between ΔDIP and NEM break down (e.g., limitation of light, nitrogen) and if it does, how can NEM be assessed?
  - Evaluate the utility and feasibility of constructing total N and total P budgets in conjunction with DIP and DIN budgets.
- *Category 2:*
  - Assess whether other "non-conservative fluxes" may be evaluated in the coastal zone (e.g., nutrient burial and sorption) and develop amended methodologies.
  - Extend nutrient budgets to budgets of other relevant materials (e.g., silica, dissolved oxygen, sediment) or at least evaluate and state where this might be feasible.
- *Categories 1–3:*
  - Consider and test the potential for fuller integration between the analysis of coastal systems and their drainage basins (e.g., breakdown of nutrient and sediment sources by source, consideration of terrestrial and aquatic processes which affect transport) either by modeling or detailed assessments.
- *Category 3:*
  - Test the application of multiple types of remote sensing to detailed coastal typologies and quantitative flux estimates. There have been major advances in remote determination of water depth, motion, colour and suspended sediment, potential for chlorophyll biomass and salinity, as well as precise measures of elevation, population and land cover. Unfortunately algorithms are not reliable for Coast II waters, which characterise much of the coastal zone. Future advances can be expected and integration of remotely sensed data may be able to fill many of the present gaps in both detail and resolution of the coastal databases.
  - Work toward a truly global interactive virtual network of coastal zone scientists, managers and relevant databases and tools, by building on the existing infrastructure and working to provide accessible, effective internet access to the entire international community.

Tools

Tools, websites and networks of both humans and data have been instrumental in the success of the project to date. The websites are an effective means of disseminating data and publications as well as supporting distance learning activities. The development of "mirror sites" should be considered. The use of tools should be strongly supported, to include:

- Expanded typology data access, including higher resolution data and more temporal components.
- On-line, interactive GIS visualisation and data input capabilities, both to enable users and to build toward the

necessary level of detail and resolution in developing the marine-system analogs of the watershed analyses.

- Active participation in the growing network of interoperable distributed database systems, such as the Open-DAP system and the Ocean Biogeographic Information System (OBIS).
- Simulation models of watershed-scale nutrient fluxes that can incorporate some of the recent findings from statistical analysis of LOICZ and other datasets, and which can be used to evaluate management and climate-change scenarios.
- Models of biogeochemical responses of the coastal zone to nutrient loads and other management-sensitive processes.
- Database systems, statistical tools, networks and coastal observing systems to take advantage of satellite imagery and other rapidly developing resources for measuring global and regional environmental processes and to link these global information resources with the local expertise needed to provide both ground truth and applications.

Some of these tools have been developed by LOICZ and can be further improved, reviewed, formalised and validated. Many others are still to be developed and utilised.

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