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Nitrogen and phosphorus budgets for a tropical watershed impacted by agricultural land use: Guayas, Ecuador

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Abstract. Large-scale changes in land use are occurring in many tropical regions, with significant impacts on nitrogen and phosphorus biogeochemistry. In this study we examine the relationships between land use, anthropogenic nutrient inputs, and riverine nutrient exports in a major agricultural watershed of the Pacific coast of South America, the Guayas River basin of Ecuador. We present comprehensive nutrient budgets for nitrogen (N) and phosphorous (P) for the Guayas River basin and 10 sub-watersheds. We quantify the four major anthropogenic nutrient fluxes into and out of the region: N and P fertilizer application, N fixation by leguminous crops, net import/export of N and P in agricultural products (food and feed), and atmospheric deposition. We also estimate inputs of N from biological N fixation in forests and of P from weathering sources in soils and bedrock. The sum of these sources represents net inputs of N and P to each watershed region. Overall, synthetic fertilizers are the largest input to the Guayas Basin for N (53%) and P (57%), and the largest outputs are N and P in crops. Losses of N and P in river export account for 14–38% of total N and P inputs, and there is significant accumulation of N and P, or unmeasured forms of N and P export, in most of the sub-basins. Nutrient balances are indicative of the sustainability of land use practices in a region, where a negative balance of N or P indicates nutrient depletion and subsequent loss of soil fertility, yield, and economic viability. Although the nutrient balance of the entire Guayas Basin is positive, there are negative or near zero balances in two sub-watersheds with extensive banana, coffee and permanent crops. In these basins, degradation of soil quality may be occurring due to these net nutrient losses. Our data show that nutrients are leaving the basin primarily as export crops, with riverine losses of nutrients smaller than crop exports. Nonetheless, there is a direct relationship between nutrient inputs and river outputs, suggesting that agricultural management practices in the basin may have direct impacts on N and P delivery to the highly productive Guayas estuary.

Introduction

Large-scale land-use changes are occurring in the tropical Americas that have important implications for the future of freshwater and coastal marine ecosystems and their management (Yanez-Arancibia and Lara-Dominguez 1998). However, relatively little is known about the potential impact of land use alteration on the large-scale biogeochemistry of tropical aquatic ecosystems

(Vitousek et al. 1997; Downing et al. 1999). Rapid population growth and the rising international demand for tropical crops has resulted in the conversion of vast land areas to intensive agricultural production in Ecuador, as is typical for many other developing tropical regions of the world (Houghton 1994; Skole et al. 1994). Agricultural production was dominated by cacao in the 1920–1930s, and from the 1950s to the present bananas have been the most important agricultural export product of Ecuador. Recently the land devoted to these export crops has increased; between 1980 and 2000 harvest area increased by about 140,000 ha for banana and 160,000 ha for cocoa (FAO 2002). Other export products, such as oil during the 1970s and shrimp farming in the 1980s, have exacerbated deforestation of the Amazonian region and the mangrove forest in coastal areas. The economic gain from exporting these products to meet international demands has been the driver for the deforestation and land use change in Ecuador and also in the Guayas Basin.

Extensive conversions in land use typically result in dramatic changes to regional hydrology (Bruijnzeel 1996; Cronan et al. 1999), alterations of biogeochemical cycles (Boyer and Howarth 2002), losses of nutrients such as nitrogen and phosphorus (Caraco 1993; Howarth et al. 1996), and soil degradation (Cole et al. 1993; Ojima et al. 1994). Previous studies in temperate and tropical areas have found strong linkages between large-scale changes in land use and associated nutrient fluxes in land and waters (Van den Bosch et al. 1988; Galloway et al. 1995; Howarth et al. 1996; Valiela and Bowen 2002; Boyer et al. 2002; Boyer and Howarth 2002; Filoso et al. 2003; Van Breemen et al. 2002).

Our work focuses on the Guayas Basin in Ecuador, which is the largest tropical agricultural watershed and estuarine system on the Pacific coast of South America. The Guayas Basin was chosen for study because it is experiencing severe environmental consequences associated with nutrient loading. This important estuary and coastal zone is experiencing major problems such as eutrophication, sedimentation, and pollution driven by urbanization, agriculture, aquaculture, and deforestation (Lacerda et al. 2002).

We examine the relationship between land use, anthropogenic nutrient inputs, and surface water nutrient exports in the Guayas watershed. We first develop comprehensive nutrient budgets for nitrogen (N) and phosphorous (P) for the overall Guayas river basin, 10 of its sub-watersheds, and subsequent nutrient loadings to the Gulf of Guayaquil. This budgeting method is useful as it provides a uniform way to quantify inputs (sources) and outputs (fate) in the region (Howarth et al. 1996; Van Breemen et al. 2002). Our nested-basin approach allows us to explore transfers and flows of nutrients within the Guayas region over a range of scales from cropland, watershed, and regional (Smaling and Oenema 1997). Next, we interpret the nitrogen and phosphorus budgets as an indicator of sustainable agricultural practices with respect to soil fertility (Pierzynski 1997). Further, we explore the relationship between nutrient inputs and subsequent nutrient loadings to the coastal zone, where water quality problems associated with eutrophication are a major concern.

Study area: the Guayas Basin

The Guayas Basin lies along the Pacific, draining a land area of 32,024 km^2 into the Gulf of Guayaquil (Figure 1a, 1b). A diversity of ecosystems is characteristic of this region: estuarine mangrove areas, dry and humid forests, Andean paramo, and agricultural land. Economic activities in this basin have changed the land use and water quality in the estuary enormously over the past 20 years (Southgate and Whitaker 1994; CAAM 1996; Twilley et al. 1998). Three main anthropogenic activities have impacted the Guayas Basin landscape: urban-industrial development, monoculture agriculture (banana, palm, soy, sugar cane, rice, and maize), and more recently shrimp pond aquaculture at the outlet of the Guayas Basin (Southgate and Whitaker 1994; Falconi-Benites 2000). The Guayas region is economically important in Ecuador because it produces 68% of the national crops, 73% of corn, 88% of bananas, 89.6% of export shrimp, 39% of cattle, and 50% of industry and manufacturing (Comisión Asesora del Medio Ambiente, CAAM 1996).

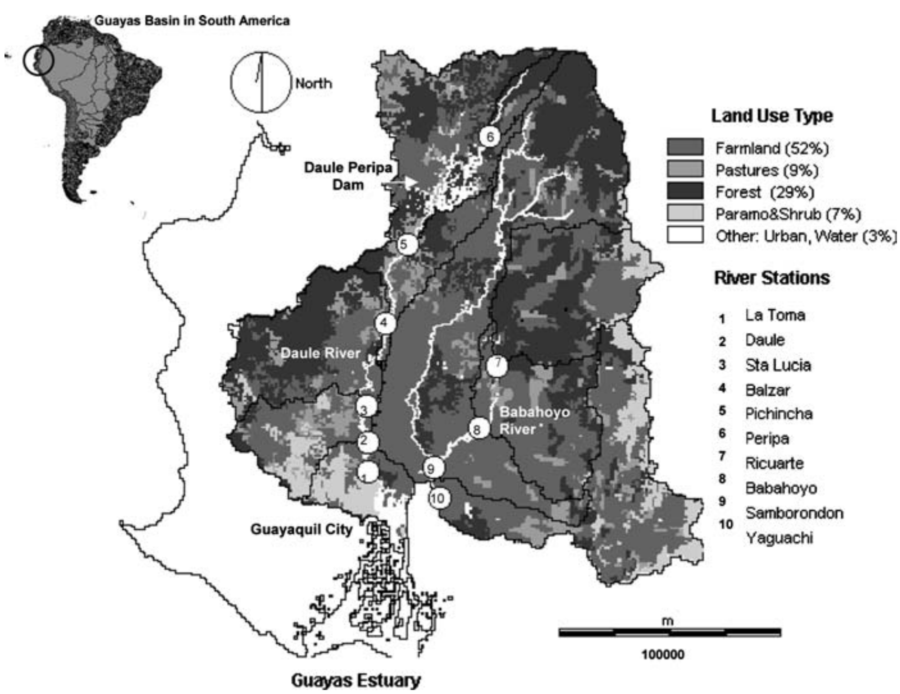

Figure 1. Watersheds and river systems in the Guayas Basin draining to the Guayas Estuary and the Gulf of Guayaquil in Ecuador.

Climate

The Guayas Basin is a humid tropical system, characterized by high solar radiation, temperatures, rainfall, and humidity. The annual mean temperature of the Guayas Basin is 24.8 °C, with lowest mean monthly temperatures in September (23 °C) and highest mean monthly temperature in April (35 °C) at Guayaquil. In the mountains toward the Andes, minimum temperatures can drop to 0–10 °C (Comision Asesora del Medio Ambiente, CAAM 1996). The basin is characterized by a rainy season from December to May each year. Mean annual precipitation is 1462 mm and ranges from 1060 to 2316 mm, with variations related to West-East orographic factors. In dry years precipitation can drop to 400 mm and it can increase to 4000 in wet years such as during El Nino events. March is the wettest month, with a mean precipitation of 365 mm; August is the driest month with a mean of 9.8 mm. Seventy eight percent of total precipitation occurs between January and April (CAAM 1996).

Watershed

We used elevation data from the USGS international elevation derivative database at 90 m resolution (USGS 2003) to delineate the boundaries of sub-watersheds within the Guayas River basin. We chose 10 sub-watersheds (Table 1) located along two main rivers, the Daule, and Babahoyo (Figure 1). The Daule and Babahoyo rivers merge downstream to form the larger Guayas River and subsequently the Guayas Estuary and Gulf of Guayaquil.

Table 1. Characteristics of the study sub-basins within the Guayas River basin.

ID	Name	Basin	Area (km^2)	%	Pop. density (hab km^{-2})	Elev. (m)	% Coverage				
							Forest	Crop	Pasture	Water	Other[a]
1	Guayaquil	Daule	1360	4.2	350	83	6.4	38.1	1.7	5.6	48.2
2	Daule	Daule	1795	5.6	53	198	7.9	51.3	17.8	0.4	22.6
3	Sta Lucia	Daule	3404	10.6	55	209	55.8	31.5	10.3	0.3	1.3
4	Balzar	Daule	1345	4.2	81	123	30.4	44.5	23.9	1.2	0.0
5	Pichincha	Daule	3768	11.8	30	216	40.6	35.1	16.2	6.8	0.9
6	Peripa	Daule	506	1.6	100	274	70.0	28.7	1.2	0.2	0.0
7	Ricaurte	Babahoyo	3567	11.1	49	1131	48.4	41.6	2.3	0.0	7.6
8	Babahoyo	Babahoyo	2894	9.0	53	551	24.1	68.7	6.1	0.4	0.7
9	Samborondon	Babahoyo	8767	27.4	89	305	31.5	62.3	4.4	0.2	0.9
10	Yaguachi	Babahoyo	4621	14.4	86	2152	11.2	56.5	7.7	0.1	23.9
	Total Guayas		32,026	100.0	90		29.0	52.0	9.0	2.0	8.0

When sub-basins are nested along the river network (downstream of each other), only the drainage area below any upstream sampling points is included in the sub-basin.
[a]Other is largely urban in watershed 1, shrubs in basin 2 and barren land (including paramo) in basin 10.

The Guayas Basin can be classified into four zones: the estuary of the Guayas (0–7 m a.s.l.), the lowlands (7–50 m a.s.l.), the uplands (> 200 m a.s.l.), and the highlands and paramos (> 1500 m a.s.l.). The Guayas estuary is a highly productive ecosystem both biologically and economically, and is a significant resource for shrimp aquaculture, which in 1998 generated 15% of the value of all Ecuadorian exports (Banco Central del Ecuador 1998). Mangrove forest ecosystems surround the estuary and are characterized by water-saturated soils (entisols and aquents) with poor drainage.

The lowlands of the Guayas Basin are primarily found downstream of the Babahoyo River, in the Lower Basin of the Guayas (Figure 1). This region is flat flood plain that is cross-cut by many rivers. Alluvial soils of volcanic origin are common in this region, and they are typically sandy clay soils with variable texture that are usually well drained. In these fertile river valleys the inhabitants have developed intensive agriculture focusing on banana, sugar cane and rice.

The Upper Basin of the Guayas is the area located upstream of the Daule River, and contains most of the uplands in the basin. The main characteristic of this region is its irregular topography that favors forest plantations and conservation of native forest; soils are entisoils and alfisoils. An important landmark of this region is the major Daule-Peripa Dam located in the Pichincha watershed (Figure 1). This reservoir has a capacity of 5.4 km^3, a flooded area of 27,000 ha, and a total average water discharge of about 71 $m^3\ s^{-1}$ (CAAM 1996; CEDEGE 2001). Purposes of this dam include irrigation, water diversion, drinking water supply, salinity control, as well as a hydropower generation capacity of 213 MW yr^{-1} (CEDEGE 2001).

The highlands and paramos are located in the foothills of the Andes Mountains. Soils in this region have low fertility, and support low human density. Only a small portion of the basin (21%) is located in the highlands.

Land use

Biophysical factors such as soil and climate, as well as socio-economic variables such as availability of labor, local need for food crops and animal products, drive changes in land use (Southgate et al. 1991). We used a high resolution base map to describe land use in the Guayas Basin that was first developed by the Comisión de Estudios para la Cuenca del Guayas (CEDEGE 2000). This original vector map was processed using a geographic information system and classified into the 16 major land use and agricultural crop types of the region (Table 2). The original land use map had an aggregated classification of ‘permanent’ and ‘annual’ crops that was maintained in this analysis. Permanent crops consist of a combination of banana, sugar cane, fruit trees, plantain, African palm, cacao, and coffee; annual crops include a combination of maize, rice, soybeans, and vegetables (INIAP 2000). We assigned fertilizer inputs to these two land use categories (permanent and annual crops) in each sub-watershed of the Guayas by first estimating the area fraction of each

Table 2. Agricultural land use and fertilizer application rates within the Guayas Basin.

Land use	Area (km^2)	% of Guayas	N fertilizer (kg ha^{-1} yr^{-1})	P fertilizer (kg ha^{-1} yr^{-1})
Permanent crops and other	2783	9	99	13
Annual crops and other	8801	28	58	6
Cocoa and coffee	381	1	90	8
Banana	1221	4	250	20
Maize	331	1	46	5
Sugar cane	481	2	150	20
Rice	2222	7	68	0
Pastures, native & cultivated	2805	9	0	0
Paramo & pasture	1325	4	–	–
Forests (native & cultivated)	9206	29	0	0
Shrubs & barren lands	1169	4	–	–
Shrimp ponds	19	0	200	70
Urban	223	1	–	–
Mangroves	8	0	–	–
Water	487	2	–	–
Soybeans	495	2	50	10

individual crop (e.g. cacao, maize, etc.) from interviews with farmers and local agricultural agents, and multiplying this area by typical fertilizer application rates for each individual crop in this region of Ecuador (Table 2). Large quantities of inorganic fertilizer such as urea, ammonium sulfate, super phosphate and diammonium phosphate are applied as routine agricultural practice in the Guayas Basin (INIAP Manual Técnico No 26). Irrigation in the Guayas Basin is uncommon due to economic constraints, and most farmers must rely on the seasonality of rain for their agricultural practices.

The pastures and forest include both cultivated and natural varieties. The most common forest species in the basin are Teak (*Tectonis grandis*), Cedro (*Cederela odorata*), Pachaco (*Schizolobium parahybium*), Guadua Cane (*Guadua angustifolia*), and Balsa (*Ochrona kagopus*). The native forest includes species such as Samanes (*Albicia samanea*), Algarrobo (*Prosophis juliensis*), Guabo (*Inga coruscans*), and Leucaena (*Leucaena leucacephala*) that are leguminous and may represent between 5 to 10% of the forest biomass. Local management practices mix native forest species with pastures such as saboya (*Panicum maximun*), elefante (*Perisetum purpurem*), or Janeiro (*Eriochloa polystachya H.B.K.*) in order to improve soil fertility (Borbor V. J. 1960; Victor A. Borbor and Carlos Martinez, personal communication).

Population

We calculated population density using census data from the Instituto de Estadisticas y Censos del Ecuador (INEC 2001) geo-referenced to the 'parroquias' digital map (Almanaque Electronico Ecuatoriano (AEE) 1998), which is the basic administrative unit of Ecuador. In the year 2000 the population density ranged from 10 to 650 inhabitants ha^{-1}, an increase over 1990 values (4–472 inhabitants ha^{-1}). The most urbanized city is Guayaquil (650 people ha^{-1}) at the outlet of the Guayas Basin (Figure 1). Its population has grown from 1.5 million to 2.5 million over the past 10 years, and it is the largest city in Ecuador. The annual population growth for Guayaquil city has averaged 1.7%, compared to an average of 0.8% annually in rural areas (ECLAC 1999). These data indicate an intense migration to the urban area and even a reduction in population in some areas of the countryside. Five million people (40% of the national population) live in the Guayas Basin, which contains 27 of the 50 most populated cities of Ecuador (INEC 2002).

Methods

In overview, we developed nutrient budgets by combining spatial land use, demographic, and economic data obtained from census or remotely-sensed approaches with data derived from field and literature studies. The major fluxes of N and P within each of the 10 sub-watersheds of the Guayas Basin were calculated. Sources of nutrient inputs include atmospheric deposition, fertilizer application, biological fixation by agricultural and forest/leguminous crops, and net import or export in food and feed.

Nutrient inputs to the Guayas Watershed

Inputs from fertilizer use

Fertilizer use was calculated from knowledge of nitrogenous and phosphate fertilizer application rates based on data collected by INIAP (Instituto de Investigaciones Agropecuarias 2000) and from interviews that we conducted with farmers in the region during the 2002 sampling season. The quantities of N and P fertilizer entering the watershed were estimated by multiplying the rate of fertilizer application (kg ha^{-1} yr^{-1}) by land area harvested for each crop, subsequently adding them to obtain a weighted fertilizer input for each watershed (Table 2). The highest rates are for banana, coffee, sugar cane, and shrimp; all but sugar cane are export crops.

Inputs from biological fixation

Fixation in cultivated crop lands and in other vegetated lands that host symbiotic, N-fixing bacteria is a significant source of new nitrogen to each watershed region (Cleveland et al. 1999) Biological N fixation in agricultural lands (leguminous and pastures) and forests was calculated using N fixation rates reported in the literature. The most important rhizobium/legume crops in Ecuador are beans (*Phaseolus vulgaris*), soybeans (*Glycine max*), and peas (*Pisum sativum*). These crops normally fix 40–168 kg ha^{-1} yr^{-1} (Freire 1982;

FAO 1999; De Koning 1999). We chose values near the low end of this range because the P-availability in the soils of Ecuador is generally low, therefore limiting N-fixation (Smaling et al. 1993). Fixation rates used in this study are listed in Table 3.

Inputs from atmospheric deposition
The spatial distribution of nutrient inputs from wet deposition was estimated based on published correlations of deposition with rainfall in the region. Following the methods of Stoorvogel (1993) and De Koning (1999), nutrients in wet deposition can be approximated by $N = 0.14\sqrt{r_n}$ and $P = 0.023\sqrt{r_n}$, where r_n is rainfall (mm yr^{-1}), and N and P are the nutrient inputs (kg ha^{-1} yr^{-1}). Digital rainfall maps were obtained from the Almanaque Electronico Ecuatoriano (AEE 1998).

Inputs in food and feed transfers
Transfers of nutrients in agricultural products account for a significant re-distribution of N and P among the Guayas watersheds and to other regions, highlighting the importance of agricultural trade. The flows of nutrients from primary production (crops) to secondary production (animals) and then to households both inside and outside the region are driven by factors such as socio-economic status and agricultural practices. Animal waste and human waste are not considered as new inputs, as they represent recycling within a region; these terms are included in the estimate of N and P as part of the net food and feed (Boyer et al. 2002). We estimated the *net import or export of N and P in food (for humans) and feed (for animals)* in each watershed as a mass balance difference between food produced and consumed within the watershed (Boyer et al. 2002). This can be further disaggregated into the components associated with human food and animal feedstocks: Net food import = human consumption − crop production for humans − animal production for humans; and similarly Net feed import = animal consumption − crop production for animals. Details of the method are summarized below:

- We calculated rates of *human consumption* based on dietary intake of N and P per year, multiplying the intake per capita per year by the population density of each watershed. We assumed that Ecuadorians consume 4 kg N and 0.66 kg P per year (OPS 1994).

Table 3. Nitrogen fixation rates in cultivated croplands and in forests used to determine rates of N fixation in sub-basins.

Crop-legume type or forest	N fixation (kg N ha^{-1} yr^{-1})	Source
Bean, soybean	25	Freire (1982)
Grassland (cultivated and native)	10	De Koning (1999)
Wetland rice	15	De Koning (1999)
Forest (cultivated and native)	25	Freire (1982)

- We estimated *crop production for human food* from agricultural data on the nutrient content of food products grown in the watersheds, as detailed in Table 4.
- We calculated rates of *animal consumption* based on dietary needs for their intake of N and P consistent with agricultural management practices, based on the rates indicated for each type of livestock in Table 5. Livestock data were obtained from Ecuador's Agricultural Census (INEC 2001).
- We estimated *crop production for animal feed* from data on animal consumption in the region, which include maize, soybeans, sub-standard banana fruits, and annual crop residues. The rest is provided by pastures. The percentages of these crops used for animal consumption are 90, 90, 10, and 20, respectively. The total pasture production is for animal consumption (V. Borbor, personal communication).
- We quantified *animal production for human foods* (i.e. meat, milk, and eggs) as the difference between animal feed consumption (intake) and animal excretion (manure waste production). Nutrient demands for animals that are not met by locally grown produce are assumed supplemented by feed imports.
- There is little information about the rate of *excretion by animals* in Ecuador, thus we used rates from other regions (Table 5). We took the data for demand or excretion (in units of kg head^{-1} yr^{-1}) and weighted them by the number of animal heads per watershed, based on animal inventory data for the region from the agricultural census. P demand in kg P head^{-1} yr^{-1} is calculated as: P in dry matter/P excretion * 100; while P excretion in kg P head^{-1} yr^{-1} is calculated as: amount manure * % solid manure * % dry matter * P content (Table 5). (Sibessen and Rutger Metzger 1995; Van Horn 1998).

Nutrient exports in the rivers of the Guayas Basin

We estimated annual exports of nutrients from each sub-watershed as the product of seasonal flow and nutrient chemistry for the wet and dry season at each station. Nutrients were sampled monthly during the wet and dry season at 10 stations along the Daule (stations 1–6) and Babahoyo Rivers (stations 7–10), the major sub-watersheds in the Guayas (Figure 1). We sampled three times during two wet seasons (February–May, in both 2002 and 2003) and twice in one dry season (August–September 2003). A total of 240 samples were collected during the fieldwork. For nested watersheds, we report the total nutrient export for the accumulated sub-watersheds located upstream of our sampling stations. Practical considerations (safety and access) dictated that some natural watershed units could not be sampled precisely at their mouths. In these cases, we have assumed that the chemistry at the point sampled is representative of chemistry at the watershed mouth.

At each station, we took three surface samples in a transect across the river for analysis of total dissolved nitrogen (TDN) and total phosphorus (TP). During all the fieldwork we filtered (Whatman GF/F;0.7 μm nominal pore size)

Table 4. Nutrient content of crops, crop residues, and pastures.

Land use type	Crop yield[a] (kg ha^{-1} yr^{-1})	Residue[a, d] (%) Wet weight basis	Moisture[c] (%)	Crop nutrient content[b] (% dry matter)		Crop residue[b] (g kg^{-1} dry matter)	
				N	P	N	P
Permanent crops	15,000	10	30	14.8	1.8	19.9	1.5
Temporary crops	12,600	10	90	15.8	1.8	27.7	2.5
Cocoa, coffee	1800	15	70	24.9	1.5	28.0	1.7
Banana	28,200	15	74	6.4	0.8	23.7	2.0
Maize	3636	15	52	23.0	5.0	16.7	3.3
Sugar cane	80,000	10	50	11.3	1.5	15.5	1.4
Rice	4200	10	50	14.1	3.8	5.5	1.3
Pasture (cultivated, native)	35,000	0	50	16.8	2.4	0.0	0.0
Forest (cultivated, native)	113,097	–	–	9.2	2.0	–	–
Shrimp from ponds[e]	3500	–	70	30.0	7.3	–	–
Soybeans	2727	10	70	41.4	3.2	43.6	3.6

Residue refers to crop residue as % of yield left on field following harvest. Moisture refers to crop moisture content as harvested.
[a]Instituto Nacional de Investigaciones Agropecuarias del Ecuador (INIAP) (2000).
[b]Van den Bosch et al. (1988).
[c]U.S. Department of Agriculture, National Nutrient Database for Standard Reference (2003).
[d]V. Borbor, Pers. Comm.
[e]Wet weight basis.

Table 5. Consumption (demand) and waste production (excretion) of nutrients by livestock.

Livestock	N demand (kg N head^{-1} yr^{-1})	N excretion (kg N head^{-1} yr^{-1})	P content mg (kg^{-1} dry matter)	Weight live (kg head^{-1})	% carcass fraction	P demand (kg P head^{-1} yr^{-1})	P excretion (kg P head^{-1} yr^{-1})	Source
Beef cattle	66.75	58.51	7.1	240	47	0.08	0.062	ARC (1984), Sibbesen (1989)
Dairy cattle	156	121	7.1	220	47	73.4	57.2	ARC (1984), Sibbesen (1989)
Chicken								ARC (1984), Sibbesen (1989)
Layers	0.84	0.55	5.8	2	80	0.93	0.54	ARC (1984), Sibbesen (1989)
Broilers	0.13	0.07	5.8	2	80	0.93	0.54	ARC (1984), Sibbesen (1989)
Pigs	8.51	5.84	5	65	70	22.7	17.2	Gunther (1972), Sibbesen (1989)
Sheep/goats	5.97	5	5	15	47	3.53	2.72	Gunther (1972), Sibbesen (1989)
Horses	44.8	40	7	180	47	59.2	45.0	Sibbesen (1989)

All data for N from Van Horn (1998), as cited in Boyer (2002). The P content of livestock commodities was calculated by multiplying the P content of live dry matter times the mean weight, then dividing by the carcass or dressing fraction which is the percentage of live weight that is considered edible. P excretion is calculated as a fraction of P demand. References as given in Tiessen et al. (1994).

and froze the 240 TDN samples immediately after collection in Ecuador and they were kept frozen until they were analyzed at the Water Quality Analysis Laboratory of the University of New Hampshire using high temperature combustion (Merriam et al. 1996). About 40 samples were not filtered and were kept frozen until analysis for TP in the Chemistry Laboratory of the Instituto Oceanografico de la Armada del Ecuador using persulfate digestion followed by ammonium molybdate analysis of phosphate. For 26 samples collected during the wet season 2003, we examined the magnitude of particulate N losses in this basin relative to TDN losses. Particulate N was measured directly on glass fiber filters (Whatman GF/F) with N analysis of the whole filter using a Perkin Elmer 2400 CHN analyzer.

We estimated average annual mass loadings of TDN and TP using measured concentrations and estimated streamflow at the 10 sampling stations. We obtained daily streamflow data for the Pichincha and Ricaurte (upstream) and Daule and Babahoyo (downstream) stations for the years 2002–2003. We used historical monthly stream flow data collected since 1980 to calculate average monthly and annual streamflow at these stations. These data were provided by the Instituto de Hidrologia y Meteorologia (INAMHI) and the Comision de Estudios para la Cuenca del Guayas (CEDEGE). We used these data to estimate flow in each of our sampling stations using a linear regression of streamflow as a function of the sub-watershed accumulated area. We used a simple volume-weighted mean concentration for calculating mean annual fluxes for 2002 and 2003 and subsequently averaged the 2 years (Webb et al. 2000). Annual Load $=\Sigma[c_i \cdot q_i]/\Sigma q_i) \cdot q_{\text{annual}}$; where c_i = concentration for samples collected; q_i = flow at the time of collection; and q_{annual} = annual flow).

Results

Our watershed-specific N and P budgets allow us to evaluate the impacts of various land uses and agricultural practices on nutrient retention and losses.

Nitrogen budget

At the level of the Guayas Basin, fertilizer applications are the dominant source of N inputs (57% of total N inputs), and food exported out of the basin is the largest loss (30.1 kg N ha^{-1} yr^{-1}, which represents 43% of total N inputs) (Table 6). A relatively small fraction of total basin inputs (10 kg N ha^{-1} yr^{-1}; 14%) is delivered to the Guayas estuary by the Guayas River. At the sub-watershed level a positive N balance was found in 9 of the 10 sub-watersheds (Table 6). The specific fluxes of nitrogen are described as follows.

Atmospheric deposition

Nitrogen deposition varied from 3 to 7 kg ha^{-1} yr^{-1} in a gradient across the watershed in accordance with rainfall patterns. We estimated a minimum value

Table 6. Annual nitrogen budgets for the Guayas Basin and its sub-watersheds.

Watershed	ID	Fertilizer	Food[a]	Feed[b]	N fix. (crops)	N fix. (forest)	Atm. Dep.	Total input[c]	Net input[d]	River export[e]	N balance
Guayaquil	1	24.6	1.9	11.8	4.3	2.7	4.0	49.3	49.3	3.7	45.6
Daule	2	32.0	−16.2	−4.2	5.2	1.7	3.9	42.8	22.4	4.6	17.9
Sta Lucia	3	19.4	−13.2	6.3	2.9	9.6	4.7	42.8	29.6	3.8	25.8
Balzar	4	37.1	−38.7	−15.4	2.5	7.2	5.9	52.7	−1.4	3.1	−4.5
Pichincha	5	35.1	−30.1	6.9	2.6	9.6	6.3	62.5	30.9	3.0	27.9
Peripa	6	27.1	−46.0	9.2	2.2	8.3	7.4	54.2	8.2	7.4	0.8
Ricaurte	7	37.2	−31.5	57.6	2.8	9.1	5.9	112.6	81.2	12.6	68.5
Babahoyo	8	57.5	−48.4	36.9	6.9	6.1	5.8	113.2	64.8	18.6	46.2
Samborondon	9	54.7	−33.0	13.1	11.1	4.0	5.6	88.5	55.0	11.0	44.0
Yaguachi	10	41.5	−43.6	50.0	3.3	3.4	3.6	101.9	58.2	2.3	55.9
Overall Basin		36.8	−30.1	17.2	4.4	6.2	5.3	69.9	39.8	10.1	29.7

Fertilizer is total fertilizer application; food is net N input to basin in human food; feed is net N input in animal feed; N fix. (crops) is average in cultivated croplands; N fix. (forest) refers to N fixation by both managed and unmanaged forests; Atm. Dep. is atmospheric deposition. River export is hydrologic loss of N as total dissolved N (TDN) contributed by each sub-basin. When sub-basins are nested, flux from upstream basins is subtracted from flux at the downstream site to obtain the flux contributed by the sub-watershed under consideration. N balance is net inputs less river export, and is a measure of N accumulation in the sub-watershed. Negative values indicate N depletion is occurring in the sub-watershed. All values kg ha^{-1} yr^{-1}.

[a]Negative values for food signify a net export of N in food from the sub-watershed.

[b]Negative values for feed signify that a surplus of feed is left as organic N input within the watershed.

[c]Total N input = summation of positive inputs only.

[d]Net N input = fertilizer + food + feed + N fixation crops + N fixation forest + N atmospheric deposition.

[e]River export was measured at the outlet of each sub-watershed and at the outlet of the Guayas Basin.

of 3.6 kg N ha^{-1} yr^{-1} in the Yaguachi watershed (South-East) and a maximum value of 7.4 kg N ha^{-1} yr^{-1} at the Peripa watershed (North). Overall, this estimated atmospheric nitrogen input represented 8% of the total nitrogen input to the entire Guayas Basin.

Fertilizer use

Annual fertilizer N inputs ranged from a mean of 19.4 kg ha^{-1} yr^{-1} in a forested watershed (Sta Lucia) to over 57.5 kg ha^{-1} yr^{-1} in the highly agricultural Babahoyo watershed (Table 6). Watersheds with permanent export crops had the highest rates of fertilizer input per area. The Babahoyo and Samborondon watersheds received high inputs of fertilizer N, due to the high application rate to crops such as banana and sugar cane (150–250 kg N ha^{-1} yr^{-1}) and coffee and cocoa (90 kg N ha^{-1} yr^{-1}). The rate of N inputs to the individual sub-watersheds was related to the percentage of cropped lands in each sub-watershed ($r^2 = 0.41$, $p < 0.05$; Figure 2a).

Net food imports

The crop biomass produced for human consumption exceeded local consumption in all but the urban watershed (Guayaquil), which imports 1.9 kg N ha^{-1} yr^{-1} as food. The remaining study watersheds exported food products, resulting in a net N export that ranged from 13.2 to 48 kg N ha^{-1} yr^{-1} (Table 6).

Net feed imports

Livestock density varied greatly across the region and livestock were significant in watershed N budgets. Most of the sub-watersheds imported additional feed beyond that which was grown in the sub-watershed, and this import was up to 57 kg N ha^{-1} yr^{-1} (Ricaurte sub-watershed). Only two sub-watersheds produced surplus feed, primarily maize, which accounted for up to −15 kg N ha^{-1} yr^{-1} (Table 6). Overall, feed N imported into the Guayas Basin represented 25% of total N inputs.

Nitrogen fixation by plants

Nitrogen fixation by leguminous crops and agricultural land (pastures, wetland rice, and soybeans) ranged from an average of 2.2 kg N ha^{-1} yr^{-1} in Peripa (location above the dam reservoir) to 11.1 kg N ha^{-1} yr^{-1} in Samborondon where the dominant land use is wetland rice (32%), which is associated with nitrogen-fixing blue green algae. Forest fixation added a small amount of N input to the budget. The Daule watershed had the lowest value of N fixed by forested land at 1.7 kg N ha^{-1} yr^{-1}, in which forest is only 7% of the total area, and the maximum occurred in the Sta Lucia and Pichincha watersheds with a mean of 9.6 kg N ha^{-1} yr^{-1} (Table 6) with a dominant land use of forest (40–50%). In the overall watershed, N fixation by agricultural land and forest contributed 6 and 9% of the total N input, respectively.

Overall nitrogen inputs
The magnitude and relative importance of the N inputs varied widely by sub-watersheds along the Daule and Babahoyo Rivers (Table 6). N fertilizer input and net food imports/exports were the largest inputs and outputs across the sub-watersheds. Total inputs of N to each sub-watershed ranged from 42.8 kg N ha^{-1} yr^{-1} in the sub-watersheds of Sta Lucia and Daule to 113 kg N ha^{-1} yr^{-1} in the Babahoyo, where cultivation of banana (a permanent export crop) is the dominant land uses. Land use was a key driver of the N sources at the overall watershed scale of the Guayas Basin. Fertilizer was the largest input of N to the watershed (53% of total inputs), N fixation accounted for 15% of total inputs, and atmospheric deposition 8%. Crop production for animal feed was highly variable from one watershed to another; at the entire basin scale local food production was not enough to meet the needs of the human and animal populations, and thus we assumed there is a net import of feed from other regions (25% of total inputs to the Guayas basin).

Nitrogen fate
Combining the estimated net N inputs (including net food and feed) and the TDN riverine export we found a net negative N balance (a net loss of N from the basin) in the Balzar sub-watershed (−4.5 kg N ha^{-1} yr^{-1}; Table 6), but in all other sub-watersheds N inputs exceeded estimated and measured outputs. N exports in rivers as TDN ranged from 2.3 to 19 kg N ha^{-1} yr^{-1} representing a variable fraction of the total N input to each sub-watershed (4–29%). Much of the N entering individual sub-basins was exported as food or feed for use in other basins. Riverine export of TDN was higher in the Babahoyo River region (16–30% N export of N inputs; watersheds Ricaurte, Babahoyo and Samborondon) compared to the Daule River region (7–20.4% N export of net N inputs; from Peripa to Guayaquil watersheds). This variation is due to differences in the amount of cropland and forest in those regions, and the effect of the Daule Peripa Dam upstream on the Daule River. The dam not only regulates the streamflow but also appears to serve as a nutrient sink. Nitrogen flux above the dam was large (7.4 kg ha^{-1} yr^{-1} at the Peripa study site), but substantially lower at the first station below the dam, Pichincha (3.0 kg ha^{-1} yr^{-1}; Table 6) suggesting intense nutrient removal at the dam.

Phosphorus budget

At the basin level, P was lost from these watersheds primarily through the export and trade of agricultural commodities to other regions (38%), and we calculated 2.4 kg P ha^{-1} yr^{-1} exported to the Guayas estuary, which represents 38% of the P inputs to the basin (Table 7). A positive P balance was found in all of the agricultural watersheds, suggesting that phosphorus is retained and immobilized in the soils. The specific fluxes of phosphorus are described as follows.

Table 7. Annual phosphorus budgets for the Guayas Basin and its sub-watersheds.

Watershed	ID	Fertilizer	Food[a]	Feed	Weathering	Atm. Dep.	Total input[b]	Net input[c]	River export[d]	P balance
Guayaquil	1	1.45	0.95	1.19	0.10	0.67	4.36	4.36	0.93	3.43
Daule	2	2.81	−1.33	0.97	0.10	0.65	4.53	3.20	1.12	2.04
Sta Lucia	3	1.86	−1.51	1.58	0.10	0.77	4.31	2.79	1.10	1.69
Balzar	4	4.30	−3.10	0.42	0.10	0.95	5.35	2.65	0.56	2.10
Pichincha	5	3.89	−2.91	1.95	0.10	1.05	6.99	4.08	0.60	3.48
Peripa	6	3.64	−3.99	2.23	0.10	1.22	7.19	3.19	0.38	2.48
Ricaurte	7	3.87	−2.88	3.03	0.20	0.96	8.05	5.18	0.68	4.50
Babahoyo	8	5.39	−3.73	2.17	0.20	0.95	8.71	4.98	0.99	3.98
Samborondon	9	4.88	−2.55	0.75	0.20	0.96	6.04	4.23	1.42	2.81
Yaguachi	10	4.38	−3.17	2.69	0.20	0.59	7.87	4.70	0.59	4.32
Overall Basin		3.65	−2.43	1.70	0.14	0.88	6.36	3.93	2.4	1.53

Fertilizer is total fertilizer application; food is net P input to basin in human food; feed is net P input in animal feed; weathering is estimated background weathering rates; Atm. Dep. is atmospheric deposition. River export is hydrologic loss of N as total phosphorus contributed by each sub-basin. When sub-basins are nested, flux from upstream basins is subtracted from flux at the downstream site to obtain the flux contributed by the sub-watershed under consideration. P balance is net inputs less river export, and is a measure of P accumulation in the sub-watershed. All values kg ha^{-1} yr^{-1}.

[a]Negative values signify a net export of P in food from the sub-watershed.

[b]Total P input = summation of positive inputs only

[c]Net P input = fertilizer + food + feed + weathering + atmospheric deposition.

[d]River export was measured at the outlet of each sub-watershed and at the outlet of the Guayas Basin.

Atmospheric deposition
Inputs of P via atmospheric deposition ranged from an estimated 0.7 kg ha^{-1} yr^{-1} in dryer areas to 1.2 kg ha^{-1} yr^{-1} in the wetter mountainous areas (Table 7). At the basin level atmospheric deposition represents 14% of total P inputs.

Fertilizer use
In the phosphorus budget of each sub-watershed, fertilizer is typically the main input, ranging from 1.4 to 5.4 kg P ha^{-1} yr^{-1} (Table 7). The land use of Samborondon and Babahoyo, which are the sub-watersheds with the highest average P inputs from fertilizer, is dominated by permanent crops such as bananas and sugar cane, which use about 13–20 kg P ha^{-1} yr^{-1} as mineral fertilizer. Overall, 57% of the total input to the Guayas Basin comes from inorganic fertilizer.

Net imports in food and feed
The high population density in the city of Guayaquil and the intensive shrimp aquaculture surrounding the Guayas estuary are the drivers of the high TP loadings in the Guayaquil sub-watershed. Human consumption that ends as sewage waste in the highly urbanized Guayaquil demands an import of food of 0.95 kg P ha^{-1} yr^{-1} (Table 7). A net export of P as food is estimated in the rest of the watersheds, with a maximum value of 4 kg P ha^{-1} yr^{-1} in the Peripa sub-watershed, in which the predominant land use is permanent export crops (banana, African palm, coffee). In all the sub-watersheds the demand of P inputs for animal feed surpassed the production of P in crops and pastures used for animal consumption, thus imports of P in mineral fertilizers supplied this deficit. Inputs in feed ranged from 0.42 kg P ha^{-1} yr^{-1} in the Balzar watershed with 24% pastures to 3.03 kg P ha^{-1} yr^{-1} in Ricaurte with less than 3% pasture.

Weathering
P input by background weathering was estimated from the lowest phosphorus concentrations in upstream reaches of the basin, which is equivalent to 0.1–0.2 kg ha^{-1} yr^{-1} (Table 7).

Phosphorus inputs
At the sub-watershed scale, Babahoyo received the highest P inputs of the Guayas Basin with 8.7 kg ha^{-1} yr^{-1}; the minimum was 4.3 kg ha^{-1} yr^{-1} in the forested Sta Lucia watershed. The net P balance varied from 1.69 to 4.5 kg P ha^{-1} yr^{-1} (Table 7). The overall average for the Guayas Basin was 6.4 kg P ha^{-1} yr^{-1}. At the scale of the overall basin, 57% of the total P inputs were from the use of inorganic fertilizers, while 14% was from rainfall, and 2% from natural rock weathering. At the same time, 27% of the P inputs were estimated to be imported as feed for animals.

Fate of P inputs
Our nutrient budgets suggest a net export of P in crop production. Phosphorus exported to the outlet of the Guayas Basin accounted for 38% of

the total P inputs to the landscape. The Daule River area carried lower TP loads (0.56–1.12 kg P ha^{-1} yr^{-1}) than the Babahoyo River (0.6–1.42 kg P ha^{-1} yr^{-1}) on average. We estimate that riverine export of TP increased downstream along the Daule and Babahoyo drainage network. The river reach with the largest P flux carried 1.42 kg P ha^{-1} yr^{-1} from the Samborondon watershed, which is subject to very intensive agriculture and livestock production.

Land use, N and P Inputs, and nutrient export in rivers

Nutrient inputs were directly related to agricultural land use in our sub-basins. We found a direct relationship between percent of cropland and N input ($R^2 = 0.41$), as well as percentage of cropland and TDN export (Figure 2b). High N inputs to the Ricuarte sub-watershed, related to livestock production and not to agricultural land, lowered the correlation coefficients relating N export to croplands and inputs. The Babahoyo, Ricaurte, and Samborondon sub-watersheds located along the Babahoyo River export greater amounts of N than those on the Daule river side of the Guayas Basin (Figure 2b).This is related to the intense agricultural management of the export crops of the Babahoyo river area versus the traditional annual crop management developed in the Daule River.

We also found that TDN exports were significantly correlated ($R^2 = 0.49$) with total N inputs (Figure 3), but not with Net N inputs ($R^2 = 0.32$; $p > 0.05$), because N is leaving the basin as export crops. The Net N input does not include losses from denitrification or volatilization, which we address in the discussion section.

Inputs of P were significantly correlated with the animal consumption represented by net feed inputs ($R^2 = 0.56$, $p < 0.05$) and were not correlated with agricultural land use. The main source of P is as fertilizer that is mainly applied to the permanent export crops. Phosphorus exported to the rivers was not correlated with total inputs, as much of the P inputs left the Guayas Basin as export crops (47% of total P input). Riverine P exports were directly correlated with river discharge at the sampling sites ($R^2 = 0.70$, $p < 0.05$; Figure 4) suggesting that phosphorus export is driven by runoff and erosion processes. The largest values of P export to rivers were found in the sub-watersheds with high livestock production (Ricaurte, Samborondon) and the Guayaquil urban area (Figure 4).

Discussion

Uncertainties in N losses

Our estimate of riverine export of N from these basins as TDN is an underestimate because we have not included particulate losses of N. Particulate N is

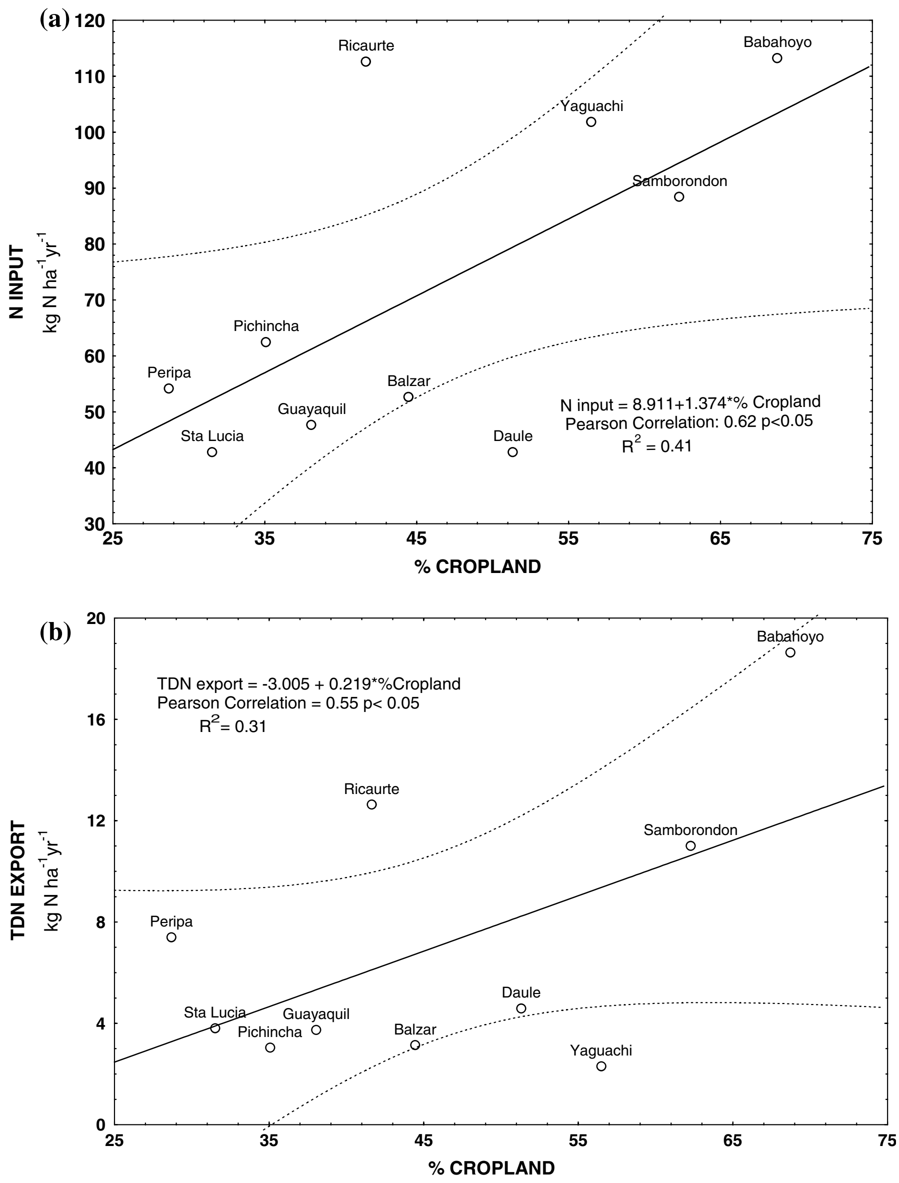

Figure 2. Nitrogen input (upper panel) and total dissolved nitrogen (TDN) export (lower panel) as a function of percentage of basin in cropland.

typically 30% of total N export in relatively undisturbed tropical rivers (Lewis et al. 1999). Comparison of TDN to particulate N for a subset of 26 samples from our study sites suggests that particulate N losses are significant in these basins, as particulate N was 72% of TDN concentrations. Because particulate

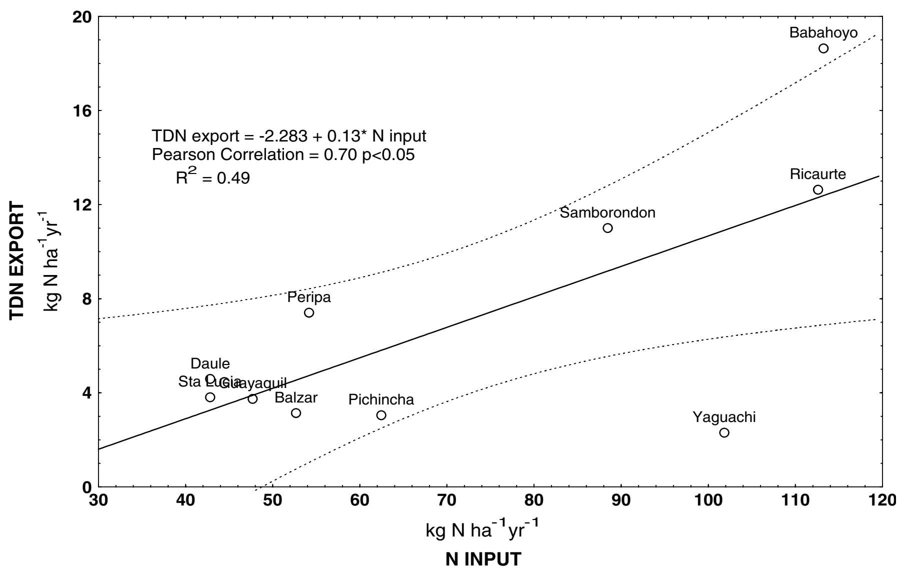

Figure 3. Export of total dissolved nitrogen (TDN) as a function of N input.

N concentrations can vary substantially with discharge in tropical rivers (McDowell and Asbury 1994), and our limited sampling of particulate N did not cover the full range of flows encountered at our site, we have not attempted

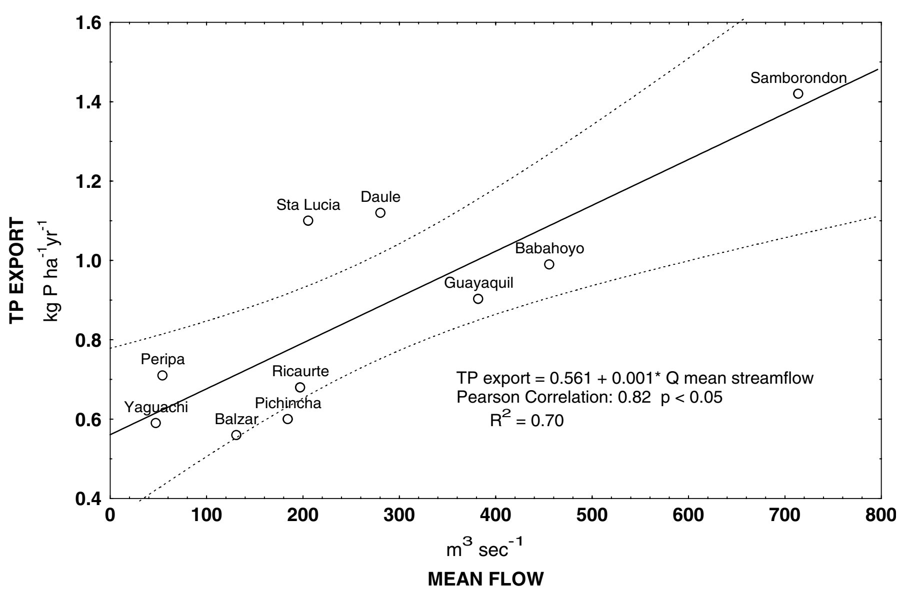

Figure 4. Export of total dissolved nitrogen (TDN) as a function of N input.

to estimate a specific value for particulate N export. However, our small data set suggests that the particulate N may be equal in magnitude to our measured TDN losses. Previous work has shown that larger watersheds tend to have higher losses of particulate N, and thus there may be proportionally more particulate N loss in the larger sub-watersheds of the Guayas Basin (Lewis et al. 1999).

We found that at the basin level the largest sink of N was via exports in food (43% of N input), followed by the N transported into the rivers (14% of N inputs), leaving 43% of N inputs unaccounted for in the landscape. We attempted to 'close' the N budget at the overall Guayas Basin scale by estimating the fate of the remaining N inputs, by considering fractions stored in soils or vegetation of landscape, or lost to the atmosphere by volatilization and denitrification processes (Jaworski et al. 1992; McMahan and Woodside 1997; Van Breemen et al. 2002). Though highly uncertain, we use literature values to establish a first guess at the overall fate of N in the basin. Denitrification in agricultural and tropical soils can be very significant, particularly in wet areas with high inputs of N fertilizers such the Guayas Basin (Velthof et al. 1997; Downing et al. 1999). Rates of denitrification in watersheds vary broadly and are dependent on pH, soil moisture, organic carbon availability and temperature (Van Breemen et al. 2002). Previous data on denitrification in tropical agricultural lands and tropical aquatic freshwater are very scarce. Losses of around 25% may be experienced following application of urea fertilizers (Vallis and Keating 1980), and up to 40% for urea application on sugar cane (McKee and Eyre 1999). We estimated denitrification in the terrestrial landscape assuming losses of 25% of applied nitrogen fertilizer in cropland, 3 kg ha^{-1} yr^{-1} from pastures, and 0.6 kg ha yr^{-1} from forest area based on literature values (McKee and Eyre 2000; Valiela and Bowen 2002). These rates of denitrification were applied to the land use map and then aggregated to obtain an average for the Guayas Basin. The exports of TDN above (7.4 kg N ha^{-1} yr^{-1}) and below (3 kg N ha^{-1} yr^{-1}) the Daule Peripa Dam suggest extensive denitrification is occurring in the reservoir. We have not considered denitrification in the sewage plants of the region. Given that only primary sewage treatment is used in the basin, and that sewage treatment is only available to 20% of the rural population and 60% of the urban population (INEC 2001), we suspect that denitrification during sewage treatment is unlikely to be significant N sink.

Ammonia volatilization is a major pathway for N loss from urea-based fertilizers (Harper and Stewart 1987). Volatilization is likely to be occurring in this tropical agricultural watershed where fertilization is based on urea application. Ammonia volatized from excreta has been estimated between 20 and 30% of the nitrogen deposited in the manure in intensive ranching areas (Vallis and Keating 1997; McKee and Eyre 2000). We estimated volatilization losses using the lowest reported rate (20%) because of the low intensity of ranching in the Basin.

Though admittedly uncertain, we estimate that 13.6 kg N ha^{-1} yr^{-1} (25% of N input) may be retained as storage in the soil, vegetation and forest Our estimate of denitrification in the overall landscape was 9.4 kg N ha^{-1} yr^{-1} (13% of N inputs) and volatilization was 6.7 kg N ha^{-1} yr^{-1} (10% of N input). Comparing our measurements of N exported to the rivers of 10 kg N ha^{-1} yr^{-1} (14% of N input), with the nutrient losses by erosion estimated by Koning (1999) of 20 N kg ha^{-1} yr^{-1} from agricultural land in the coastal region, suggests that our estimation of denitrification and volatilization in the landscape (about 15 N ha^{-1} yr^{-1}) may be an adequate first estimation.

We did not evaluate the amount of denitrification in the rivers, though it may be important in closing the N cycle. Rates of denitrification in aquatic systems are thought to be more rapid in the tropics than the temperate zone (Downing et al. 1998), hence riverine denitrification may be playing an important role in reducing N loading to the coastal zone in the Guayas estuary.

Nutrient balances and agricultural practices

Land use is the key factor contributing to the nutrient loadings to the landscape in this region. Agricultural land use in particular dominates nutrient cycling in the region, in terms of both inputs to the basin (via fertilizer applications and crop & animal production) and exports from the basin (in vegetables, meat, milk, and eggs). This highlights the importance of international trade in determining the nutrient budgets for the region. Ecuador is a net importer of fertilizers and agrochemicals and a net exporter of tropical food products. For example, of the bananas, coffee and shrimp produced each year, 60, 80, and 98% respectively are exported (FAO 2003). Fertilizers and agrochemicals represent between 30 and 40% of agricultural production costs.

Regional differences in nitrogen export in the two major rivers of the basin, the Babahoyo and Daule, are probably the result of several factors. Riverine export as TDN was higher in the Babahoyo River than in the Daule River (Table 6). Export of TDN in the Daule may be reduced by denitrification in the reservoir above the Daule-Peripa Dam, as denitrification is an important process in tropical reservoirs (Downing et al. 1999). The dam also regulates N flux by decreasing streamflow during the rainy season, thereby decreasing nitrogen loading to the rivers. Differences in land use patterns between the two basins may also explain differences in nutrient export. In the Daule, with its lower N export, cropland is 51% of land area, whereas in the Babahoyo River watershed it is 65%. Crops such as banana and sugar cane, which are more abundant in the Babahoyo watershed, also require more fertilizer additions than annual crops such as rice, maize and soybeans. The rate of fertilizer application to the permanent crops is high (>200 kg N ha^{-1} yr^{-1}), contributing to greater leaching of N to the rivers. Large leaching losses of nutrients also commonly occurs after sugar cane harvest and burning vegetation (Vallis and Keating 1997), and this may also contribute to the higher N loading in the Babahoyo River.

With respect to soil fertility, our nutrient budgets are a useful indicator of sustainability. In cases of negative balances where net nutrient outputs exceed the inputs, stocks of soil nutrients are probably declining, endangering agricultural production which may trigger land degradation (Stoorvogel 1993; De Koning 1999; Van den Bosch et al. 1988; Priess et al. 2001). On the other hand, if the balance is strongly positive, nutrient enrichment may lead to eutrophication in rivers and downstream in coastal areas. At the regional level there is a net accumulation of nutrients (both N and P) in the Guayas Basin. At the sub-watershed level there is a positive balance in most of the watersheds suggesting that N and P inputs introduced into the systems by farming practices introduce external inputs to offset nutrient removal in exported crops. If no losses had occurred, these basins may qualify as sustainable with respect to soil fertility, at least by these criteria (Stoorvogel 1993; De Koning 1999; Van den Bosch et al. 1988; Priess et al. 2001). However, direct assessments of soil fertility should be conducted to verify that nutrients are retained in the soil.

Two of our study basins with intensive agriculture (Balzar and Peripa) have net N balances near or below zero, indicating soil degradation and potential loss of productive capacity. Even the intensive addition of nutrients in fertilizers did not compensate for the nutrients leaving in the crops exported from these basins, which are devoted mainly to bananas and rice production. A previous assessment of the banana industry in Ecuador (Borbor 1999) showed that even though fertilizer application has increased from 150 kg ha^{-1} in 1985 to 550 kg ha^{-1} in 1998, banana yields have decreased from 30 to 20 Mt ha^{-1} (Mt – metric ton). In these watersheds that are losing N and P there is a considerable risk of a decline in soil fertility and long-term economic losses for farmers.

Despite the possibility of N depletion in some sub-watersheds, our assessment of the entire Guayas Basin shows that it is retaining a significant fraction of total N inputs (25%), and an even greater fraction of net N inputs. There is considerable uncertainty about the proportion of N and P retained in the soil due, however, due to the lack of empirical data on soil nutrient retention. Random soil samples analyzed by Instituto Investigaciones Agropecuarias (INIAP) suggest a great variability in nutrient content depending on the region and type of land use (unpublished data). In general, nutrient content is higher in the lower basin in the upper basin (INIAP, unpublished reports). Although we were unable to tightly constrain estimates of denitrification, we estimate that there were significant N losses via denitrification in this wet region, in particular due to those associated with the use of urea-based fertilizers. Rice paddies actually fix and retain N within the soil, but during wet and warm conditions they may also favor denitrification.

Land use decisions are linked to biophysical (local level) and socio-economic factors (regional and international level). In Ecuador, the fertile soils of the Guayas Basin, the national population growth, and the international demand for tropical crops have combined to create strong pressures on the land of this region. This has led to shorter fallow periods and the conversion of non-suitable agricultural land to agricultural crops and grasslands, often in marginal areas (Southgate and Whitaker 1994), resulting in greater potential for nutrient depletion especially in the highlands (De Koning 1999). We have identified areas within the Guayas basin where nutrient depletion is already evident, which suggests that agricultural productivity in the region may be affected in time as food production intensifies.

The sustainability of a land use system is comprised of ecological, agro-technical, and socio-economic dimensions (Van Ittersum et al. 1998). In the case of the Guayas Basin the main concerns are economic efficiency and the agro-technical performance. Thus, the export farming of this region has relied on large applications of fertilizers and agrochemicals to obtain high yields. However, it is important to differentiate between sustainable agricultural management and simply more energy intensive production processes. These may increase yield, but if the fertilizer is removed yields probably would fall to levels below their original pre-fertilization value because site quality has declined (Hall and Hall 1993; Hall et al. 1998). Since N fertilizers are very energy intensive this may become a much larger issue in the future if energy prices increase greatly, especially after Ecuador ceases to be a net producer of petroleum (Hall et al. 2003; Hallock et al. 2004).

Conclusions

Nutrient budgets in the Guayas watershed are driven largely by agricultural production. Nutrient inputs to the terrestrial landscape are dominated by fertilizer inputs, accounting for about 50% of N and P inputs. These nutrient inputs provide economic return in the form of agricultural commodities, most of which are exported out of the country. Although at the overall basin level there is a net accumulation or stable amounts of nutrients in the system, there are signs of nutrient loss and soil degradation in portions of the landscape that are subject to intensive fertilization, irrigation, and ranching activities. Further, there is a direct relationship between nutrient inputs to the landscape and nutrient loadings in surface waters of the region. However, only a small fraction of N (14%) and a larger fraction of P (38%) inputs was leached to rivers. Our analysis suggests that N river export is more related to land use and agricultural practices, while P is driven by runoff and erosion process. This highlights the need for research to understand the nutrient dynamics in the landscapes of this region. Understanding nutrient budgets is a useful analysis tool in order to incorporate better management practices that avoid soil degradation in the long run and mitigate N and P pollution problems in the coastal zone. Further research in this tropical agricultural watershed should be able to extend the comparisons to smaller watersheds where data acquisition can be more extensive.

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