Coral Reefs (2013) 32:691–699
DOI 10.1007/s00338-013-1040-2

REPORT

# Tourism's nitrogen footprint on a Mesoamerican coral reef

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Received: 24 July 2012 / Accepted: 10 April 2013 / Published online: 26 April 2013

**Abstract** Globally, the eutrophication of coastal marine environments is a worsening problem that is accelerating the loss of biodiversity and ecosystem services. Coral reefs are among the most sensitive to this change, as chronic inputs of agricultural and wastewater effluents and atmospheric deposition disrupt their naturally oligotrophic state. Often, anthropogenic alteration of the coastal nitrogen pool can proceed undetected as rapid mixing with ocean waters can mask chronic and ephemeral nitrogen inputs. Monitoring nitrogen stable isotope values ($\delta^{15}$N) of benthic organisms provides a useful solution to this problem. Through a 7-yr monitoring effort in Quintana Roo, Mexico, we show that $\delta^{15}$N values of the common sea fan *Gorgonia ventalina* were more variable near a developed (Akumal) site than at an undeveloped (Mahahual) site. Beginning in 2007, the global recession decreased tourist visitations to Akumal, which corresponded with a pronounced 1.6 ‰ decline in sea fan $\delta^{15}$N through 2009, at which time $\delta^{15}$N values were similar to those from Mahahual. With the recovery of tourism, $\delta^{15}$N values increased to previous levels. Overall, 84 % of the observed variation in $\delta^{15}$N was explained by tourist visitations in the preceding year alone, indicating that variable nitrogen source contributions are correlated with sea fan $\delta^{15}$N values. We also found that annual precipitation accounted for some variation in $\delta^{15}$N, likely due to its role in groundwater flushing into the sea. Together, these factors accounted for 96 % of the variation in $\delta^{15}$N. Using a mixing model, we estimate that sewage can account for up to 42 % of nitrogen in sea fan biomass. These findings illustrate the high connectivity between land-based activities and coral reef productivity and the measurable impact of the tourism industry on the ecosystem it relies on.

**Keywords** Mesoamerican barrier reef · Coastal aquifers · Stable isotope · Nitrogen · Eutrophication · Coral · Sewage · Tourism · Gorgonian · Monitoring · *Gorgonia ventalina*

## Introduction

Many global and localized stressors threaten the future of tropical coral reefs (Fabricius 2005; Hoegh-Guldberg et al. 2007). Unlike global stressors requiring international coordination for mitigation, local stressors like pollution and overfishing can be lessened with sound policy and management at the local level (Smith et al. 1981). Human sources of nitrogen, including sewage, agriculture, and atmospheric deposition, are known to disrupt the coral symbiosis and reef community structure (Fabricius 2005).

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Communicated by Biology Editor Dr. Stephen Swearer

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For decades, management solutions have relied on conventional water quality monitoring of nitrogen concentrations that are difficult to associate with a particular source (Jones and Boyer 2000). The ability to distinguish different sources in the marine environment is critical, given that water column concentrations can be influenced by the natural processes of nitrogen fixation (Karl et al. 1997), upwelling (Leichter et al. 2003), and rapid biological assimilation (Furnas et al. 2005), thus confounding detection of anthropogenic contributions to the total nitrogen pool. To obtain source information, stable isotope ratios of marine organisms are increasingly employed (McClelland et al. 1997; Savage and Elmgren 2004; Ward-Paige et al. 2005; Marion et al. 2005; Williams et al. 2006; Baker et al. 2010a; Sherwood et al. 2010). Yet, most studies are temporally limited to a snapshot in time or a before–after impact comparison. Fewer studies have monitored stable isotope ratios in select taxa for more than 7 yr (see Fourqurean et al. 2005), which limits detection of longer-term variation and important departures from baseline values associated with human activities (Costanzo et al. 2005).

The challenge of detecting change in environmental nitrogen sources hinders remediation efforts, which is particularly evident in the rapidly developing world (Murray 2007). The Caribbean coast of the Yucatan Peninsula has an expansive tourism industry that is economically and ecologically reliant upon the Mesoamerican barrier reef that parallels the Mexican state of Quintana Roo. Today, Quintana Roo has the most hotel rooms in Mexico with a clear gradient of development concentrated from Cancun to Tulum in the north and decreasing from Tulum to the southern border with Belize (Fig. 1). The number of hotel rooms in Quintana Roo has increased from 3,206 in 1975 to 82,983 in 2010, while the resident population grew from less than 100,000 in 1970 to 1,325,578 in 2010 (INEGI 2011).

This explosive growth threatens the region's freshwater resources and "downstream" coastal ecosystems as it is built upon the karst aquifer that underlies the Yucatan Peninsula (Back et al. 1979; Hernández-Terrones et al. 2011). Knowledge of groundwater flow paths is limited in relation to pollution inputs, and there are only a few documented maps of groundwater "catchments". Groundwater discharges from submarine sinkholes (*cenotes*) and surface fractures in the karst capstone, which, through erosion and dissolution, can form shallow lagoons (*caletas*) where the groundwater mixes with seawater. As the karst is highly porous, any pollutants applied to the surface will passively infiltrate into the aquifer with precipitation, or directly via injection (Metcalfe et al. 2011). Many residential areas have no access to wastewater treatment (Murray 2007). Thus, sewage-derived nitrogen from cesspits and outhouses flows freely into groundwater with precipitation. Further, large resorts and hotels manage their own wastewater treatment and typically use deep injection wells to pump sewage into the aquifer. Given the lower density of wastewater effluents and associated low rates of denitrification in the carbonate aquifer, concentrations of dissolved inorganic nitrogen (primarily nitrate) can exceed 300 µM (Pacheco et al. 2001; ArandaCireol et al. 2006). This situation threatens both human and environmental health via high nitrate contamination of drinking water and eutrophication of coastal habitats, respectively (Pacheco et al. 2001; Moynihan et al. 2012). Unless proportional advances in wastewater management are made, nitrogen pollution will increase with growing coastal populations.

As the "end-point" for polluted groundwater, benthic marine environments are simultaneously threatened and important for their role in monitoring this anthropogenic impact (Carruthers et al. 2005). Through fractionations associated with microbial nitrogen metabolism and ammonia volatilization, the remaining nitrogen in sewage effluents tends to be enriched by >10 ‰ (Heaton 1986). In nitrogen-limited marine environments like coral reefs, sewage-derived ammonium and nitrate are rapidly assimilated by autotrophs, forming records of these inputs (Costanzo et al. 2005; Risk 2009; Lapointe et al. 2011; Moynihan et al. 2012). Macroalgae are useful integrators over shorter time frames (a few days to weeks) (Gartner et al. 2002) and have been successfully used to map sewage inputs with high spatial resolution (Costanzo et al. 2005). However, macroalgae are limited in that they must be frequently collected owing to rates of growth, turnover, and seasonal abundance. For longer-term records, long-lived benthic invertebrates can be sampled (Baker et al. 2011).

Indeed, sea fans (*Gorgonia ventalina*) and other zooxanthellate gorgonian species are ubiquitous members of Caribbean reefs and are sensitive recorders of sewage-derived nitrogen (Ward-Paige et al. 2005; Baker et al. 2010a, b; Sherwood et al. 2010). In Mexico, $\delta^{15}$N values of sea fans collected near developed coastlines had similar $\delta^{15}$N values as groundwater nitrate (up to 7.6 ‰; Mutchler et al. 2007) and were correlated with fecal *Enterococcus* concentrations (Baker et al. 2010b). In a different study, Ward-Paige et al. (2005) reported $\delta^{15}$N values >7.0 ‰ from the gorgonian *Plexaura* spp. growing ~200 m from a major tourist development in Mexico. These samples were over 5.0 ‰ enriched relative to samples collected from Lighthouse atoll in Belize, a site far from human influence. Similarly, relative to samples from undeveloped coastlines in Mexico, *G. ventalina* $\delta^{15}$N was up to 3.4 ‰ enriched near developed coastlines (Baker et al. 2010b) and $\delta^{15}$N enrichment was detectable over 1 km from shore on the deeper forereef (15 m). This suggests that sewage-derived nitrogen can affect a large portion of the Mesoamerican barrier reef system and is not sufficiently diluted by mixing

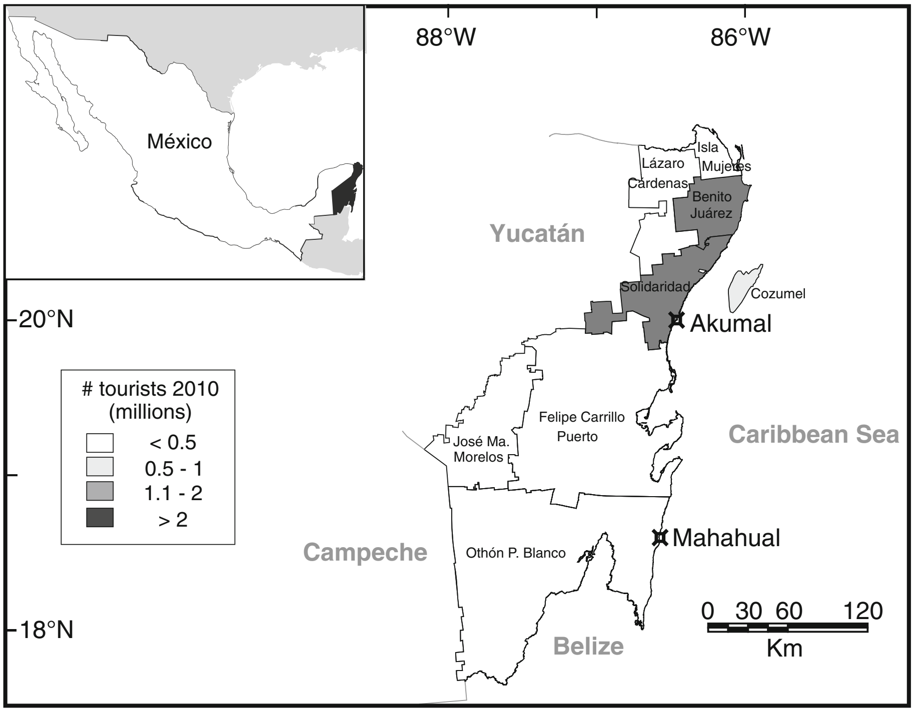

**Fig. 1** Map of Quintana Roo, Mexico, and associated municipalities, highlighting the two sites sampled in this study. *Shading* indicates the most recent number of tourist visitations reported by government agencies

with seawater (Ward-Paige et al. 2005; Baker et al. 2010b). Relative to macroalgae and hard coral tissues, gorgonian biomass turns over slowly (Yoshioka and Yoshioka 1991), and their $\delta^{15}$N represents an integrated measurement of assimilated nitrogen sources over 6–12 months (Baker et al. 2011). Thus, gorgonian corals like *G. ventalina* are ideal integrators for annual changes in environmental sources of nitrogen.

Given that (1) groundwater in the Yucatan is easily contaminated by sewage, (2) the majority of sewage on the coast is generated by tourists occupying hotels and resorts, and (3) groundwater ultimately enters the coastal ocean through submarine discharges influenced by precipitation, we hypothesized that the $\delta^{15}$N of *G. ventalina* sampled near a developed coastline would be positively correlated with tourist visitations over time (variable nitrogen source) and precipitation (variable flushing). To test this hypothesis, we conducted an annual sampling of *G. ventalina* from a developed and undeveloped site to monitor variation in $\delta^{15}$N over time.

## Methods

### Study sites

Akumal town is located in the northern sector of Quintana Roo and until 2008 belonged to the Solidaridad municipality and is currently included within the Tulum municipality. In 2010, 14 % of Quintana Roo's resident population resided within these municipalities (INEGI 2011), and from 2005 to 2010 they hosted 29 % of the hotel tourists per year (SECTUR 2011; SEIGE 2012). Akumal has no large-scale municipal wastewater treatment infrastructure, poorly designed subsurface-flow constructed wetlands, and resort-operated injection wells (Zurita et al. 2012). Thus, sewage pollution represents a serious public and environmental health threat in Akumal. In comparison, Mahahual is within the Othón P. Blanco municipality, where 19 % of the state population resided in 2010. Mahahual hosted just 5 % of the state's hotel tourists per year from 2005 to 2010 (SECTUR 2011; SEIGE 2012) and operates its own municipal wastewater treatment facility that covers 100 % of the developed areas with access to primary treatment (SEIGE 2012). At the town level, the 2010 census reported 1362 residents in Akumal, versus 920 in Mahahual.

Precipitation in the Yucatan Peninsula is seasonal, with a relatively dry season from December through April and a wet season from May through November. From 2004 to 2011, annual precipitation was similar between Akumal and Mahahual, averaging 955 ± 107 and 919 ± 77 mm, respectively, with 80 % of the annual precipitation falling between May and October (Fig. 2). Approximately 85 % of precipitation is recycled via evapotranspiration, leaving 15 % to infiltrate as groundwater, the only means of recharge to the aquifer (Villasuso and Méndez 2000; Cervantes Martínez 2007). Annually, 65 % of the water extracted from the aquifer along the Caribbean coast is used by the tourism industry (Estadísticas del Agua en

México; www.conagua.gob.mx, 2010). The region is frequently impacted by strong storms and hurricanes from September through December. During this study, several major storms affected the coast, including three category-5 hurricanes, which impacted both Akumal (Emily, July 2005; Wilma, October 2005) and Mahahual (Dean, August 2007). These strong hurricanes and several tropical storms were associated with high daily precipitation (Fig. 2).

## Coral collections

We collected five fragments of *G. ventalina* from monitored reefs (described in Rodríguez-Martínez et al. 2012) at 10 m depth offshore of Akumal (UTM 16 Q 468829 2256665) and south of Mahahual (UTM 16 Q 424954 2065902; Fig. 1). All samples were collected in the summer (July–August) from 2005 to 2011 with the exception that no samples were collected from Akumal in 2005. Sampling was conducted by removing 2 cm$^2$ fragments from the colony edge using scissors. This portion of the colony likely represents accumulated growth within the previous year (Yoshioka and Yoshioka 1991). Fragments were air-dried and shipped to the Carnegie Institution of Washington, Geophysical Laboratory, for subsequent analyses.

## Stable isotope analysis

The outer tissue (coenenchyme) containing coral polyps, zooxanthellae, and structural components was gently separated from the skeleton using a mortar and pestle and then finely ground into a powder. Approximately 0.6 mg of each sample was weighed into a 4 × 6 mm silver capsule and acidified with direct application of 2 × 20 μL of 6 N constant boiling HCl (Pierce) to remove inorganic carbon. Each aliquot of acid was evaporated in a fume hood and then oven-dried at 80 °C overnight. All samples were analyzed via elemental analyzer–isotope ratio mass spectrometry (EA–IRMS) via combustion in a Carlo-Erba NC2500 elemental analyzer or an Elementar varioMICRO Cube, coupled to a Thermo Delta V isotope ratio mass spectrometer through a Conflo III open-split interface. Reported $\delta^{15}$N values are relative to atmospheric N$_2$. Throughout each run, precision was determined using an in-house acetanilide standard (−0.8 ‰), as well as a gorgonian coral standard (4.0 ‰). Precision for these standards was better than 0.2 ‰.

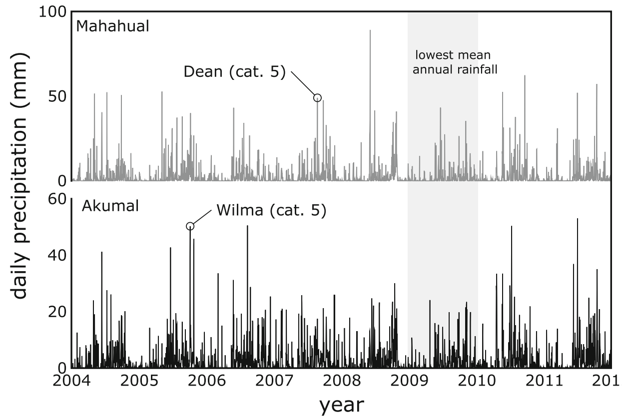

**Fig. 2** Daily precipitation measurements for Akumal (*bottom*) and Mahahual (*top*) during the period of study. Note significant storms and dry periods are *highlighted*

## Statistical analyses

As the isotope data varied over space and time, all data were screened for normality using a generalized linear model (GLM) and homoscedasticity using the Shapiro–Wilk test on the conditional residuals and Levene's test comparing the variance between sites for each year, respectively. The overall difference between mean $\delta^{15}$N from all sea fans collected in all years from Akumal and Mahahual was assessed using a post hoc *t* test on the GLM least-squares means. Year of sampling was designated as a nominal factor, and one-way ANOVA was used to evaluate the effect of year of sampling on $\delta^{15}$N within each site. *Post hoc* comparisons to test for significant pairwise differences in $\delta^{15}$N values between years were conducted using Tukey's HSD test.

To test the hypotheses that $\delta^{15}$N variability is associated with sewage-derived nitrogen inputs (variable sources) and/or precipitation (variable flushing), we obtained annual tourist visitation and precipitation data from several government databases. The tourism data were compiled from two sources to test the hypothesis that observed variation in $\delta^{15}$N values was correlated with differential wastewater input from a changing tourist population within the municipalities of Solidaridad and Othón P. Blanco, within which the towns of Akumal and Mahahual are located, respectively (Fig. 1). We used data on hotel guests only and excluded data on cruise ship tourists based on the assumption that passengers spend most of their time on board and cruise ships maintain their own wastewater treatment systems and discharge in the open ocean.

Tourism statistics were obtained from the Quintana Roo State System for Geographical and Statistical Information (SEIGE 2012) and from the Tourism Secretary (SECTUR 2011). In 2008, the Tulum municipality was created, which includes Akumal. Therefore, from 2008 onward we combined data from the Solidaridad and Tulum municipalities to maintain consistency. Daily precipitation data were obtained from NOAA's National Centers for Environmental Protection and Climate Prediction Center's online regional US-Mexico database (http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.CPC/.REGIONAL/.US_Mexico/.daily/.gridded/.realtime/; Fig. 2).

Given that gorgonian $\delta^{15}N$ values represent a 6–12-month integration time of new source information (Yoshioka and Yoshioka 1991; Baker et al. 2011), we accounted for a 1-year temporal lag in both the tourist and precipitation datasets. For example, the $\delta^{15}N$ values from 2007 were aligned with tourist visitations and precipitation values reported in 2006 for each locality. We used stepwise linear regression analysis with all temporally adjusted and unadjusted data to determine which combination of factors best described the variation in $\delta^{15}N$ using a $p$ value threshold ($\alpha = 0.05$). The resulting factors were included in a standard least-squares regression model to test for their influence on variation in $\delta^{15}N$.

## Results

The GLM revealed a significant effect of region ($p < 0.0001$) and year of collection ($p = 0.02$) on $\delta^{15}N$ ($df = 2$; $R^2 = 0.62$). The resulting residuals were normally distributed within Mahahual (Shapiro–Wilk test, $n = 35$; $W = 0.95$, $p = 0.18$) and Akumal ($n = 30$; $W = 0.94$, $p = 0.09$). Both datasets were homoscedastic within each year (Levene's test; all $p < 0.05$).

From 2005 to 2011, sea fan $\delta^{15}N$ ranged from 2.2 to 4.3 ‰ ($n = 30$; mean = 3.3 ‰) in Akumal and from 1.8 to 2.8 ‰ ($n = 35$; mean = 2.2 ‰) in Mahahual (Fig. 3). Overall, sea fans collected from Akumal were 1.2 ‰ enriched relative to Mahahual ($t$ test; $df = 61$, $t = -9.36$, $p$ (two-tailed) $<0.0001$). Moreover, $\delta^{15}N$ values from Akumal were twice as variable than from Mahahual (std dev. = 0.60 vs. 0.29, respectively). This variation occurred between years, as the standard deviation within each year averaged 0.2 ‰ for both locations, which represents the precision of the EA–IRMS analysis.

### Annual and site-specific variation

There was a significant effect of year (as a categorical variable) on $\delta^{15}N$ in Akumal (ANOVA; $n = 30$, $F_5 = 26.02$, $p < 0.0001$) and Mahahual ($n = 35$, $F_5 = 3.06$, $p = 0.02$). In Akumal, $\delta^{15}N$ values decreased significantly from 3.8 ‰ in 2007 to 3.1 ‰ in 2008 and reached a minimum of 2.3 ‰ in 2009 (Tukey's post hoc test, all $p < 0.05$). Although the ANOVA indicated a significant year effect on $\delta^{15}N$ in Mahahual, the post hoc analysis detected no significant differences between years.

### Identifying sources of variation in $\delta^{15}N$

Stepwise regression analysis identified year, 1-year adjusted annual tourist visitations, annual precipitation, and 1-year adjusted annual precipitation as having significant effects on $\delta^{15}N$ (Table 1). The standard least-squares model built from these factors accounted for 99 % of the variation in $\delta^{15}N$ ($n = 12$, $F_3 = 135.1$, $R^2 = 0.99$; $p < 0.0001$; Table 1). Linear regression revealed a strong positive correlation between $\delta^{15}N$ and 1-year adjusted tourist visitations alone when both sites were combined ($n = 12$, $R^2 = 0.84$, $p < 0.0001$; Fig. 4). However, the strength of this relationship was driven in part by grouping of the data among both regions. The relationship was not significant for either region alone, though a pattern was more apparent in Akumal ($R^2 = 0.60$, $p = 0.07$) than in Mahahual ($R^2 = 0.00$; $p = 0.95$; Fig. 4).

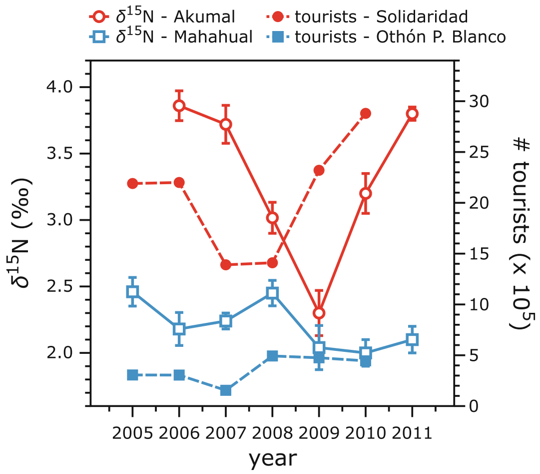

**Fig. 3** Sea fan $\delta^{15}N$ (*open shapes*, left $y$-axis) and number of tourist visitations (*closed shapes*, right $y$-axis) between 2005 and 2011 in a developed (Akumal; Solidaridad municipality—*red*) and undeveloped (Mahahual; Othón P. Blanco municipality—*blue*) coastline. *Bars* represent standard error of five replicate samples

## Discussion

On Caribbean reefs, gorgonian corals are superior recorders for sewage pollution (Ward-Paige et al. 2005; Risk et al. 2009), and previous works have detailed the relationship between gorgonian $\delta^{15}N$ values and sewage inputs (Ward-Paige et al. 2005; Baker et al. 2010b; Sherwood et al. 2010). In this study, we have taken a step forward by

**Table 1** Standard least-squares regression model results following stepwise linear regression explaining variation in $\delta^{15}N$ ($n = 12$)

| Factor | *df* | *F* | *p* value | $R^2$ |
|---|---|---|---|---|
| Year | 1 | 36.64 | <0.001 | |
| Tourist visitations (1-yr lag) | 1 | 167.3 | <0.0001 | |
| Annual precipitation | 1 | 36.22 | <0.001 | |
| Annual precipitation (1-yr lag) | 1 | 15.66 | <0.01 | |
| Model | 3 | 135.1 | <0.0001 | 0.99 |

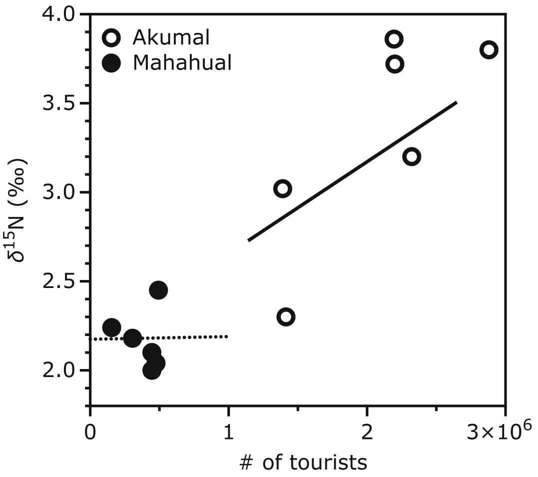

**Fig. 4** The relationship between average sea fan $\delta^{15}$N and reported numbers of tourist visitations in the preceding year for each site's municipality as determined by linear regression. *Note*: sampling did not occur in Akumal in 2005

advancing the application of coral $\delta^{15}$N analysis through monitoring discrete populations over time. Indeed, $\delta^{15}$N values of *G. ventalina* varied among years, and the interannual variation was greater than that within a given year. This suggests that changes in either (1) the nitrogen source "baseline" $\delta^{15}$N or (2) processes that fractionate that source in the environment are occurring, as opposed to variation among individual gorgonian colonies. We observed that sea fans from Akumal were, on average, +1.2 ‰ enriched relative to Mahahual. A similar difference was previously observed between these locations (Baker et al. 2010b) and correlated with fecal *Enterococcus* concentrations.

By monitoring $\delta^{15}$N, we have observed that temporal variability is higher on a reef adjacent to human development, and this variation is correlated with tourist visitations. In Akumal, sea fan $\delta^{15}$N values decreased by 1.6 ‰ from 2006 to 2009 (Fig. 3). During this time, tourist visitations to the Solidaridad municipality declined nearly 37 % as a consequence of the global economic downturn, several major hurricanes, drug-related violence, and the swine flu outbreak. Tourist visitations remained low through 2008 but then recovered to previous levels by 2009. Following this recovery, sea fan $\delta^{15}$N increased by nearly 1.0 ‰, reaching former values by 2010. By this time, nearly three million tourist visitations were reported for the Solidaridad municipality, an all-time high. In contrast, $\delta^{15}$N values of sea fans from Mahahual were relatively static while tourist visitations to the Othón P. Blanco municipality remained consistently low relative to Akumal by one order of magnitude. Given that there was no significant variation in the natural, unimpacted site near Mahahual, we refute the alternative hypothesis that natural nitrogen sources such as fixed nitrogen or upwelled nitrate were changing along the coast and therefore cannot explain the long-term pattern of $\delta^{15}$N in Akumal. Thus, we conclude that the observed variation in $\delta^{15}$N in the Akumal population is a result of varied inputs of $\delta^{15}$N-enriched sewage year to year.

Our data illustrate the direct and measurable impact of tourism development on coral reefs. We have shown that year-prior tourist visitations to Akumal follow the $\delta^{15}$N pattern, but not in Mahahual where tourist visitations were comparatively low. Taken together, tourist visitations in the year prior to sampling explained 87 % of the variation in sea fan $\delta^{15}$N, though we caution that this relationship is influenced by grouping of data by site (Fig. 4). Nevertheless, the pattern suggests that human-derived nitrogen constitutes a major portion of the nitrogen pool in this formerly oligotrophic, nitrogen-limited habitat and further monitoring will continue to resolve the relationship. The y-intercept of the overall regression is useful for estimating the natural "baseline" $\delta^{15}$N for *G. ventalina* is approximately 1.9 ‰. This relatively depleted value may reflect the importance of nitrogen from diazotrophic microbial mats (−0.9 ‰) and fringing mangroves (−0.6 ‰) to nearshore reef environments (Fogel et al. 2008), which may become enriched via microbial and trophic fractionations prior to assimilation by reef corals. Using this as a lower end-member and the measured $\delta^{15}$N of nitrate from Yalku lagoon (7.6 ‰; Mutchler et al. 2007) as the upper end-member, we estimated the percentage wastewater-derived nitrogen comprising sea fan biomass with a two-end-member mixing model:

$$\%\,\text{sewage N} = \left(1 - \frac{\delta^{15}\text{N}_{\text{sea fan}} - \delta^{15}\text{N}_{\text{sewage}}}{\delta^{15}\text{N}_{\text{baseline}} - \delta^{15}\text{N}_{\text{sewage}}}\right) * 100,$$

where $\delta^{15}\text{N}_{\text{sea fan}}$ is that of *G. ventalina* and the end-members $\delta^{15}\text{N}_{\text{baseline}}$ and $\delta^{15}\text{N}_{\text{sewage}}$ equal 1.9 and 7.6 ‰, respectively, which assumes no fractionation. This model illustrates that overall a maximum of 42 % (mean ± SEM.; 24.8 ± 1.5 %; $n = 30$) of the nitrogen in sea fans from Akumal is potentially derived from wastewater compared to a maximum of 15.8 % (5.7 ± 1.4 %) in Mahahual. That up to 42 % of the nitrogen on a reef 0.5 km from shore and at 10 m depth is potentially sewage-derived is disconcerting, given the known negative impacts of sewage nutrients (Fabricius 2005), microbes (Patterson et al. 2002), pharmaceuticals (Costanzo et al. 2005), and other toxins on corals and other marine organisms (Walker and Ormond 1982; Kaczmarsky et al. 2005).

In our effort to explain the variation in $\delta^{15}$N, annual precipitation and that of the year prior were important predictors, albeit less so than tourist visitations. Precipitation is the single source of groundwater recharge to the aquifer and thus an important vehicle for transporting pollutants, including nutrients, to the sea (Mutchler et al. 2007; Metcalfe et al. 2011). That both the 1-year lag adjusted and unadjusted precipitation records were both significant factors in describing variability in $\delta^{15}$N suggests that both short-term and long-term variation in precipitation can influence the flux of sewage into the marine environment. In 2009, lower than average rainfall was recorded in Akumal, and this coincided with the lowest $\delta^{15}$N values from this site during our study (Fig. 2). A slight but insignificant decrease in $\delta^{15}$N was also observed in Mahahual in 2009, which also may be due to reduced terrestrial inputs to the reef. In 2007, Hurricane Dean brought high amounts of rainfall to Mahahual prior to our sampling (Fig. 2). This may explain the slight, but insignificant enrichment observed in $\delta^{15}$N in 2008 and thus caused a contrast between values from the following dry year. Ultimately, $\delta^{15}$N did not vary significantly in Mahahual, regardless of precipitation. This relatively stable $\delta^{15}$N baseline highlights the importance of anthropogenic activities and minimizes the potential for natural processes (i.e., nitrogen fixation, denitrification, etc.) to explain the patterns observed in Akumal. The effects of precipitation on coral $\delta^{15}$N values may be augmented when coupled with lower sewage production as observed in Akumal. A reduced rate of flushing and groundwater flow through the aquifer would slow the transport of nitrogen to the reef and perhaps facilitate, via longer retention times, nitrogen removal via denitrification.

In addition to the large difference in tourist visitations, Mahahual and Akumal differ with respect to groundwater hydrogeology in ways that have important implications to this and future studies in Quintana Roo. Models illustrate that Akumal and indeed the entire Solidaridad municipality are in a region of major groundwater flow to the sea, from inland areas and potentially from nearby towns including Tulum (Bauer-Gottwein et al. 2011; Hernández-Terrones et al. 2011). This is supported by hydrogeological and groundwater mapping, which have highlighted the *Sistema Aak Kimin* cave system surrounding Akumal as unusually voluminous for coastal environments (Smart et al. 2006). Further, this cave system intersects the coastline at Yalku lagoon, a formation known as a *caleta* which is created by the gradual dissolution of carbonate by groundwater emanating from a fracture in the karst capstone (Back et al. 1979; Smart et al. 2006). Our monitoring site in Akumal is <500 m from the mouth of Yalku lagoon, where large outflows of freshwater are evidenced by an elevated waterline within the lagoon relative to the ocean and an extensive layer of freshwater on the surface (pers. obs.; Baker et al. 2010b). Furthermore, the cave systems and cenotes common from Akumal to Tulum are aligned with the Holbox fracture line, a major fault in the karst platform, which serves as a regional conduit for groundwater within the entire Solidaridad municipality (Bauer-Gottwein et al. 2011). Metcalfe et al. (2011) suggested the Holbox fracture zone transports pollutants through the region, at times parallel to the coastline. Thus, coastal *caletas* like Yalku lagoon, much like a river mouth, are important areas for monitoring the effect of changing groundwater quality on marine ecosystems. In contrast, Mahahual is located on the Caribbean coast of a largely uninhabited peninsula bordered on the west by Chetumal Bay. Given the lack of regional development and the likelihood that Chetumal Bay intercepts the majority of groundwater flow in the area (particularly drainage from the state capital of Chetumal), Mahahual may be less exposed to regional sources of groundwater pollution than Akumal (Bauer-Gottwein et al. 2011).

However, Mahahual is nonetheless at risk from its own local development. A 2010 snapshot assessment of fecal *Enterococcus* along the shoreline indicated that the municipal sewer system and wastewater treatment plant in the town center are sufficient in preventing bacterial contamination of popular swimming areas (Baker et al. 2010b). However, the extent of this system is limited, and areas near the treatment plant and unsewered residences had elevated fecal *Enterococcus* concentrations (Baker et al. 2010b). Compounding this problem, cruise ship arrivals have increased from 37 in 2000 to 223 in 2010, bringing over 800,000 short-term visitors to shore per year. At this time, the proportion of nutrient pollution from cruise ship tourists on short-term shore excursions is unknown. Future projections for development, tourism, and an increasing resident population in Mahahual rival that of Cancun. Thus, Mahahual represents an important site for continued isotope monitoring efforts as we have established a predevelopment baseline from which we can compare future change. It is critical that rapid economic growth in this region is balanced with investment in wastewater management infrastructure and water quality monitoring with the goal of protecting freshwater and marine resources, including the reefs that are the keystones of the entire economy.

Indeed, sewage-derived nitrogen is likely contributing to algal overgrowth, disease outbreaks, and ultimately a regional loss of coral cover and diversity, even among "eco-tourist" localities such as Akumal. In estimating sewage nitrogen contributions to reefs associated with tourism, our study also shows how this "nitrogen footprint" is easily reduced. A 37 % reduction in the number of tourist visitations to the Solidaridad municipality significantly reduced the amount of sewage-derived nitrogen reaching reefs in Akumal within a year-long time frame. This reduction was enough that by 2009 $\delta^{15}$N values overlapped with those observed in Mahahual for the first and only time during the period of observation. Thus, our data suggest that without improved wastewater management, tourist visitations to the Solidaridad municipality should be limited to <150,000 per year. Assuming that such a restriction is not economically viable, substantial investment in wastewater management, including nutrient removal, must be implemented. Continued monitoring of stable nitrogen isotope ratios of common reef organisms is an easy, cost-effective way of identifying and quantifying the impacts of future development and the efficacy of improved policy and management. Thus, annual $\delta^{15}$N monitoring of gorgonian populations represents an ideal bioindicator for reef water quality, as the response is specific to environmental nitrogen sources, monotonic in reflecting the intensity and duration of nutrient pollution, variable over time and space, and the application is both practical and ecologically relevant to reef health and productivity (Cooper et al. 2009).

**Acknowledgments** Special thanks to CD Harvell, E Jordán-Dahlgren, MA Maldonado, AG Jordán-Garza, L. Vázquez, P Sánchez-Navarro, and the Centro Ecológico Akumal for logistical support. J García Barbabosa and the staff of Bucaneros del Caribe, and the staff of La Posada de los 40 Cañones assisted with sample collection in Mahahual. We thank CW Kwan for statistical advising. This work was supported by the Coral Disease Working Group of the Global Environment Facility Coral Targeted Research program, the W.M. Keck Foundation to MLF, a U.S. Environmental Protection Agency Science to Achieve Results fellowship to DMB, and a Smithsonian Marine Science Network Fellowship to DMB. The authors claim no conflict of interest with this work.

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