Land use change affects coastal water quality around Borneo

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Abstract – Environmental change usually occurs at centennial or greater time scales, except when driven by human activities. Sediment input into freshwater and marine ecosystems is a result of natural processes. However, mining, deforestation, unsustainable agricultural practices can greatly increase sediment input into marine and aquatic systems. This study analyzed the particular year-to-year changes of the water characteristics in Borneo's proximity using MERIS water color data from 2003-2010 with a semi-automatic approach by combining BEAM, GRASS and R. According to this time series analysis of the coastal waters around Borneo, water quality shows spatial heterogeneity but corresponds to land development patterns in the last 8 years. Land cover was found to explain downstream water quality, with dominance of variables related to land development. Further development on the island of Borneo, without proper planning. could continue to worsen water quality around Borneo and deteriorate conditions for coral reefs and other coastal ecosystems.

Keywords: remote sensing, water color, sediments, MERIS, degradation

1. INTRODUCTION

Terrestrial changes on the earth surface can be observed across the globe (e.g. Balmford et al. 2005, Foley et al. 2005, Laurance et al., 2002), as well as changes in water quality and coral reef degradation. Water integrity shifts are partly independent from each other; however, many patterns of coastal and inland waters are due to pollution run-off (Edinger et al. 1998; Dosskey et al., 2010). Remote sensing has broad applications and implications for conservation efforts, because it offers an affordable source of high quality data that has special meaning for environmental change monitoring efforts, especially for marine waters. Moreover, the broad-scale interaction of coastal waters and land cover changes in the catchment areas of rivers can be analyzed by the means of remote sensing.

The wide-reaching benefits of healthy coastal ecosystems are multidimensional with relevance to economy, ecology, and livelihoods. As certain environmental issues and initiatives such as ecosystem services become clearer and more important, managers and government officials seek win-win situations for their economies and environment. Providing breeding grounds, nurseries, and security from predators, coastal and coral reef ecosystems not only represent a vital necessity to marine ecosystems and species, but also offer a handful of ecosystem services, such as storm protection, biodiversity, and carbon sequestration. Occurring in the photic zone, coral reef ecosystems are dependent on ample sunlight, are one of the world's most diverse ecosystems flourishing in oligotrophic waters, and rely on symbiotic, coralline algae to gather energy. This relationship is altered by changing water quality. Perturbations such as overfishing, disease, and pollution, force a shift in species composition and collapse of coral reef ecosystems (Bellwood et al, 2004; Edinger et al., 1998), and has reached a critical point in southeast Asia (Carone and Simoniello, 2009; Croke and Hairsine, 2006; Dodds and Oakes, 2008; Todd et al., 2010).

Relatively recent developments in remote sensing technologies has led to increased ability to monitor and detect changes in ocean water color. The Envisat Medium Resolution Imaging Spectrometer (MERIS), which became operational in 2002 and offered fully global coverage starting 2003, offers five water color products, two of which were used in this study. Important for judging water quality, the reprocessed product bands total suspended matter (TSM) and colored dissolved organic matter (CDOM), also known as yellow substance or gelbstoff, were investigated. Their utility lies in the ability to estimate turbidity and judge the trophic state of water, both of which are very important for marine ecosystems. The final aim is to investigate which, and where land-based sources of sediments and nutrients are most important at the outflow points of rivers.

1.2 Study region

This study investigated the implications of land use change and development around Island of Borneo, the third largest island of the world and home to one of the richest terrestrial ecosystems, constituting the cornerstone of the important Indo-Malayan ecoregion (Olson, 2001). Borneo's coasts also harbor one the richest marine ecosystems, bounding the so-called "coral triangle" in the northern coastal waters and it. Land-use change on Borneo is mainly related to increasing pulp production and oil palm agriculture (Ziegler & Weber, 2009). The effects on land can be drastic and, when considering the carbon balance, even have global implications. Furthermore, the effects of deforestation and industrialization are important for downstream water integrity (Edinger et al. 1998; Dosskey et al., 2010). Land cover was assessed and quantified on the Island of Borneo for the years 2007 & 2008, and divided into hydrological catchments (Shapiro et al, 2011). Water color data were summarized for the period 2003-2010. The land cover characteristics were investigated for their influence on the water quality directly off of the coast, starting at the river mouth in order to possibly offer management recommendations for land development. We hypothesize that land-cover influences can explain a great deal of the variance observed in the water quality at the river outflow points around Borneo.

2. METHODS

MERIS imagery data (Reduced Resolution) provided by the European Space Agency (ESA) from the period 2003-2010

(385 images) were selected for least cloud cover.. Processing was done using the BEAM software (Brockmann Consulting, 2010). The two reprocessed bands, TSM & CDOM were extracted and pixel values were removed if they had a relevant (poor) quality flag (ESA, 2006). Subset images were subsequently imported in Geographic Resource Analysis Support System (GRASS) for temporal analysis. The commands carried out from all software were given from R, the statistical programming language (R Core Development Team, 2010).

2.1 Analyses

Intra-annual analyses were performed for each year of the time series (mean, minimum, maximum, standard deviation). The result for each particular raster cell is a function of the cell value across the time-period. The intra-annual result raster images were then taken and analyzed again across all 8 years. A linear regression was performed on each set of intra-annual results to determine the behavior in the 8-year interannual period.

Land cover data from 2007 and 2008 were obtained from SarVision LLC and World Wildlife Fund. Climate data were taken from the Worldclim dataset (Hijmans et al. 2005). Watershed delineation polygons were from Hydrosheds (Lehner et al., 2008). Physical, biotic, and human land cover types and characteristics that could be related erosion and subsequent downstream transport were summarized for each catchment (Table 1; see Shapiro et al. 2011 for more details). Rectangular outflow sample polygons were created at the river mouth/outflow point of each major catchment extending perpendicularly to land, in order to consistently sample the potential downstream impact area from each watershed. Downstream area was determined to be perpendicular to shore, unless it flowed into a bay, in order to assess the unbiased magnitude of outflow related sediments and water quality from shore. Water color data within the polygons was extracted and averaged for each polygon. Each sample polygon corresponded to 250 raster cells with 1040m by 1160m resolution (1.46 km^2), equaling a total area of 364 km^2 per polygon. Each polygon was paired with its respective catchment, and land cover characteristics and water color data were compared across Borneo (see table 1 for variables compared). Statistical analyses were carried out in the following manner: collinear variables (Spearman's rho > 0.5) were excluded based on their individual ability to explain variation, ranked via an information criterion (Akaike, 1974), and were then investigated for their importance using hierarchical partitioning (Chevan and Sutherland, 1991;) in explaining the observed water color variation that was observed during the year 2008. Multiple regression analyses were performed to investigate the relationship of the explanatory variables and the mean yellow substance for 2008. As these analyses deal with spatial data from outflow points that are near others, spatial structure was incorporated into the linear regression model.

3. RESULTS AND DISCUSSION

The investigation of the yearly dynamics yielded many interesting maps of the studied bands. In Figure 1, a general increase can be observed of coastal CDOM standard deviation. Increases in standard deviation from 2003-2010 tend to be near shore.

The exploratory analysis results using hierarchical partitioning of the relationship between intra-annual water color characteristics and land cover yielded many important explanatory variables. Both TSM and CDOM share explanatory variables, which are the proportion of watershed in a logging concession (log_prop), proportion of riparian area that is forested (rip_prop), mean soil loss index (mean_rusle), proportion of bare ground to total catchment area (p_bare), proportion of swamps (swamp_prop) to total catchment area, the km of roads in a catchment (km_roads), proportion of crop cover, and the mean erosivity factor (mean_rfact).

Table 1. Land cover characteristics investigated for explanatory ability of water color.

Variable	Description
Area_km2	Total area of watershed (km2)
Mean sdr	A function of watershed size, slope length
mean_prec	Average precipitation (mm) in watershed
mean_slope	Average slope (%) of watershed
mean_rfact	Average rainfall runoff erosivity factor in watershed
mean_cfact	Average cover factor in watershed
mean_kfact	Average soil erodibility of watershed
mean_vuln	Average physical vulnerability in watershed (rfactor x k factor x slope)
mean_rusle	Average RUSLE in watershed
mean_elev	Average elevation (m) of the watershed
forest	Total natural forest area
for_prop	Total natural forest area / watershed area
log_prop	Proportion of forest in logging concession
log_acc	Accessibilty to logging concessions
rip_area	Total amount of riparian area that was natural forest in 2007
rip_prop	Riparian area in forest/total riparian area
swamp_prop	swamp forest / watershed area
mang_prop	Mangrove / watershed area
lowland	lowland forest / watershed area
upland	upland forest / watershed area
lower_mont	lower montane forest / watershed area
upper_mont	upper montane forest / watershed area
plant	Total plantation area (from 2007 land cover)
p_plant	Plantation area / watershed area
mean_roadd	Watershed road density index
km_roads	Total length of roads in watershed
road_acc	Road accessibility
p_bare	Total bare area / watershed area
p_crops	Total crop area / watershed area
fires2008	Number of 2008 fire events in watershed
burnt	Burnt area in 2008

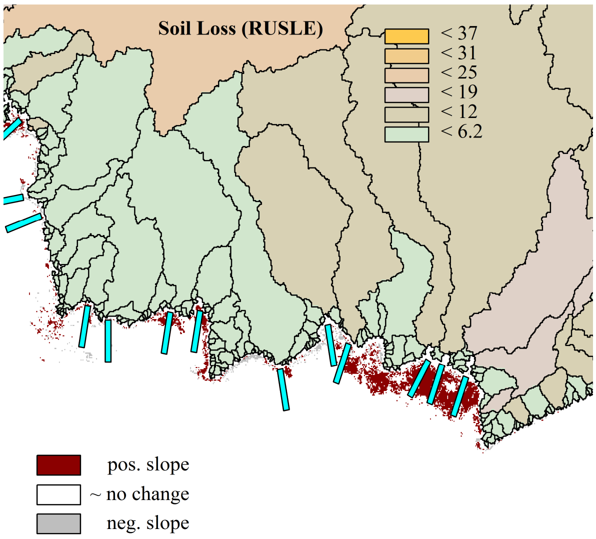

Figure 1. The standard deviation of CDOM results of the interannual time series (2003-2010) regression analysis. Results were placed into three categories: negative slope (<-0.1), no slope (-0.1> slope <0.1), and positive slope (<-0.1).

Further investigations with multiple regression yielded similar relationships between land cover and coastal water quality. Average CDOM exhibited a decent amount of heteroscedasticity, which was removed by placing CDOM on a natural logarithmic scale. In the resulting equation (not shown), all of the terms are significant or highly significant and explain a large portion of the observed variation (R^2 = 0.56). On a logarithmic scale, CDOM increases greatly with increasing proportion of bare soil (coef. of 1.5, $p<0.0005$). Positive effects are also seen with increasing erosivity factor (mean_rfact, coef. of 0.0014, $p<0.000001$) and the square of the average annual soil loss of a catchment ($mean\_rusle^2$, coef. of 0.0036, $p<0.05$) in a catchment. The interaction of erosivity - proportion of bare soil exhibit a small negative effect on CDOM (coef. of 0.0002, $p<0.0001$). In summary, CDOM increases with the proportion of bare ground, erosivity, and the annual soil loss. In order to illustrate interactions, a regression tree was fitted (not shown) using binary recursive partitioning, and indicates that proportion the soil erosivity factor explains the variation of CDOM best when CDOM is lower. However, annual soil loss and the soil erosivity factor explain the higher values of mean CDOM. Given the complexity of the question being asked and the many possible influences as well as natural variability, the model appears to embody a dominant relationship between land cover and downstream water quality. Analysis of TSM bands and their statistical summary statistics also yield a similar model structure, with a dominant effect of proportion of bare ground.

The linear modeling results offer some simple insight into the specific processes that are responsible for the water color characteristics near outflow points. However, most of the variables resulting from the exploratory data analyses exist because of human activities (see Shapiro et al. 2011). This simple fact emphasizes that management decisions play an extremely important role in maintaining the proper function of ecosystems. According to these results, management decisions concerning land development should take every possible measure to prevent land use which creates bare ground on the Island of Borneo. This includes the integration of ‘wise’ policy and corresponding regulatory mechanisms in order to prevent land clearing practices such as clear-cutting and fire.

4. CONCLUSIONS

Conservation efforts worldwide are constantly pitted against economic agendas and underfunding. Many conservation efforts are also at the same time financially viable but poorly aimed. This study demonstrates the utility of remote sensing data to aide conservation efforts in developing countries, which tend to have a low sampling density and rapidly increasing human population density. It also highlights the use of open source software in performing data analysis, and gives an example for conducting low-budget research with arguably the best analytical tools.

Finally, the subject of Borneo illustrates the need to rapidly increase efficient conservation efforts, while highlighting opportunities to synergetically satisfy political agendas, such as REDD+. This study also serves to illustrate the severity and scale of the effects resulting from poor land stewardship on Borneo. Results from this study emphasize that ‘wise’, local development planning would reduce biodiversity loss and loss of ecological resilience at local scales as well as at regional scales. Satellite imagery and statistical analysis are not necessary to deduce that, when forests are clear-cut, soil will erode into the rivers, which will have an effect on those living downstream. However, it can provide objective identification of the drivers of environmental change and offer options to streamline measures to prevent further degradation. Integrated development planning and watershed management is becoming critically important on the Island of Borneo.

References

Akaike, H., (1974) A new look at the statistical model identification. IEEE Transactions on Automatic Control. 19:716-723.

Balmford, A., Bennun, L., ten Brink, B., Cooper, D., Côté, I. M., Crane, P., Dobson, A., Dudley, N., Dutton, I., Green, R. E., Gregory, R. D., Harrison, J., Kennedy, E. T., Kremen, C., Leader-Williams, N., Lovejoy, T. E., Mace, G., May, R., Mayaux, P., Morling, P., Phillips, J., Redford, K., Ricketts, T. H., Rodríguez, J. P., Sanjayan, M., Schei, P. J., van Jaarsveld, A. S. & Walther, B. A. (2005) The Convention on Biological Diversity's 2010 Target. Science, 307, 212-213.

Bellwood, D.R., Hughes, T.P., Folke, C. & Nyström, M. (2004) Confronting the coral reef crisis. Nature, 429, 827-33.

Carone, M. T. and T. Simoniello. (2009) Watershed influence on fluvial ecosystems: an integrated methodology for river water quality management. Env. Mon. and Assessment, 152: 327-342.

Chevan, A. and M. Sutherland. (1991). Hierarchical Partitioning. The Am. Stat. 45 (2): 90-96.

Croke, J. C., P. B. Hairsine. (2006) Sediment delivery in managed forests: a review. Env. Rev., 14: 59-87.

Dodds, W. K., R. M. Oakes. (2008) Headwater influences on downstream water quality. Env. Mgmt. 41: 367-377.

Dosskey, Michael G., P. Vidon, N. P. Gurwick, C.J. Allan, T.P. Duval, and R. Lowrance, 2010. The Role of Riparian Vegetation in Protecting and Improving Chemical Water Quality in Streams. J. of the Am. Water Resources Asc. (JAWRA) 46:261-277.

Edinger E.N., J. Jompa, G. V. Limmon, W. Widjatmoko, M.J. Risk (1998) Reef degradation and coral biodiversity in Indonesia: effects of land-based pollution, destructive fishing practices and changes over time. Mar. Pollut. Bull. 36:617–630

European Space Agency 2006. MERIS Product Handbook. Issue 2.1

Fabricius, K. E. (2005) Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Mar. Pollut. Bull. 50:125–146.

Fitzherbert, E. B, M. J. Struebig, A. Morel, F. Danielsen, C. A. Brühl, P. F. Donald, and D. Phalan. (2008) How will oil palm expansion affect biodiversity? TREE, 23 538-545.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N. & Snyder, P. K. (2005) Global Consequences of Land Use. Science, 309, 570-575.

Halpern, B.S., Walbridge, S., Selkoe, K. a, Kappel, C.V., Micheli, F., D□Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R. & Watson, R. (2008) A global map of human impact on marine ecosystems. Science, 319, 948-52.

Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. of Climatology 25: 1965-1978.

Langner, A., J Miettinen, and F. Siegert. (2007) Land cover change 2002-2005 in Borneo and the role of fire derived from MODIS imagery. Global Change Biology, 13: 2329-2340.

Langner, A., and F. Siegert. (2009). Spatiotemporal fire occurrence in Borneo over a period of 10 years. Global Change Biology. 15: 48-62.

Laurance, W. F., Lovejoy, T. E., Vasconcelos, H. L., Bruna, E. M., Didham, R. K., Stou□er, P. C., Gascon, C., Bierregaard, R. O., Laurance, S. G.,Sampaio, E., (2002) Ecosystem Decay of Amazonian Forest Fragments: a 22-Year Investigation. Cons. Biol. 16 (3), 605–618.

Lehner, B., Verdin, K., Jarvis, A. (2008): New global hydrography derived from spaceborne elevation data. EOS, Transactions, AGU, 89(10): 93-94.

Mac Nally R. and C. Walsh, (2004). Hierarchical Partitioning Public Domain Software. Biodiv. and Cons. 13:659-660.

Neteler M. and H. Mitasova, (2008) *Open Source GIS: A GRASS GIS Approach*. The International Series in Engineering and Computer Science: Volume 773. 406 pages, Springer, New York

NOAA (2008). Nonpoint-Source Pollution and Erosion Comparison Tool (N-SPECT): Technical Guide. Version 1.5.

Olson, D. M., E. Dinerstein, E. D. Wikramanayake, N. D. Burgess, G. V. N. Powell, E. C. Underwood, J. A. D'Amico, I. Itoua, H. E. Strand, J. C. Morrison, C. J. Loucks, T. F. Allnutt, T. H. Ricketts, Y. Kura, J. F. Lamoreux, W. W. Wettengel, P. Hedao, K. R. Kassem, 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth. BioScience 51:933-938.

R Core Team. (2010) R: A language and environment for statistical computing. R Foundation for Statistical Computing Vienna Austria, 1.

Renard, K. G. (1997). Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). USDA, Agricultural Research Service.

Shapiro, A., J. Morrison, S. Wulfraat., 2011, Borneo Watershed Atlas. World Wildlife Fund Science Technical Report. (in press).

Soto, I., Andréfouët, S., Hu, C., Muller-Karger, F.E., Wall, C.C., Sheng, J. & Hatcher, B.G. (2009) Physical connectivity in the Mesoamerican Barrier Reef System inferred from 9 years of ocean color observations. Coral Reefs, 28, 415-425

Todd, P.A., X Ong, L. M. Chou. (2010). Impacts of pollution on marine life in Southeast Asia. Biodivers. Conserv. 19:1063-1082

Ziegler, A. D., J. N. Negishi, R. Sidle, T. Gomi, S. Noguchi, A. R. Nik. (2007) Persistence of road runoff generation in a logged catchment in Peninsular Malaysia. Earth Surf. Proc. and Landforms, 32: 1947-1970

Ziegler S. and P. Weber, 2009. Das Schwinden der Tieflandregenwälder auf Borneo – Eine Untersuchung zum Lebensraumverlust des Borneo-Orang-Utans (Pongo pygmaeus). Zeitschrift des Kölner Zoos, 52nd yr.

Internet References

Brockmann Consulting GmbH, (2010) BEAM Software. <http://www.brockmann-consult.de/cms/web/beam/>

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