LAND DEGRADATION & DEVELOPMENT
Land Degrad. Develop. (2015)
Published online in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ldr.2430

LAND USE EFFECTS ON MANGROVE NUTRIENT STATUS IN PHANG NGA BAY, THAILAND

Jan-Willem Wolters[1,2*†], Lucy G. Gillis[2‡], Tjeerd J. Bouma[2], Marieke M. van Katwijk[1], Alan D. Ziegler[3]

[1]*Radboud University Nijmegen, Department of Environmental Science, Institute for Water and Wetland Research, Heyendaalseweg 135, 6525 AJ Nijmegen, The Netherlands*
[2]*Royal Netherlands Institute for Sea Research (NIOZ), Department of Spatial Ecology, Korringaweg 7, 4400 AC Yerseke, The Netherlands*
[3]*National University of Singapore, Department of Geography, 1 Arts Link, Singapore, 117570, Singapore*

Received 14 July 2014; Revised 19 August 2015; Accepted 19 August 2015

ABSTRACT

Tropical mangrove forests can play an important role in the functioning of adjacent marine ecosystems, by protecting them from an excess in land-derived sediment and nutrients. The strength of this interaction may however depend on the nutrient status of the mangrove forest. This study related the nutrient status of eight mangrove forests in Phang Nga Bay (Thailand) to the land-cover distributions in the upstream catchment areas. Nutrient status was assessed using indicators integrating over short (porewater and sediment nutrient composition) and long timespans (mangrove leaves and sesarmid crab tissue characteristics). Using multivariate statistics (PCA analysis), these nutrient status data were then related to the land cover data, which were obtained through the analysis of satellite imagery. Nutrient availability was lowest for mangroves in catchments with large natural vegetation cover and was elevated in catchments with increasing levels of anthropogenic influence. Furthermore, nutrient availability was significantly correlated with several forms of land use, including natural forest, rice paddies, cleared ground and urban areas. While all indicators supported these results, relationships were strongest for long-term indicators. Information on the relationship between land use in the catchment area and mangrove nutrient status may be important for the effective management of this habitat, as well as adjacent marine systems. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: eutrophication; urbanization; South-East Asia; porewater; stable isotopes

INTRODUCTION

Wetlands and coastal systems play key roles in the functioning of earth and human systems, but are worldwide adversely affected by land degradation processes and land use changes (Mitsch & Gosselink, 2000; Duke *et al*., 2007). Mangrove ecosystems play an important role in tropical coastal systems by providing biotic and abiotic benefits to adjacent marine ecosystems, including seagrass beds and coral reefs. Biotic benefits may come in the form of providing a feeding or nursery habitat for reef and seagrass associated organisms (Robertson & Duke, 1990; Nagelkerken *et al*., 2000). Abiotic benefits may come in the form of coastal protection through the reduction of the hydrodynamic energy of incoming waves and currents (Othman, 1994; Quartel *et al*., 2007). Additionally, the intricate network of mangrove trees provides resistance to flowing water (Wolanski *et al*., 1992; Quartel *et al*., 2007), leading to a reduction in current velocity and the retention of suspended sediment and organic material (Furukawa *et al*., 1997). In this way, less suspended sediment is exported to adjacent marine systems, such as sensitive seagrass beds and coral reefs.

The capacity of mangrove forests to provide the aforementioned benefits partially depends on their nutrient status (Valiela & Cole, 2002). Many mangrove forests are naturally nutrient poor (Reef *et al*., 2010). It might therefore be expected that nutrients from external sources are readily taken up by these forests, thereby acting as a buffer to protect adjacent marine ecosystems from an excess in nutrients (Valiela & Cole, 2002). However, in cases of extreme nutrient enrichment, the buffering capacity may diminish. An increasing proportion of the received nutrients is then outwelled to the ocean (Boto & Wellington, 1988; Dittmar & Lara, 2001; Valiela & Cole, 2002). Furthermore, nutrient enrichment in mangroves may lead to a relatively smaller biomass allocation to root structures (Lovelock *et al*., 2009; Naidoo, 2009). Decreases in root biomass result in fewer aerial root structures that can provide resistance to flowing water and facilitate sedimentation (Nepf, 1999; Lopez & Garcia, 2001; Bouma *et al*., 2009). It may be expected that nutrient-rich mangroves will therefore trap less sediment and absorb a smaller amount of nutrients than nutrient-poor mangroves. The subsequent increased nutrient levels and turbidity in coastal waters can be expected to have great impact on the adjacent seagrass meadows and coral reefs, ecosystems that are already stressed by habitat destruction and ocean changes related to global warming (Duarte, 2002; Anthony *et al*., 2011).

*Correspondence to: J. Wolters, Department of Biology, Ecosystem Management Research Group, University of Antwerp, Universiteitsplein 1C, B-2610 Wilrijk, Belgium.
E-mail: Jan-Willem.Wolters@uantwerpen.be
†Present address: University of Antwerp, Department of Biology, Ecosystem Management Research Group, Universiteitsplein 1C, B-2610 Wilrijk, Belgium
‡Present address: Leibniz-Zentrum für Marine Tropenökologie GmbH, Department of Mangrove Ecology, Fahrenheitstrße 6, 28359 Bremen, Germany

Changes in catchment land use, particularly forest conversion to agriculture and urban areas, potentially affect in situ catchment soil processes (Fialho & Zinn, 2014; Zhao *et al.*, 2015) as well as the nutrient status of downstream mangroves. For example, increased nutrient concentrations in the water column of streams and estuaries have been linked to land use conversion (Howarth *et al.*, 1991; Beckert *et al.*, 2011). Increases in sediment export in mangrove estuaries and other watersheds have also been linked to upstream deforestation (Valiela *et al.*, 2014; Borrelli *et al.*, 2015). To our knowledge, however, no direct correlation between changes in land use and mangrove nutrient status has been determined. This study primarily focuses on the relationship between land use and nutrient status of mangrove forests on three islands in southern Thailand. We anticipate that the amount of available nutrients will be higher for catchments with greater anthropogenic activity. This hypothesis is based on the idea that compared with natural systems, disturbed catchments will export more nutrients, experience accelerated erosion and have a reduced capacity for nutrient retention (Vitousek & Melillo, 1979; Reef *et al.*, 2010). Although it is not possible to correlate mangrove nutrient status to one isolated form of land use, the study allows for an integrated, landscape-scale comparison of mangroves with differentially impacted catchments for tests of nutrient indicators operating at different time-scales.

Including nutrient status indicators that reflect differences in nutrient availability over different time-scales is important because collectively they provide a more reliable view of the ecosystem, compared with approaches that utilize indicators indicative of only a single time-scale. The three indicators used in this study were chosen for their practicality in the field and their expected response to land use changes. First, direct nutrient measurements from porewater and sediment are greatly influenced by daily events, including tidal inundation and rainfall, and thus integrate over the shortest timespan with daily fluctuations (Lee *et al.*, 2008). These parameters therefore display the greatest spatial and temporal variability (Lee & Joye, 2006; Jennerjahn *et al.*, 2009; Reef *et al.*, 2010). Second, stable isotope signatures of sesarmid crabs reflect the stable isotope signatures of their diet sources (Peterson & Fry, 1987), and can therefore provide information on the origin of nitrogen in the system. This is because a high $\delta^{15}N$ signature is associated with high nitrogen contents and high inputs of anthropogenic nitrogen into the system (Fry *et al.*, 2000; Teichberg *et al.*, 2010). This variable is an indicator of a longer period of nutrient uptake than the abiotic parameters, generally on the order of a few months (Gearing, 1991; Lorrain *et al.*, 2002). Third, the composition of mangrove leaves reflects the longest period of nutrient uptake, ranging from around six months to a year (Boto & Wellington, 1983; Feller *et al.*, 2003b). In addition to reflecting environmental nutrient levels, mangrove leaf $\delta^{15}N$ signature can also provide information on the natural vs. anthropogenic origin of the nitrogen (Barile, 2004; Lapointe *et al.*, 2005). Furthermore, leaf nitrogen resorption efficiency can provide information on foliar nitrogen economy and thus on the general nitrogen availability around the trees (Feller *et al.*, 2003a). It is expected that, in this multiple time-scale analysis, long-term indicators are more reliable for indicating nutrient status than their short-term counterparts (van Katwijk *et al.*, 2011).

MATERIALS AND METHODS

The study sites chosen in Phuket and Phang Nga provinces of southern Thailand provided good examples of mangrove forests with differing anthropogenic influences in their respective catchments areas. Field measurements were conducted in November 2011 in eight mangrove forests on the islands of Phuket, Koh Yao Yai and Koh Yao Noi (Figure 1, Table S1). The mangroves were all classified as tidal, according to Woodroffe (1992). Seagrass beds were found adjacent to all study sites, although they were less developed for site 3 (on Phuket Island). Coral reefs were only present next to the Koh Yao Yai sites 6 and 8. The tidal range was approximately 1.75 m throughout Phang Nga Bay (Khokiattiwong *et al.*, 1991).

The climate is monsoonal with a dry season from November to April and a wet season lasting from May to October. Mean annual rainfall and temperature are 2300 mm and 28 °C, respectively. Temperature varies little year-round, with March being the hottest month (29 °C) and January being the coldest (27 °C). 75% of the yearly precipitation falls during the wet season, with September being the wettest (400 mm). The driest month is April with only 30 mm of precipitation. The soil of the Phuket catchment areas consisted mostly of sedimentary rock (mud stone, siltstone and sandstone), with small areas of granite on the higher parts. The catchments in the Koh Yao sites contained sedimentary rock only (Ampaiwan *et al.*, 2009). At the time of study, the land use on all three islands was largely natural forest and rubber plantations, particularly on steeply sloped lands. Other land uses included rice paddies, shrimp and fish farms, cleared ground and urbanized areas. Rubber tree plantations and tourism (the latter particularly in Phuket) have largely replaced tin mining as a major source of income in the area. Phuket Island was more developed and urbanized than the other two islands, of which Koh Yao Noi was more developed than Koh Yao Yai. During the last few years the entire study area has become more developed, with increasing urbanization, agriculture encroaching into terrestrial forest and shrimp farms encroaching on mangrove forests (Hossain *et al.*, 2009).

Catchment Area Land Use Composition and Measuring Points

The borders of the catchment area of each study site were delineated in ArcMap Geographic Information Services (GIS) v.9·2, using the digital elevation data from the area. Using Quickbird, WorldView-1 and WorldView-2 satellite imagery, the land use in the catchment area was classified as mangrove

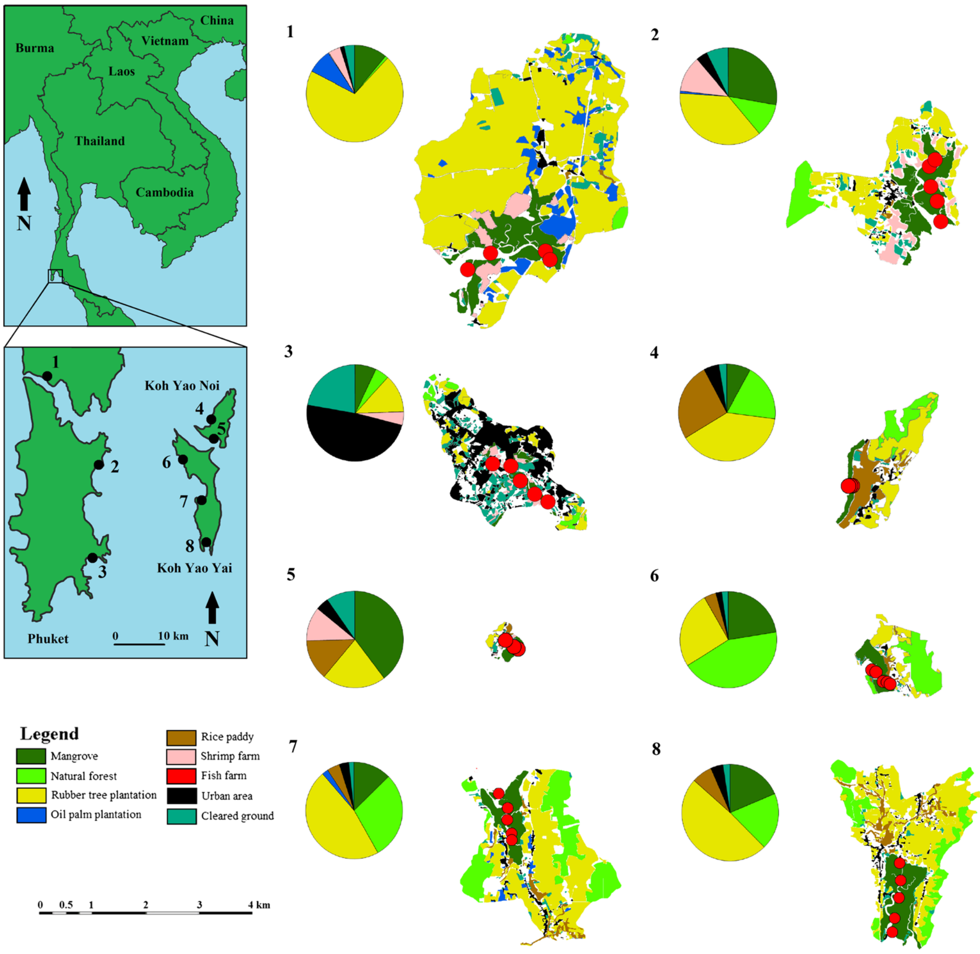

Figure 1. Study site location and land use composition of the study sites used during this study. Study sites are indicated as black dots on the map showing Phuket Island, and sampling points are indicated as red dots in the individual catchment areas.This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

forest, natural tropical evergreen forest, rubber or palm oil plantations (henceforth grouped as plantations), rice paddies, shrimp and fish farms, cleared land or urban areas. Areas for these land uses were then calculated in ArcMap Geographic Information Services (GIS) v.9·2.

At each study site, measuring points were located along the tidal creek running through the mangrove forest. These ranged from the most seaward point where the creek reaches the ocean (0% up the tidal creek) through the most landward point where the creek begins (100% up the tidal creek); three points were located in between (25, 50 and 75%). For the best accessibility, sites were sampled starting at the interior of the forest at high tide then following the retreating tide seaward. All measuring points were located within 10 m of the tidal creek in the forest. Indicators were only measured at three points (0, 50 and 100%) at sites 4 and 5 because of the small size of the mangroves in those areas and the corresponding close proximity of measuring points. The most seaward point at site 1 was also not measured because of high tide levels which rendered the site inaccessible.

Mangrove Forest Nutrient Status

Abiotic parameters: porewater and sediment sampling

Three replicate porewater samples were collected at each measuring point from the upper 10 cm of the sediment, in the active root zone at each measuring point using tension lysimeters. Immediately after sampling, samples (between 50 and 100 ml) were analyzed for pH and redox potential using a handheld multiprobe meter (YSI 556MPS). Afterwards, they were stored in polyethylene containers and transported to the field laboratory where they were frozen until analysis. Samples were analyzed for nitrate (NO_3^-), nitrite (NO_2^-), dissolved silica (DSi) and ortho-phosphate (PO_4^{3-}), using a DR2800 portable spectrophotometer (Hach Lange GmbH, Germany) and Hach Lange powder pillows. Porewater NO_3^-, NO_2^-, DSi and PO_4^{3-} were measured with the Cadmium reduction, Diazotization, Silicomolybdate and the PhosVer 3 (Ascorbic Acid) methods respectively (Hach Lange GmbH, Germany). Ammonium, the dominant form of nitrogen in mangrove forests (Reef *et al.*, 2010), was unfortunately not included in the analyses because of technical problems.

Three sediment samples were also collected at each measuring point by inserting a handheld PVC core 5 cm into the soil. These samples were then oven-dried in the field laboratory at 60–70 °C for at least 48 h before they were stored temporarily. The organic carbon potentially lost from drying at 60–70 °C was not deemed to significantly affect TOC values. Within a month, the samples were taken to NIOZ Yerseke, the Netherlands for analysis. The samples were first ground, using a mixer mill (Retsch, type MM301), after which the carbonates were removed by acidification (Nieuwenhuize *et al*., 1994). Samples were then measured for total organic carbon (TOC) and total nitrogen (TN) content using a Flash EA 1112 Elemental Analyzer (Thermo Finnigan).

Mangrove crab isotopes

Three to five individuals of the sesarmid crab *Perisesarma erythrodactyla* (hereafter mentioned as 'sesarmid crabs'), with a carapace width ranging from 10 to 25 mm, were hand caught at the majority of measuring points. It was attempted to catch five crabs at each measuring point, but fewer crabs were caught at the most seaward points, which were often inundated and seldom showed signs of crab presence. For this reason, no crabs were caught at sites 1 and 4 because of high tide levels at the time of sampling. Crabs were taken to the field laboratory where they were dissected. Only muscle tissue was extracted for isotope analysis. Structures such as the hepatopancreas and gonad tissue were avoided because they have high turnover rates and are therefore less reliable for reflecting the long term $\delta^{15}N$ signature of the crab's diet (Hesslein *et al*., 1993; Lorrain *et al*., 2002). Muscle tissue was rinsed with deionized water and oven-dried at 60–70 °C for at least 48 h. Samples were then stored dry and transported to NIOZ. The ^{15}N stable isotope signatures were measured using a Delta V Advantage isotope ratio mass spectrometer (Thermo Finnigan) that was coupled, via a ConFlo III interface (Thermo Finnigan), to the Flash EA 1112 Elemental Analyzer (Thermo Finnigan).

Mangrove leaf samples

Three fresh green leaf and three decomposing brown leaf samples were collected at each measuring point. Each sample consisted of five mangrove (*Rhizophora apiculata*, hereafter mentioned as 'mangrove') leaves that were either hand-picked from five separate living trees (i.e. green leaves) of heights ranging from 3 to 7 m or collected from the water and sediment (i.e. brown leaves). Before further analyses, brown leaves were rinsed with deionized water to remove any attached sediment. The samples were oven-dried in the field laboratory at 60–70 °C for at least 48 h before they were stored and transported within a month to the NIOZ. The leaves were ground, using a mixer mill (Retsch, type MM301), and TOC and TN were measured using a Flash EA 1112 Elemental Analyzer (Thermo Finnigan). Leaf nitrogen resorption efficiency was calculated using the formula in Feller *et al*. (2003a). ^{15}N stable isotopes of the green leaf samples were measured using the same methods as described for the mangrove crab tissue samples.

Statistical Analysis

The Shapiro–Wilk test was used to verify that measured parameters were normally distributed, although the power of the test was low because of the small sample size. Data were then checked for equality of error variances using Levene's test. Significant differences between groups were assessed using one-way ANOVA with a Tukey post-hoc test for equal variances or using a Welch test and a Games–Howell post-hoc test for non-equal variances. Relationships between different parameters were defined using the Pearson correlation coefficient and tested for significance using a two-tailed *t*-test.

Multivariate analyses of the different measured parameters ('response variables') and the land use in the catchment area ('explanatory variables') were performed in Canoco for Windows version 4·5 (ter Braak & Smilauer, 2002). Because the response curve of the response variables could be best described by a linear response model rather than a unimodal model, principal component analysis (PCA) was performed. Occasional missing values were substituted by median values, after Ter Braak & Smilauer (2002).

RESULTS

Within and Among-Site Variability

Porewater, sediment, mangrove leaves and sesarmid crab tissue parameters displayed great variability among sites (Table I). Abiotic parameters varied more among sites (almost a factor 10 for porewater ortho-phosphate (Table I)), than biotic parameters. Although redox and pH values varied slightly between study sites (Figure S1), no significant differences were observed. Porewater nitrate, ortho-phosphate and dissolved silica increased significantly in the landward direction at sites 3, 7 and 8, respectively ($r = 0{\cdot}93$, $p = 0{\cdot}022$; $r = 0{\cdot}89$, $p = 0{\cdot}043$; $r = 0{\cdot}908$, $p = 0{\cdot}033$ respectively, Figure S1). Brown mangrove leaf TOC content and sediment C:N ratio decreased significantly in the landward direction at sites 6 and 8 respectively ($r = -0{\cdot}903$, $p = 0{\cdot}036$; $r = -0{\cdot}931$, $p = 0{\cdot}022$ respectively, Figure S1). While TOC content did not vary significantly between green and brown mangrove leaves ($p = 0{\cdot}150$), leaf N content was significantly ($p < 0{\cdot}01$) higher in green leaves, which also caused the significantly ($p < 0{\cdot}01$) lower C:N ratio of green leaves. Furthermore, the positive relationship between mangrove leaf $\delta^{15}N$ signature and nitrogen content, which is often cited in literature (Fry *et al*., 2000; Teichberg *et al*., 2010), was also found during this study ($r = 0{\cdot}389$, $p = 0{\cdot}021$, Figure S1). Sesarmid crab $\delta^{15}N$ signatures were also significantly ($p < 0{\cdot}01$) higher than those of green mangrove leaves.

Relationship between land use and Mangrove Nutrient Status

Significant linear correlations were found between total area occupied by all forms of land use, except shrimp and fish farms, and parameters indicative of nutrient status (Table II). The mangrove leaf indicators, particularly green mangrove leaf $\delta^{15}N$ signature, displayed the most (15) significant relationships with land use. The abiotic indicators had less significant relationships with land use (3), while sesarmid crab tissue $\delta^{15}N$ showed none at all (Table II).

Area increases of anthropogenically impacted landscapes, in particular cleared and urban areas, were generally positively correlated with indicators of nutrient-rich conditions such as high mangrove leaf $\delta^{15}N$ values. Furthermore, the

Table I. Site average for all measured parameters, values are presented as mean ± S.E. Different letters indicate significant differences between sites at $p \leq 0{\cdot}05$

Variables	1 Phuket	2 Phuket	3 Phuket	4 Koh Yao Noi	5 Koh Yao Noi	6 Koh Yao Yai	7 Koh Yao Yai	8 Koh Yao Yai
Porewater nutrients								
Nitrate (μM)	0·40 ± 0·17	0·15 ± 0·05	0·16 ± 0·05		0·41 ± 0·19	0·24 ± 0·07	0·22 ± 0·08	0·25 ± 0·11
Nitrite (μM)	0·29 ± 0·10	0·30 ± 0·09	0·27 ± 0·10		0·11 ± 0·03	0·19 ± 0·04	0·12 ± 0·04	0·15 ± 0·03
Silica (μM)	136·25 ± 27·4	96·21 ± 7·6	70·95 ± 12·6		212·92 ± 35·9	87·1 ± 14·4	149·62 ± 42·7	143·83 ± 32·6
Ortho-phosphate (μM)	23·31 ± 5·93^{a}	15·76 ± 4·3^{abc}	17·46 ± 4·18^{ac}		5·55 ± 2·30^{bc}	2·61 ± 0·33^{b}	6·03 ± 1·98^{bc}	7·42 ± 4·84^{bc}
Sediment								
TOC (%)	2·57 ± 0·44	4·98 ± 0·39	2·20 ± 0·37	1·361 ± 0·47	3·09 ± 1·50	3·86 ± 0·42	2·83 ± 0·32	2·19 ± 0·21
TN (%)	0·13 ± 0·03^{ab}	0·22 ± 0·0^{a}	0·11 ± 0·0^{b}	0·06 ± 0·0^{b}	0·13 ± 0·06^{ab}	0·17 ± 0·02^{ab}	0·13 ± 0·02^{ab}	0·11 ± 0·01^{ab}
C:N ratio	20·36 ± 1·08	22·16 ± 0·87	19·36 ± 1·18	23·60 ± 5·32	17·64 ± 2·47	23·35 ± 1·11	21·02 ± 0·54	20·45 ± 1·57
Brown mangrove leaves								
TOC (%)	42·25 ± 0·79	41·06 ± 0·33	41·14 ± 0·33	42·29 ± 0·53	40·87 ± 0·35	41·89 ± 0·31	41·36 ± 0·26	41·61 ± 0·36
TN (%)	0·30 ± 0·01^{a}	0·33 ± 0·01^{ab}	0·42 ± 0·02^{b}	0·39 ± 0·01^{ab}	0·29 ± 0·02^{ab}	0·32 ± 0·01^{a}	0·35 ± 0·02^{ab}	0·34 ± 0·01^{ab}
C:N ratio	142·79 ± 5·5^{a}	129·11 ± 5·3^{a}	99·96 ± 4·0^{b}	123·48 ± 13·1^{ab}	147·70 ± 13·4^{a}	130·94 ± 2·9^{a}	122·4 ± 5·15^{ab}	124·0 ± 2·22^{ab}
Resorption efficiency	0·70 ± 0·02	0·66 ± 0·03	0·62 ± 0·01	0·61 ± 0·07	0·69 ± 0·01	0·64 ± 0·02	0·61 ± 0·02	0·68 ± 0·02
Green mangrove leaves								
TOC (%)	41·49 ± 0·60	41·79 ± 0·76	41·18 ± 0·34	42·35 ± 0·32	42·17 ± 0·50	42·25 ± 0·41	42·15 ± 0·37	42·02 ± 0·27
TN (%)	1·05 ± 0·06	0·95 ± 0·05	1·11 ± 0·05	1·01 ± 0·04	0·94 ± 0·06	0·91 ± 0·05	0·90 ± 0·05	1·08 ± 0·04
C:N ratio	41·27 ± 2·50	44·37 ± 1·59	37·96 ± 1·78	42·33 ± 1·50	46·19 ± 3·34	48·19 ± 2·50	49·36 ± 3·73	39·76 ± 1·56
$\delta^{15}N$ (‰)	3·80 ± 0·39^{ab}	3·18 ± 0·30^{a}	5·75 ± 0·83^{b}	3·76 ± 0·31^{ab}	2·76 ± 0·45^{a}	2·78 ± 0·19^{a}	3·19 ± 0·15^{a}	2·77 ± 0·22^{a}
Sesarmid crab tissue								
$\delta^{15}N$ (‰)		8·81 ± 0·76^{a}	8·83 ± 0·24^{a}		4·48 ± 0·29^{b}	6·00 ± 0·12^{b}	6·65 ± 0·38^{ab}	4·79 ± 0·51^{b}

Table II. Pearson's *r* values for all significant linear relationships between the percentage of a particular type of land use in the catchment area and parameters indicative of nutrient status (the rationale for the division of parameters can be found in the Introduction). Green values show significant positive relationships between the percentage of land use and the parameter, while red values indicate significant negative relationships. All presented relationships were found to be significant at the $p \leq 0{\cdot}05$ level, while relationships with asterisks were significant at the $p \leq 0{\cdot}01$ level. Only parameters and (combinations of) forms of land use for which significant relationships were found are shown.

	Parameters indicative of nutrient-poor conditions			Parameters indicative of nutrient-rich conditions				
	Green leaf org C	Green leaf C:N ratio	Brown leaf C:N ratio	Porewater PO_4^{3-}	Sediment N	Green leaf N	Green leaf $\delta^{15}N$	Brown leaf N
Natural Forest (NF)	0·790	0·766		-0·942**				
Mangrove (M)+NF	0·725	0·762		-0·860		-0·767	-0·746	
M+NF+Plantation (P)							-0·785	
Rice Paddy (RP)					-0·813			
Cleared ground (C)	-0·717						0·788	
Urban area (U)			-0·782				0·902**	0·728
C+U	-0·722		-0·718				0·883**	

area occupied by urban and cleared lands was negatively correlated with indicators of nutrient-poor conditions, such as a high mangrove leaf TOC content and C:N ratio (Table II). In contrast, mangrove and natural forest areas were positively correlated with indicators of nutrient-poor conditions such as a high mangrove leaf TOC content and C:N ratio. The area occupied by mangrove and natural forest was negatively correlated with porewater ortho-phosphate concentrations, mangrove leaf TN content and $\delta^{15}N$ signature, indicators of nutrient-rich conditions. No significant relationships were found for plantations (rubber and palm oil) and aquaculture (shrimp and fish farms).

Principal component analysis provided further distinction between natural and anthropogenically impacted land uses (Figure 2). Mangroves and natural forests are situated in the upper left quadrant of the plot together with indicators of nutrient-poor conditions, including a high green and brown mangrove leaf C:N ratio. Anthropogenically impacted land uses, such as cleared and urban areas, were located on the opposite side, in the lower right part of the plot. Indicators of nutrient-rich conditions, such as high porewater ortho-phosphate concentrations, were also positioned in this section of the plot. These findings illustrate the correlations between land use and nutrient status elaborated in the previous paragraph (Table II). Agricultural land uses, including plantations and rice paddies, plot in the lower left section. Thus, they show more similarity with natural forms of land use than with cleared and urban areas. Dissolved silica and nitrate also plot in this section. The first two PCA-axes in this plot explained 63·7% (41·6% and 22·1% respectively) of the variation in response data.

DISCUSSION

The results of this study stress the importance of selecting appropriate nutrient status indicators. With 15 significant relationships, mangrove leaf TOC and TN content and $\delta^{15}N$ signature correlated the most with land use. These were also the only indicators that showed significant relationships with anthropogenically impacted forms of land use including cleared and urban areas. The abiotic indicators that integrated over shorter timespans (i.e. porewater

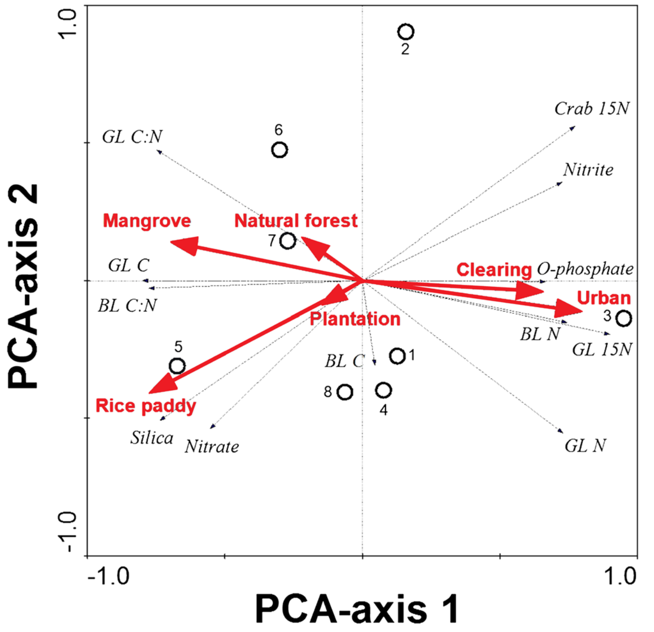

Figure 2. Principal component analysis triplot of the parameters indicative of nutrient status (black dotted arrows) and the types of land use (red solid arrows); the study sites are indicated as circles. GL and BL represent green and brown *R. apiculata* leaves and C and N carbon and nitrogen. Crab 15N represents *P. erythrodactyla* tissue stable isotope signature. Only the forms of land use which have significant relationships with parameters indicative of nutrient status are shown. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

nutrients and sediment TOC and TN content) only showed three significant correlations with land use. These abiotic parameters tend to fluctuate over time, and they are therefore less reliable long-term indicators of nutrient status (Lee & Joye, 2006; Jennerjahn *et al*., 2009). Additionally, these abiotic parameters also integrated information on a small spatial scale, because they are heavily influenced by local conditions such as redox potential, which in turn is affected by factors that act on a very small scale, including crab activity and duration of tidal inundation (Reef *et al*., 2010). Our study therefore suggests that long-term indicators, such as mangrove leaf nutrient content and stable isotope signature, are better indicators to identify mangrove nutrient status than indicators that integrate over shorter timespans.

Because the Phuket sites are generally richer in nutrients than the Koh Yao Noi and Koh Yao Yai sites, region-specific effects might also cause the differences in nutrient status among the different sites. For example, the Phuket sites are richer in nutrients because the surrounding ocean in that region is richer in nutrients because of a general higher nutrient export from Phuket to the surrounding ocean. For silica, differences in catchment geology might also cause different silica weathering rates. Porewater ortho-phosphate concentrations were indeed higher on Phuket island than on the Koh Yao islands (18·8 µM vs. 5·4 µM), but other parameters that integrate over longer timespans displayed fewer region-specific patterns. In addition, the PCA plot indicates that study sites 1, 4 and 8 (located on Phuket, Koh Yao Noi and Koh Yao Yai respectively) are more similar to each other than to the other study sites in the region. Site-specific effects therefore appear to be more important than regional effects in determining the nutrient status of the mangroves. For silica, no great difference in weathering rates is expected between the different soil types found in our study area (granite vs. sedimentary rock) (Bluth & Kump, 1994). Finally, the spatial distribution of different indicator values, along a seaward-landward gradient, suggests that landward points are generally richer in nutrients than seaward points. This trend suggests that nutrients mostly originate from the inland catchment area, not from the ocean. It can thus be concluded, because of the relatively even spread of the different forms of land use and data from various long-term nutrient status indicators among our study sites, that the differences in nutrient status among sites were probably caused by site specificity and not regional phenomena.

Relationship between Land Use and Mangrove Nutrient Status

The general trends, supported by all analyses, were that mangroves in catchments with substantial anthropogenic influence show increased nutrient availability, and mangroves situated in less disturbed catchments displayed a low nutrient availability.

The area of mangroves and natural forest in the catchment was found to be positively correlated with mangrove leaf TOC and C:N ratio and negatively correlated with porewater phosphate concentrations, leaf TN and $\delta^{15}N$ signature. These relations indicate lower nitrogen and phosphorus availability as well as a lower input of anthropogenic nitrogen, which might be caused by a higher retention and lower export of nutrients by these natural land use types (Vitousek & Melillo, 1979; Reef *et al*., 2010).

Rubber and palm oil plantations in the catchment were also correlated with nutrient-poor conditions in mangroves, although PCA analysis indicated that this effect was not as profound as that caused by the presence of forest area. Plantations at the study sites are therefore expected to export very few nutrients to the adjacent mangrove forests. Based on previous studies, rice paddies were expected to create nutrient-rich conditions in downstream mangroves by leaching nitrogen into the surrounding ecosystems (Choudhury & Kennedy, 2005). However, our study showed no correlation between rice paddy area and indicators of mangrove nutrient status. This lack of correlation is possibly because of low fertilizer inputs or the use of organic amendments, reducing nutrient runoff (Yang *et al*., 2008; Srinivasarao *et al*., 2014), during rice cultivation in this area.

The amount of cleared or urbanized area was negatively correlated with mangrove leaf TOC and C:N ratio. It was also positively correlated with mangrove leaf nitrogen content and $\delta^{15}N$ signature. These correlations reflect a higher nitrogen availability, which was probably created by inputs of anthropogenic nitrogen. In general, urban areas are often a major source of nutrient enrichment of coastal areas and mangroves (Carpenter *et al*., 1998; Basnyat *et al*., 1999). Correlations between the area of cleared land and nutrient availability are probably related to increased surface runoff following clearance and reduced soil infiltrability (Likens *et al*., 1978; Ziegler *et al*., 2004). It should be noted that the high amounts of urban and cleared area from study site 3 play a large role in these correlations, a phenomenon we did not observe for other types of land use and other study sites. The lack of relationships between mangrove nutrient status and the area devoted to shrimp and fish farming was surprising at first sight. These types of aquaculture have been reported to export nutrients originating from applied shrimp feed or trash fish to surrounding ecosystems (Briggs & Funge-Smith, 1994; Wu, 1995). The area devoted to these practices, or the intensity in which they are operated, however, is likely not sufficient to effect mangrove nutrient status at our sites. Prior research in the study area (site 2) also observed that shrimp farms had a very limited impact on mangrove nutrient status (Kristensen & Suraswadi, 2002). Other factors, such as the position of aquaculture in the tidal creek and the temporal variability in nutrient loading may further have limited the effect aquaculture had on mangroves.

The observation that mangrove forests in catchments with substantial anthropogenic influence were richer in nutrients than those in less disturbed catchments does not only have great effects on the forests themselves, but also potentially on adjacent ecosystems. In nutrient-enriched mangroves, a smaller portion of the received nutrients can be taken up by the trees and thus, a greater total amount is exported to the ocean (Boto & Wellington, 1988; Dittmar & Lara, 2001; Valiela & Cole, 2002), potentially affecting seagrass meadows and coral reefs (Gillis *et al*., 2014).

CONCLUSIONS

In this study we found that urbanization and land clearance in the catchment area can lead to nutrient enrichment in mangrove forests, with a potential consequence of contributing to a greater total amount of nutrients exported to coastal ecosystems. Furthermore, our study stresses the importance of selecting appropriate nutrient status indicators for monitoring and management of mangrove forests and adjacent ecosystems and for effective evaluation of the effect of (changes in) land use in catchment areas.

ACKNOWLEDGEMENTS

Our thanks go to Kalaya Kantawong, Nam Wani, Boonchai Phrathaan and Bedeen Phrathaan for their logistic help with the fieldwork in Thailand and to the NIOZ analysts for the laboratory measurements. This study was funded by the Building with Nature project (NUS SDWA Grant #R303-001-020-414 & R109-000-131-133). The first author would like to thank the Nijmegen University Fund for providing an individual travel grant. Furthermore, we would like to thank the two anonymous reviewers, whose comments have significantly improved the manuscript.

REFERENCES

Ampaiwan T, Hisada KI, Charusiri P. 2009. Lower Permian glacially influenced deposits in Phuket and adjacent islands, peninsular Thailand. *Island Arc* **18**: 52–68. DOI: 10.1111/j.1440-1738.2008.00653.x

Anthony KRN, Maynard JA, Diaz-Pulido G, Mumby PJ, Marshall PA, Cao L, Hoegh-Guldberg O. 2011. Ocean acidification and warming will lower coral reef resilience. *Global Change Biology* **17**: 1798–1808. DOI: 10.1111/j.1365-2486.2010.02364.x

Barile PJ. 2004. Evidence of anthropogenic nitrogen enrichment of the littoral waters of east central Florida. *Journal of Coastal Research* **20**: 1237–1245. DOI: 10.2112/04-0212.1

Basnyat P, Teeter LD, Flynn KM, Lockaby BG. 1999. Relationships between landscape characteristics and nonpoint source pollution inputs to coastal estuaries. *Environmental Management* **23**: 539–549. DOI: 10.1007/s002679900208

Beckert KA, Fisher TR, O'Neil JM, Jesien RV. 2011. Characterization and comparison of stream nutrients, land use, and loading patterns in Maryland Coastal Bay watersheds. *Water, Air, and Soil Pollution* **221**: 255–273. DOI: 10.1007/s11270-011-0788-7

Bluth GJS, Kump LR. 1994. Lithologic and climatologic controls of river chemistry. *Geochimica Et Cosmochimica Acta* **58**: 2341–2359. DOI: 10.1016/0016-7037(94)90015-9

Borrelli P, Marker M, Schutt B. 2015. Modelling post-tree-harvesting soil erosion and sediment deposition potential in the Turano river basin (Italian Central Apennine). *Land Degradation & Development* **26**: 356–366. DOI: 10.1002/ldr.2214

Boto KG, Wellington JT. 1983. Phosphorus and nitrogen nutritional-status of a northern Australian mangrove forest. *Marine Ecology-Progress Series* **11**: 63–69. DOI: 10.3354/meps011063

Boto KG, Wellington JT. 1988. Seasonal-variations in concentrations and fluxes of dissolved organic and inorganic materials in a tropical, tidally-dominated, mangrove. *Marine Ecology-Progress Series* **50**: 151–160. DOI: 10.3354/meps050151

Bouma TJ, Friedrichs M, van Wesenbeeck BK, Temmerman S, Graf G, Herman PMJ. 2009. Density-dependent linkage of scale-dependent feedbacks: a flume study on the intertidal macrophyte *Spartina anglica*. *Oikos* **118**: 260–268. DOI: 10.1111/j.1600-0706.2008.16892.x

Briggs MRP, Funge-Smith SJ. 1994. A nutrient budget of some intensive marine shrimp ponds in Thailand. *Aquaculture Research* **25**: 789–811. DOI: 10.1111/j.1365-2109.1994.tb00744.x

Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* **8**: 559–568. DOI: 10.2307/2641247

Choudhury A, Kennedy IR. 2005. Nitrogen fertilizer losses from rice soils and control of environmental pollution problems. *Communications in Soil Science and Plant Analysis* **36**: 1625–1639. DOI: 10.1081/css-200059104

Dittmar T, Lara RJ. 2001. Driving forces behind nutrient and organic matter dynamics in a mangrove tidal creek in North Brazil. *Estuarine, Coastal and Shelf Science* **52**: 249–259. DOI: 10.1006/ecss.2000.0743

Duarte CM. 2002. The future of seagrass meadows. *Environmental Conservation* **29**: 192–206. DOI: 10.1017/s0376892902000127

Duke NC, Meynecke JO, Dittmann S, Ellison AM, Anger K, Berger U, Cannicci S, Diele K, Ewel KC, Field CD, Koedam N, Lee SY, Marchand C, Nordhaus I, Dahdouh-Guebas F. 2007. A world without mangroves? *Science* **317**: 41–42. DOI: 10.1126/science.317.5834.41b

Feller IC, McKee KL, Whigham DF, O'Neill JP. 2003a. Nitrogen vs. phosphorus limitation across an ecotonal gradient in a mangrove forest. *Biogeochemistry* **62**: 145–175. DOI: 10.1023/a:1021166010892

Feller IC, Whigham DF, McKee KL, Lovelock CE. 2003b. Nitrogen limitation of growth and nutrient dynamics in a disturbed mangrove forest, Indian River Lagoon, Florida. *Oecologia* **134**: 405–414. DOI: 10.1007/s00442-002-1117-z

Fialho RC, Zinn YL. 2014. Changes in soil organic carbon under Eucalyptus plantations in Brazil: a comparative analysis. *Land Degradation & Development* **25**: 428–437. DOI: 10.1002/ldr.2158

Fry B, Bern AL, Ross MS, Meeder JF. 2000. δ15N studies of nitrogen use by the red mangrove, Rhizophora mangle L. in South Florida. *Estuarine, Coastal and Shelf Science* **50**: 291–296. DOI: 10.1006/ecss.1999.0558

Furukawa K, Wolanski E, Mueller H. 1997. Currents and sediment transport in mangrove forests. *Estuarine, Coastal and Shelf Science* **44**: 301–310. DOI: 10.1006/ecss.1996.0120

Gearing JN. 1991. The study of diet and trophic relationships through natural abundance 13C. In *Carbon isotope techniques*, Colemang DC, Fry B (ed). Academic Press: London, UK; 201–218.

Gillis LG, Bouma TJ, Jones CG, van Katwijk MM, Nagelkerken I, Jeuken CJL, Herman PMJ, Ziegler AD. 2014. Potential for landscape-scale positive interactions among tropical marine ecosystems. *Marine Ecology Progress Series* **503**: 289–303. DOI: 10.3354/meps10716

Hesslein RH, Hallard KA, Ramlal P. 1993. Replacement of sulfur, carbon, and nitrogen in tissue of growing broad whitefish (*Coregonus nasus*) in response to a change in diet traced by δ34S, δ13C, and δ15N. *Canadian Journal of Fisheries and Aquatic Sciences* **50**: 2071–2076. DOI: 10.1139/f93-230

Hossain MZ, Tripathi NV, Gallardo WG. 2009. Land used dynamics in a marine protected area system in lower Andaman coast of Thailand, 1990–2005. *Journal of Coastal Research* **25**: 1082–1095. DOI: 10.2112/08-1058.1

Howarth RW, Fruci JR, Sherman D. 1991. Inputs of sediment and carbon to an estuarine ecosystem—influence of land-use. *Ecological Applications* **1**: 27–39. DOI: 10.2307/1941845

Jennerjahn TC, Nasir B, Pohlenga I. 2009. Spatio-temporal variation of dissolved inorganic nutrients related to hydrodynamics and land use in the mangrove-fringed Segara Anakan Lagoon, Java, Indonesia. *Regional Environmental Change* **9**: 259–274. DOI: 10.1007/s10113-008-0077-1

Khokiattiwong S, Limpsaichol P, Petpiroon S, Sojisuporn P, Kjerfve B. 1991. Oceanographic variations in Phangnga Bay, Thailand, under monsoonal effects. *Phuket Marine Biological Center Research Bulletin* **55**: 43–76.

Kristensen E, Suraswadi P. 2002. Carbon, nitrogen and phosphorus dynamics in creek water of a southeast Asian mangrove forest. *Hydrobiologia* **474**: 197–211. DOI: 10.1023/a:1016544006720

Lapointe BE, Barile PJ, Littler MM, Littler DS. 2005. Macroalgal blooms on southeast Florida coral reefs II. Cross-shelf discrimination of nitrogen sources indicates widespread assimilation of sewage nitrogen. *Harmful Algae* **4**: 1106–1122. DOI: 10.1016/j.hal.2005.06.002

Lee RY, Joye SB. 2006. Seasonal patterns of nitrogen fixation and denitrification in oceanic mangrove habitats. *Marine Ecology-Progress Series* **307**: 127–141. DOI: 10.3354/meps307127

Lee RY, Porubsky WP, Feller IC, McKee KL, Joye SB. 2008. Porewater biogeochemistry and soil metabolism in dwarf red mangrove habitats (Twin Cays, Belize). *Biogeochemistry* **87**: 181–198. DOI: 10.1007/s10533-008-9176-9

Likens GE, Bormann FH, Pierce RS, Reiners WA. 1978. Recovery of a deforested ecosystem. *Science* **199**: 492–496. DOI: 10.1126/science.199.4328.492

Lopez F, Garcia MH. 2001. Mean flow and turbulence structure of open-channel flow through non-emergent vegetation. *Journal of Hydraulic Engineering-Asce* **127**: 392–402.

Lorrain A, Paulet Y-M, Chauvaud L, Savoye N, Donval A, Saout C. 2002. Differential δ13C and δ15N signatures among scallop tissues: implications for ecology and physiology. *Journal of Experimental Marine Biology and Ecology* **275**: 47–61. DOI: 10.1016/S0022-0981(02)00220-4

Lovelock CE, Ball MC, Martin KC, Feller IC. 2009. Nutrient enrichment increases mortality of mangroves. *Plos One* **4**: e5600. DOI: 10.1371/journal.pone.0005600

Mitsch WJ, Gosselink JG. 2000. The value of wetlands: importance of scale and landscape setting. *Ecological Economics* **35**: 25–33. DOI: 10.1016/s0921-8009(00)00165-8

Nagelkerken I, van der Velde G, Gorissen MW, Meijer GJ, van't Hof T, den Hartog C. 2000. Importance of mangroves, seagrass beds and the shallow coral reef as a nursery for important coral reef fishes, using a visual census technique. *Estuarine, Coastal and Shelf Science* **51**: 31–44. DOI: 10.1006/ecss.2000.0617

Naidoo G. 2009. Differential effects of nitrogen and phosphorus enrichment on growth of dwarf Avicennia marina mangroves. *Aquatic Botany* **90**: 184–190. DOI: 10.1016/j.aquabot.2008.10.001

Nepf HM. 1999. Drag, turbulence, and diffusion in flow through emergent vegetation. *Water Resources Research* **35**: 479–489. DOI: 10.1029/1998wr900069

Nieuwenhuize J, Maas YEM, Middelburg JJ. 1994. Rapid analysis of organic carbon and nitrogen in particulate materials. *Marine Chemistry* **45**: 217–224. DOI: 10.1016/0304-4203(94)90005-1

Othman M. 1994. Value of mangroves in coastal protection. *Hydrobiologia* **285**: 277–282. DOI: 10.1007/bf00005674

Peterson BJ, Fry B. 1987. Stable isotopes in ecosystem studies. *Annual Review of Ecology and Systematics* **18**: 293–320. DOI: 10.1146/annurev.ecolsys.18.1.293

Quartel S, Kroon A, Augustinus P, Van Santen P, Tri NH. 2007. Wave attenuation in coastal mangroves in the Red River Delta, Vietnam. *Journal of Asian Earth Sciences* **29**: 576–584. DOI: 10.1016/j.jseaes.2006.05.008

Reef R, Feller IC, Lovelock CE. 2010. Nutrition of mangroves. *Tree Physiology* **30**: 1148–1160. DOI: 10.1093/treephys/tpq048

Robertson AI, Duke NC. 1990. Mangrove fish-communities in tropical Queensland, Australia—spatial and temporal patterns in densities, biomass and community structure. *Marine Biology* **104**: 369–379. DOI: 10.1007/bf01314339

Srinivasarao C, Venkateswarlu B, Lal R, Singh AK, Kundu S, Vittal KPR, Patel JJ, Patel MM. 2014. Long-term manuring and fertilizer effects on depletion of soil organic carbon stocks under pearl millet-cluster bean-castor rotation in western India. *Land Degradation & Development* **25**: 173–183. DOI: 10.1002/ldr.1158

Teichberg M, Fox SE, Olsen YS, Valiela I, Martinetto P, Iribarne O, Muto EY, Petti MAV, Corbisier TN, Soto-Jimenez M, Paez-Osuna F, Castro P, Freitas H, Zitelli A, Cardinaletti M, Tagliapietra D. 2010. Eutrophication and macroalgal blooms in temperate and tropical coastal waters: nutrient enrichment experiments with Ulva spp. *Global Change Biology* **16**: 2624–2637. DOI: 10.1111/j.1365-2486.2009.02108.x

ter Braak CJF, Smilauer P. 2002. Canoco reference manual and Canodraw for Windows user's guide: software for canonical community ordination (version 4.5). Microcomputer power, Ithaca, NY.

Valiela I, Bartholomew M, Giblin A, Tucker J, Harris C, Martinetto P, Otter M, Camilli L, Stone T. 2014. Watershed deforestation and down-estuary transformations alter sources, transport, and export of suspended particles in Panamanian mangrove estuaries. *Ecosystems* **17**: 96–111. DOI: 10.1007/s10021-013-9709-5

Valiela I, Cole ML. 2002. Comparative evidence that salt marshes and mangroves may protect seagrass meadows from land-derived nitrogen loads. *Ecosystems* **5**: 92–102. DOI: 10.1007/s10021-001-0058-4

van Katwijk MM, van der Welle MEW, Lucassen ECHET, Vonk JA, Christianen MJA, Kiswara W, al Hakim II, Arifin A, Bouma TJ, Roelofs JGM, Lamers LPM. 2011. Early warning indicators for river nutrient and sediment loads in tropical seagrass beds: a benchmark from a near-pristine archipelago in Indonesia. *Marine Pollution Bulletin* **62**: 1512–1520. DOI: 10.1016/j.marpolbul.2011.04.007

Vitousek PM, Melillo JM. 1979. Nitrate losses from disturbed forests —patterns and mechanisms. *Forest Science* **25**: 605–619.

Wolanski E, Mazda Y, Ridd P. 1992. Mangrove hydrodynamics. In *Tropical mangrove ecosystems*, Robertson AI, Alongi DM (eds). American Geophysical Union: Washington D.C; 43–62.

Woodroffe C. 1992. Mangrove sediments and geomorphology. In *Tropical mangrove ecosystems*, Robertson AI, Alongi DM (eds). American Geophysical Union: Washington D.C.; 7–41.

Wu RSS. 1995. The environmental impact of marine fish culture: towards a sustainable future. *Marine Pollution Bulletin* **31**: 159–166. DOI: 10.1016/0025-326x(95)00100-2

Yang YG, He ZL, Stoffella PJ, Yang XE, Graetz DA, Morris D. 2008. Leaching behavior of phosphorus in sandy soils amended with organic material. *Soil Science* **173**: 257–266. DOI: 10.1097/SS.0b013e31816d1edf

Zhao X, Wu P, Gao X, Persaud N. 2015. Soil quality indicators in relation to land use and topography in a small catchment on the loess plateau of China. *Land Degradation & Development* **26**: 54–61. DOI: 10.1002/ldr.2199

Ziegler AD, Giambelluca TW, Tran LT, Vana TT, Nullet MA, Fox J, Vien TD, Pinthong J, Maxwell JF, Evett S. 2004. Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: evidence of accelerated overland flow generation. *Journal of Hydrology* **287**: 124–146. DOI: 10.1016/j.jhydrol2003.09.027

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web site.