Partitioning of anthropogenic CO_2 by C-N-P-S cycle coupling on land and in coastal oceanic environment

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The terrestrial phytomass and soil humus are important reservoirs of carbon within its global biogeochemical cycle and the interactive system of the atmosphere, land, coastal oceanic zone, and open ocean. The mass of carbon in living land plants and soils is greater than in the present-day atmosphere, and land is also the source of anthropogenic emissions from fossil fuel burning and land-use activities. The flows of carbon between the atmosphere and other major reservoirs, driven by inorganic as well as biological processes, have been significantly affected during the past 300 years of human industrial and agricultural activity, with the well established results of accumulation of CO_2 in the atmosphere, oceans, and oceanic sediments.

The partitioning of the atmospheric CO_2 and, in particular, of the anthropogenic emissions to the atmosphere among the major global reservoirs depends on the driver roles of the nitrogen and phosphorus cycles within the coupled C-N-P-S system. The coupling between the biogeochemical cycles of carbon (C), and other biologically essential elements nitrogen (N), phosphorus (P), and sulphur (S), is evidenced by their joint occurrences as the major constituents of organic matter, and by the roles of N and/or P as limiting nutrients that control primary production in the terrestrial and aquatic environments. For the past 300 years, since the year 1700, the global system of the coupled cycles was analysed by a process-based model *TOTEM* (*T*errestrial *O*cean a*T*mosphere *E*cosystem *M*odel), based on 13 reservoirs in the four major environmental domains: atmosphere (1); land (6); coastal zone (3), and open ocean (3). In every biological transfer process, the individual element cycles are coupled through the average C:N:P:S ratios, such as the Redfield ratios in terrestrial and oceanic primary production, humus formation, and organic matter burial in sediments. The global system in the past 300 years experienced five perturbations that were included as external forcings in the model. One is a forcing due to changes in a global climatic variable, mean global temperature; and four are due to human activities: fossil fuel burning, land-use activities, application of N and P fertilizers to agricultural soils, and disposal of municipal and industrial sewage. On a time scale of the past 300 years, the most important forcings that control the coupled C-N-P-S cycles are fossil fuel burning and changes in land-use activities. However, extrapolation to the future of the present-day uses of chemical fertilizers and sewage disposal to rivers and the coastal zone indicates, in our model analysis, that increases in the N and P input rates from land to the coastal zone may lead to its much stronger role as a CO_2 sink through increased primary production.

Land-use activities (deforestation, reforestation, shifting agricultural cultivation) impact the carbon cycle via three mechanisms. First, through emissions of CO_2 from these activites. Second, through a negative feedback to rising atmospheric CO_2 concentrations. And third, through material transfer from land to the oceanic coastal zone by soil erosion, mineral dissolution, and surface water runoff. Land-use activities generally change the reservoir size and residence time of terrestrial organic matter, releasing CO_2, and N and S gases to the atmosphere, and remobilizing N, P, and S to the soil-water reservoir. The increased availability of nutrients in soil water, coupled with rising atmospheric CO_2 and rising temperature, promotes enhanced primary production and storage of carbon in the organic matter of the land phytomass. Because of the differences between the C:N:P ratios in humus (140:10:1) and living plants (510:4:1), remineralization of N and P in humus can result in 370 moles C becoming sequestered in new biomass, while 6 moles of N are released to continental soil waters, from where they are eventually transported to the atmosphere by denitrification or to the coastal zone by rivers.

Our model analysis shows that during most of the 300-year period of human forcings, land was a net source of carbon through emissions to the atmosphere and transport to the coastal zone. This indicates that the negative feedback through the release of N and P from remineralized organic matter in soils and their availability for fertilization did not overcome the general trend of carbon loss from land. Reversals of the trend from loss to gain of carbon by the terrestrial domain are shown by the model only for the second half of the 1900s. The latter period was also one of a faster increase in anthropogenic CO_2 emissions and a greater rise of CO_2 concentration in the atmosphere (Fig. 1).

In the coastal zone, primary production depends on input of nutrient elements (N and P) from land and from the upwelling of the deeper oceanic waters to the coastal zone. On land, land-use activities have been responsible for a stronger transport of organic matter to the coastal zone. There, its partial remineralization together with the organic matter produced *in situ* generates more dissolved inorganic carbon than was taken up in photosynthesis, thereby counteracting the flux of CO_2 from its rising concentration in the atmosphere to coastal waters. *TOTEM* analysis indicates that during most of the 300-year period of human forcings, coastal oceans were net sources of CO_2 to the atmosphere owing to the remineralization of land-derived organic matter and deposition of $CaCO_3$ in sediments. The trend shows a reversal in the second half of the 1900s, in response to the rising atmospheric CO_2. Continued input of terrestrial organic matter into the coastal oceans is likely, however, to oppose the CO_2 flux from the atmosphere and reduce the ability of the coastal ocean to act as a sink for the atmospheric carbon dioxide.

An additional role of the coastal ocean in the global carbon cycle, as indicated by the model analysis, is its response to possible changes in the global thermohaline circulation. A weakening or cessation of the thermohaline circulation, as suggested by some of the ocean-circulation and climate models, diminishes the transport of CO_2 from the atmosphere to the deep ocean. The opposite, however, may be expected for the coastal oceans: less of coastal upwelling would decrease input of dissolved inorganic carbon to the coastal zone, thereby also decreasing CO_2 production in coastal waters, and lowering its back pressure with respect to the flux from the atmosphere.

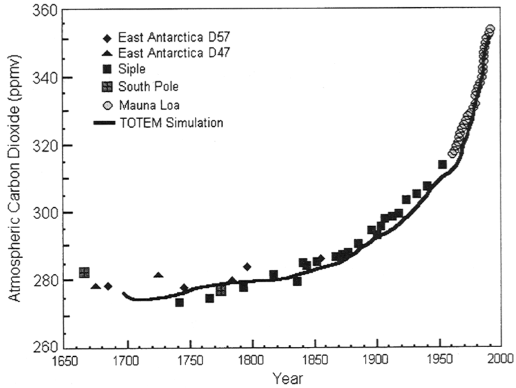

FIG. 1. *TOTEM* simulation of the rise of atmospheric CO_2 compared to ice-core and atmospheric measurements, as reported by other investigators. The computed curve is the atmospheric response to the five forcings on the coupled C-N-P-S cycles.

Increased inputs of nutrients (N and P) from land to coastal ocean can, as indicated by *TOTEM*, increase primary production to a point where uptake of CO_2 would exceed its production by remineralization, $CaCO_3$ deposition, and coastal upwelling of dissolved inorganic carbon. This conclusion is relevant to the general state of the carbon cycle and the nutrient cycles coupled to it in the atmosphere–land–coastal margin system: changes in carbon uptake or release on land are rapidly transported downcycle to the coastal margin, where increased accumulation or remineralization of organic matter is one of the controlling factors of the direction and magnitude of flow of CO_2 between the atmosphere and surface waters.

One of the *TOTEM* results for the coupled C-N-P-S cycles during the past 300 years of human forcings is the computed rise of CO_2 in the atmosphere, as shown in Fig. 1. The computed rise (solid curve) agrees well with the results from ice-cores and atmospheric analyses of other investigators, and it serves as a measure of some confidence in the conclusions derived from this global model.