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Supporting information

MARICULTURE: SIGNIFICANT AND EXPANDING CAUSE OF COASTAL NUTRIENT ENRICHMENT

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This supplementary information includes brief descriptions of the models used:

1. Global Nutrient Export from Watersheds (NEWS);
2. Mariculture nutrient budget models for shellfish (2.1) and finfish (2.2), and a description of the scenarios used (2.3).

Elsewhere, detailed descriptions can be found of the Global NEWS models (Mayorga et al., 2010), the Millennium Ecosystem Assessment (MEA) scenarios used in Global NEWS (Van Drecht et al., 2009, Bouwman et al., 2009), nutrient budget models and MEA scenarios in freshwater and marine aquaculture (Bouwman et al., 2013, Bouwman et al., 2011).

1. Global Nutrient Export from Watersheds (NEWS)

The global NEWS framework includes river-basin scale models for predicting export of dissolved inorganic nitrogen and phosphorus (DIN, DIP), dissolved organic carbon, nitrogen and phosphorus (DOC, DON, DOP), total suspended solids (TSS), particulate organic carbon (POC), particulate nitrogen and phosphorus (PN and PP), and dissolved silica (DSi) (Figure 1). NEWS sub-models represent a hybrid of empirical, statistical and mechanistic model components and include both natural and anthropogenic influences. Dissolved nutrient sub-models are broadly based on a mass-balance approach for the land surface (watershed) and river system, while particulate sub-models are largely statistical and based on a multiple linear regression and several single-regression relationships developed by Global NEWS or taken from the literature. For dissolved forms, inputs into watersheds and rivers are assessed from fluxes (estimated through bottom-up, spatially distributed calculations based on land use types, regional agronomic and sanitation statistics, and atmospheric transport and deposition models); terrestrial retention parameterizations (dependent on runoff), and a refinement of the export coefficient approach (based on modulation by runoff) (Mayorga et al., 2010).

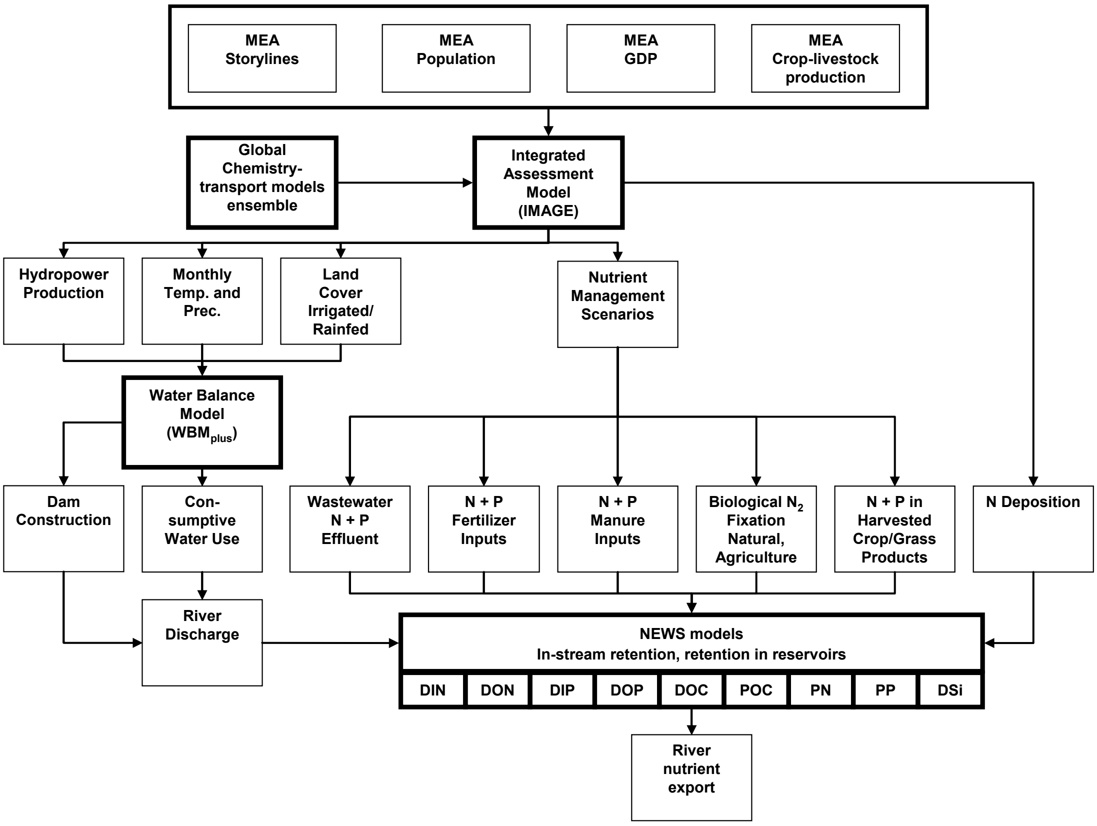

Figure 1. Data and information flows to the Global NEWS models. Additional spatially explicit information used in the NEWS models, such as basins and river networks, cell and land areas, continents, lithology, topography, are not shown. A full list of data can be found in Mayorga et al. (2010). Figure reprinted from Seitzinger et al. (2010).

NEWS model output is currently annual export at the mouth of the river. Natural and anthropogenic nutrient sources in watersheds, hydrological and physical factors, and in-river N and P removal are important model components. Since the first generation NEWS model, there have been a number of revisions (Mayorga et al., 2010), and models for simulating dissolved inorganic silica (NEWS-DSi) (Beusen et al., 2009) and dissolved inorganic carbon (DIC) have been developed. The models were re-calibrated with input data for the year 2000 using internally consistent model drivers (Mayorga et al., 2010)

Global NEWS uses various anthropogenic drivers for retrospective analysis (1970-2000) and for future years (2000-2050) based on the Millennium Ecosystem Assessment (MEA) scenarios (Alcamo et al., 2006) as input to the NEWS models (Figure 2). The estimates for coastal river inputs for 2010 were obtained by interpolation between 2000 and 2030 (GO scenario), which is considered as a business-as-usual scenario.

The Integrated Model for the Assessment of the Global Environment (IMAGE) (Bouwman et al., 2006) was used to develop the input datasets for the NEWS model including future scenarios. Data from many different sources were used to calibrate the energy, climate and land-use variables in IMAGE over the period 1970-2000. Although IMAGE 2.4 is global in application with data and scenarios at the scale of 24 world regions, it performs many of its calculations on a terrestrial 0.5 by 0.5 degree resolution (crop yields and crop distribution, land cover, land-use emissions, nutrient surface balances and C cycle).

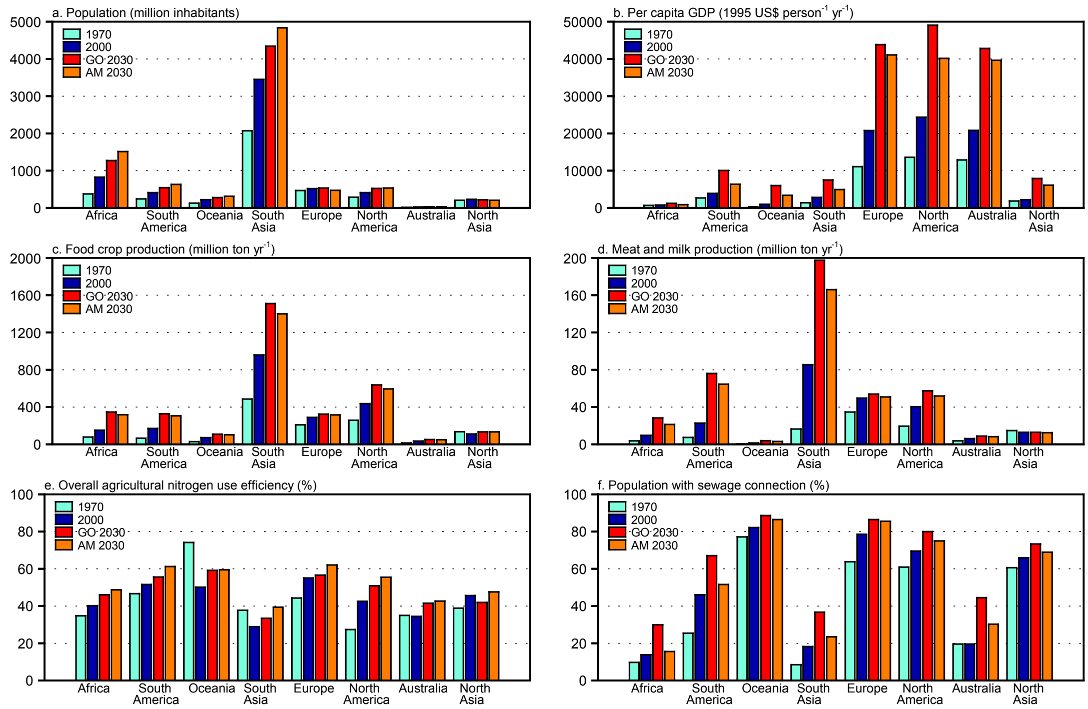

Figure 2. Anthropogenic drivers of nutrient flows for 8 world regions for 1970, 2000, and for 2030 for the Global Orchestration (GO) and Adapting Mosaic (AM) scenarios. Data taken directly from MEA (Alcamo et al., 2006) on the scale of the 24 world regions of IMAGE include: a) population, b) per capita gross domestic product, c) crop production expressed as dry matter; d) meat and milk production in dry matter. Values computed in this study, used as indirect drivers, include: e) the percentage of the population with a sewage connection from Van Drecht et al. (2009); and f) overall agricultural efficiency (including crop and livestock production systems) of nitrogen use from Bouwman et al. (2009); this efficiency is from a surface balance perspective, ignoring imports and exports of fertilizers, feedstuffs, agricultural products, and other N- and P-bearing materials. Figure reprinted from Seitzinger et al. (2010).

For agricultural areas NEWS-DIN and NEWS-DIP use the net surface N and P balances in agriculture as input. These surface balances are based on the N and P inputs from fertilizer use, animal manure application, N_2-fixation by crops, atmospheric N deposition, and sewage N and P (in some scenarios), minus N and P removal terms from crop harvest and animal grazing. These fluxes are calculated in the IMAGE model by land-use type, crop characteristics, animal type, and national agricultural information as detailed in Bouwman et al. (2009). The regional MEA scenarios for the use of N and P fertilizers are based on fertilizer use efficiency of N and P in crop production (Figure 2c; 2f). For the year 2030 regional data were used from the Agriculture Towards 2030 study (Bruinsma, 2003) as a basis. Manure production is computed from the livestock production (Figure 2d), animal numbers and excretion rates, and distributed over different animal manure management systems (Bouwman et al., 2009). For natural ecosystems the inputs include biological N_2 fixation and atmospheric nitrogen deposition. Net uptake by natural vegetation is ignored, assuming that these systems would not have a net accumulation of biomass (Bouwman et al., 2009).

N and P flows in urban wastewater (Figure 1) are based on country-level data and estimates for the period 1970 to 2000 (Figure 2e). Wastewater discharge to surface water is the sewage effluent after wastewater treatment. For the years 2030 and 2050 the calculated influents to wastewater treatment systems (if any) are computed from per capita incomes, and stem from human N and P emissions and P-based detergent use (Van Drecht et al., 2009).

For atmospheric N deposition, data from an ensemble of atmospheric chemistry-transport models presented by Dentener et al. (2006) for the year 2000 were used as a basis. To ensure consistency between MEA scenario-derived N emission estimates and the deposition patterns of Dentener et al. (2006), we scaled the deposition fields for 2000 using gaseous N emission estimates generated by the IMAGE model (Bouwman et al., 2006) from fossil fuel combustion, agricultural and natural biological sources for the period 1970-2000 and scenarios for 2000-2050 as detailed in Bouwman et al. (2009).

Part of the IMAGE output feeds into the NEWS models through the Water Balance Model WBM_{plus} (Figure 1). Scenarios for hydropower production, monthly temperature and precipitation data, and land use, irrigated and rainfed crop production areas from the IMAGE model are used by WBM_{plus} to develop scenarios for the construction of reservoirs (dams) and consumptive water use and irrigation, to generate monthly river water discharge (Fekete et al., 2010) (Figure 1) which is an important input to the NEWS model.

All information from the above gridded input data (0.5 x 0.5 degree) are passed on to the NEWS models after lumping to the river basin scale. In total 5761 distinct exoreic basins are modeled by NEWS. All NEWS models predict nutrient export at the mouth of the rivers as a function of these inputs and biophysical properties of their basins. The contribution of the watershed nutrient sources to river N and P export is analyzed and linked back to changing socio-economic, agricultural, and other practices in the watersheds.

2. Inventory of nutrient budgets in aquaculture

Simple nitrogen and phosphorus budget models were developed that describe the major flows of nutrients in finfish, crustacean and molluscan aquaculture systems, i.e. nutrients in feed inputs (fed finfish, crustaceans, gastropods) or natural feeds (e.g. carp), and filtered suspended matter (bivalves), nutrients in the harvested product, and outflows in the form of particulate and dissolved nutrients.

Total production was obtained from the global, country-scale FISHSTATJ database, for the period from 1970 to 2010 (FAO, 2013). Annual data are provided per country, species group and environment (fresh water, brackish water and marine cultures). The database contains extensive descriptions of the species reared and the area where production takes place. The FISHSTATJ data for crustaceans and molluscs are in wet live weight (including shell and skeleton).

2.1. Shellfish

The group of shellfish comprises crustaceans (shrimp, prawns, lobsters, crabs) and molluscs. Two molluscan groups are distinguished: (i) suspension-feeding bivalve molluscs (hereinafter referred to as bivalves, such as oysters, clams, cockles, mussels, and scallops), and (ii) gastropods (mainly abalone and other snails that graze on seaweed, and predatory gastropods). Production characteristics are considered for groups of species, where relevant. The budget approach describes nutrients in feed inputs (crustaceans, gastropods) and filtered suspended matter (bivalves), nutrients in the harvested product, and outflows in the form of particulate and dissolved nutrients.

For estimating total feed used in the production of crustaceans and gastropods, the model uses the concept of feed conversion ratio (FCR), i.e. the amount of feed or food required to produce one kg of body weight. FCR values for crustaceans are taken from a global inventory covering 1995-2006 (Tacon and Metian, 2008) based on a questionnaire that was sent over 800 feed manufacturers, farmers, researchers, fishery experts and other stakeholders, in more than 50 countries. For the group of gastropods, literature data for FCRs were used. Nutrient intake was estimated using N and P contents of the feed.

The model for filter-feeding bivalves uses N and P conversion ratios (*NCR* and *PCR*), inferred from the assimilation efficiencies for N and P and the fraction of dissolved N and P in the excretion. Assimilation efficiency is the difference between nutrient intake by filtration and nutrient excretion as faeces and pseudofaeces, expressed as a fraction of nutrient intake by filtration (Conover, 1966). We combined the assimilation efficiency with the fraction dissolved N and P to compute the N and P conversion ratios, i.e. the ratio of the nutrient in the harvested product to the nutrient intake in the suspended matter. For the molluscs we also accounted for the P in the shells.

Excreta are computed as the difference between feed nutrient inputs and nutrients in the harvested product. Excreta consist of dissolved and particulate forms of N and P. Nutrient loss through volatilization and denitrification is accounted for in crustacean pond systems to obtain the nutrients released to the aquatic environment. Since mussel farms are not confined systems, it is difficult to obtain reliable estimates of the role of denitrification.

2.2. Finfish

The model distinguishes two broad groups of fish, i.e. carnivores and omnivores, and three broad types of fish feed: (i compound feed, usually) industrially manufactured, including fishmeal, fish oil, soybean meal, and other ingredients; (ii) non-compound feed, consisting of locally available feeds that are not industrially compounded, such as trash fish, home-made aquafeed and rice bran (New et al., 1994), but excluding natural production such as aquatic plants and algae. This non-compound feed is used in production of carnivorous species; (iii) 'natural' feed is natural production of aquatic plants typical for extensive production systems with omnivorous species such as carp and tilapia.

Feed intake is calculated from the feed conversion ratio (FCR) for both compound and non-compound feed. Global estimates of the fraction of the production relying on compound feed and FCR values for the period from 1995 to 2006 were taken from the global inventory presented by Tacon and Metian (2008). FCR values from Tacon and Metian (2008) were modified using estimates of Bureau and Hua (2010) for rainbow trout, Naylor et al. (2009) for Atlantic salmon, European seabass, gilthead seabream, carp and tilapia, Fernandes et al. (2007) for tuna and Fernandes et al. (2008) for yellowtail kingfish. FCRs for non-compound feed exceed those for compound feed because of the lower nutritional value and digestibility (Hasan, 2001) and are based on literature estimates (Bouwman et al., 2013).

A conversion factor of 95% of the FAO production data was used to convert production data to weight gain for all species (i.e. initial weight is 5% of the production), except for tuna, where a weight gain of 67% of the production was assumed based on various reports (Tičina et al., 2007, Tzoumas et al., 2010).

Nutrient intake for compound and non-compound feeds is based on the FCR and nutrient contents of the feed. Since FCR values are not available for natural feeds (algae) in the production of relevant omnivorous fish species, the nutrient intake from for natural feed is computed from the nutrient retention fraction. This retention fraction accounts for the efficiency of the uptake of N and P from manure and fertilizers by phytoplankton, and thus for the nutrient losses associated with pond fertilization. Human and animal excreta, crop residues and fertilizers are often added to the water to increase the natural production in aquatic plants (New et al., 1994). These nutrient inputs are thus implicitly taken into account in the calculations for natural feed.

Nutrient contents of fish based on literature are used to compute nutrient retention in the product (fish) of aquaculture systems (Bouwman et al., 2013). The difference between the intake and the retention is the nutrient release. Part of this is in dissolved form, and the remainder is in solid (faeces) form. Differences in the anatomy and physiology of the gastrointestinal tracts of fish species result in significant differences in digestibility of certain nutrients and minerals (Bureau et al., 2003, Hua and Bureau, 2010). The fraction dissolved nutrients is calculated from the apparent digestibility coefficients (ADC) for protein and phosphorus in the feed (similar to e.g. Cho et al., 1994, Lupatsch and Kissil, 1998, Cho et al., 1991, Hua and Bureau, 2006, Azevedo et al., 2011). The fraction solid nutrients in the total excretion equals the non-digestible fraction.

For non-compound (farm-made) feedstuffs the digestibility coefficients for N (0.7) and P (0.45) are on the low end of the literature values for compound feed, assuming that these feeds contain less fish meal and more plant products than the compound feeds, and based on lower protein digestibility of plant-based than of fish-meal based diets, particularly for P.

For natural feed, low values for the digestibility coefficients for N (0.6) and P (0.35, are used based on Baruah et al. (2007) and Van Weerd et al. (1999)). Since the digestibility coefficients are variable and uncertain, the sensitivity of the model results to changes in this parameter was analyzed.

Losses due to ammonia volatilization and denitrification may be large in shrimp (Burford and Williams, 2001) ponds. However, these losses were ignored for fish ponds because (i) insignificant ammonia volatilization loss at $pH<7.5$, and (ii) anaerobic conditions in pond sediment leading to near absence of nitrification, and thus low denitrification rates (Hargreaves, 1998).

All nutrients excreted in cages are assumed to be released to the aquatic environment. However, nutrients released by omnivorous and carnivorous finfish may also be recycled in integrated aquaculture systems, for example, by shellfish or aquatic plants, or removed by wastewater treatment.

2.3 Mariculture scenarios

The Millennium Ecosystem Assessment (MEA) scenarios were implemented to analyze possible future trends in coastal nutrient delivery from mariculture. The MEA scenarios consider future aquaculture production on the basis of the future outlook from the International Food Policy Research Institute (IFPRI) (Delgado et al., 2003, IFPRI, 2003). These scenarios provide regional estimates of the production of high-value and low-value finfish, for the period up to 2100. Here, annual growth rates were calculated to estimate future aquaculture production in high-value and low-value finfish. The growth rate for a specific species is assumed to be the same for inland and marine production.

For salmon, with FCR values close to 1.0, apparent digestibility coefficients of close to 90% for N and 60% for P, future improvements in production and reduction of waste output are assumed to be much more limited than those achieved in the past decades; however, for other low and high value species, the FCR and digestibility of the feeds are assumed to converge to current (2000-2010) values for salmon and rainbow trout (Bureau and Hua, 2010). Estimates presented by Tacon and Metian (2008) were used for 2020; estimates for 2050 were generated using different developments depending on the scenario, with FCR decline for 2020-2050 equal to 2010-2020 in Technogarden, or 0.8 of this decline in Global Orchestration, 0.6 in Adapting Mosaic, and no further decline after 2020 in Order from Strength.

This development is accompanied by increasing digestibility coefficient (*ADC*) of N and P. Overall digestibility increases in two ways: (i) by increasing use of compound feed, which has a higher digestibility than non-compound feed, and (ii) by improving the digestibility of compound feed. Compound feeds are assumed to converge to the values for currently available salmon feeds, i.e. 0.9 for N and 0.6 for P. The Global Orchestration assumes that by technological improvement, the P digestibility will increase further to 0.7.

With this increase in ADC, N and P contents were assumed to be constant in future decades in all scenarios.

Similarly, the penetration of integrated aquaculture systems (wherein more than one organism at different trophic levels are combined within one production system) depends on the scenario, but is assumed to be negligible in the Global Orchestration scenario.

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