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Global assessment of damage to coastal ecosystem vegetation from tropical storms

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This study reports on the first comprehensive global assessment of tropical storm (TS) impacts on coastal ecosystem vegetation along the landfall pathways of major hurricanes, cyclones and typhoons using satellite data of land cover vegetation for the years 2006 to 2012. Wind damage has been shown to reduce live vegetation pools of carbon, accelerate ecosystem respiration fluxes of carbon dioxide and thereby represent a potentially significant positive feedback to terrestrial greenhouse gas emissions. Based on quarterly detection of changes in Moderate Resolution Imaging Spectroradiometer (MODIS) satellite vegetation greenness, all major TS pathways during the time period were ranked in terms of area of vegetation damage observed. Comparison of vegetation disturbance area along major TS pathways to average rates of disturbance within the same coastal zones (for years during which no TS activity was observed) verified the satellite capability to detect TS ecosystem impacts.

1. Introduction

In recent decades, economic damage from tropical storms (TS) around the world has increased notably (Emanuel 2005; Weinkle, Maue, and Pielke 2012). Intense cyclones and hurricanes can extensively damage coastal vegetation and have the potential to alter ecosystem structure and function by accelerating rates of biomass transfer (from live standing pools to down and decomposing pools) and associated nutrient cycles (Brokaw and Walker 1991; Whigham et al. 1991). Quantifying these TS disturbance areas on a global level is crucial to evaluating regional carbon budgets, and for improving land use management decisions following TS events.

Damage to coastal vegetation can result from a combination of high wind speeds, waves from storm surges and floods following heavy rainfall. Several previous studies have quantified vegetation disturbance produced by selected TS events (Zimmerman et al. 1994; Zhao, Allen, and Sharitz 2006; Chambers et al. 2007; Negrón-Juárez et al. 2010; Rogan et al. 2011; Lewis and Bannar-Martin 2012). A small set of post-storm survey studies have examined the relationships between field-measured tree mortality and vegetation cover indices that can be computed from the satellite sensor data from Landsat and the Moderate Resolution Imaging Spectroradiometer (MODIS), which in turn can be broadly applied to regional forest ecosystems impacted by TS events (Chambers et al. 2007; Rogan et al. 2011).

The purpose of this study was to conduct the first comprehensive global assessment of TS impacts on coastal ecosystem vegetation along the landfall pathways of major hurricanes,

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*Corresponding author. Email: chris.potter@nasa.gov cyclones and typhoons using MODIS remote sensing data from the years 2006 to 2012. A consistent method to detect changes in the MODIS satellite vegetation index (VI), based on the previously published studies by Potter et al. (2005, 2007) and Rogan et al. (2011), within landfall zones was applied to all major TS events during this seven-year period, ranked by their maximum recorded wind speeds over land areas. Vegetation damage areas were assessed along major TS pathways and compared to disturbance rates within the same coastal zones during years when no TS activity was observed.

2. Methods and methods

A new MODIS product called the 'Quarterly Indicator of Cover Change' (QUICC) has been implemented at NASA Ames Research Center. The QUICC product is based on comparison of MODIS global VI images at the exact same time period each year (ending of March, June, September and December) in consecutive years. Seasonal variation in perennial canopy cover can be controlled for in the QUICC product's quarterly baseline.

The 5600-m resolution global MODIS QUICC product identifies all land areas that have lost at least 40% of their perennial green vegetation cover over the past year. This level of green canopy loss is commonly associated with major forest wildfires and deforestation events detected using previously published satellite time-series data analyses (Potter et al. 2005, 2007), which constitute the verified foundation for the QUICC methodology. Timeliness of the QUICC product enables organizations that are monitoring forests and woodlands anywhere in the world, with the capacity to respond within weeks or months (rather than years) to threats to protected reserves and parks.

Collection 5 MODIS data sets beginning in the year 2005 were obtained from NASA's Land Processes Distributed Active Archive Center (LP-DACC 2007) site. MODIS enhanced vegetation index (EVI) layers (MOD13C2 Terra vegetation indices) were obtained from the spatial composites of the gridded 16-day 1-km MOD13A2 products. MODIS EVI has been calculated from red, blue and NIR bands as described by Huete et al. (2002). EVI data were obtained as a level-3 product projected on a 0.05° (5600-m) geographic climate modelling grid (CMG). Cloud-free global EVI coverage at 5600-m spatial resolution was achieved by replacing cloudy image values with the historical MODIS time-series EVI record.

For this study, the December QUICC products at the 5600-m resolution of vegetation cover loss were assessed within a 50-km buffer zone surrounding the vector landfall pathways of all major TS events recorded between 2006 and 2012 in the IBTrACS (International Best Track Archive for Climate Stewardship) global tropical cyclone best track data record (Knapp et al. 2010). The IBTrACS vector line for each TS was first intersected with the continental land boundary to determine the landfall location and TS pathway inland (Figure 1). The date of each TS path, its maximum wind speed (MWS in knots) and minimum central pressure (MSP in mb) at landfall were assigned from the IBTrACS database. According to the WMO (1983), the maximum sustained wind is a 10-min average wind speed at 10-m height above level ground. The major TS pathways selected all had a recorded MWS of greater than 65 knots (120 km hr^{-1}) at landfall. As exceptions, owing to the potential for snow and deciduous forest cover in the northeastern United States and Canada in December, Hurricanes Florence (in 2006) and Sandy (in 2012) were not included in this analysis.

Tests of statistical significance between the areas of QUICC vegetation change points during TS seasons and the average area disturbed in those years between the TS events at any given landfall path location were carried out using the two-sample Mann–Whitney *U*-test and the Kolmogorov–Smirnov (K–S) test. These non-parametric methods compare the

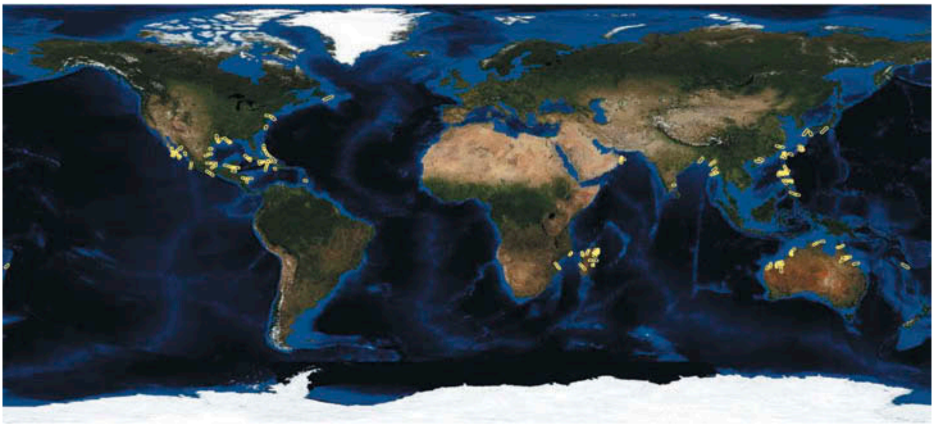

Figure 1. IBTrACS major TS events recorded from 2006 to 2012 showing the 50-km landfall buffer zones as yellow-coloured polygons.

cumulative distributions of two data sets (Lehmann 2006) and do not assume that data were sampled from Gaussian distributions (nor any other defined distributions).

The K–S test reports the maximum difference between the two cumulative distributions and calculates a *p*-value from that difference and the sample sizes. It tests the null hypothesis that both groups were sampled from populations with identical distributions according to different medians, variances or outliers. If the K–S *p*-value is small (i.e. <0.05), it can be concluded that the two groups were sampled from populations with significantly different distributions. To achieve an adequate sample size for these tests of significance, all TS were considered together in the distribution comparisons.

3. Results and discussion

A consistently higher QUICC vegetation disturbance area was detected within 50-km buffer zones surrounding the vector landfall paths of most major TS events recorded between 2006 and 2012, compared to the QUICC vegetation disturbance areas within the same 50-km landfall buffer zones during years when no major TS events were recorded (Table 1). The ratio of QUICC areas from the year of each TS to all other years in the 2006 to 2012 period averaged 2.4:1, and the ratio exceeded 4:1 in 13 of the 76 major TS reported.

The *p*-value for both the Mann–Whitney *U*-test and the K–S ranked sum comparison was less than 0.035, such that it could be concluded that the two groups of QUICC points (TS year and the average for all other years) were sampled from populations with significantly different distributions. Only three major TS events were associated with zero QUICC points detected within their 50-km landfall buffer zones (Table 1). These three TS events were not among the strongest TS events in the 2006–2012 listing, since they were recorded with MWS at landfall of less than 91 knots and MSP higher than 935 mb.

Closer examination of the TS events that were associated with the most extensive vegetation disturbance area (of between 1700 and 7000 km^2 each) was headed by Cyclone Fanele (Figure 2), which made landfall along the southwestern coastline of Madagascar in 2009 where it destroyed many buildings and flooded large areas (OCHA 2009). Post-storm surveys of the dry tropical forest areas affected by TS Fanele were conducted by Lewis and Bannar-Martin (2012), who found that over 95% of trees experienced some

Table 1. Major TS events from 2006 to 2012 ranked by the area of vegetation disturbance from QUICC totals associated with the TS in the surrounding 50-km landfall buffer zone.

TS name	Year	WMO Wind speed (knots)	WMO Pressure (mb)	Ratio of QUICC points in year of TS to all other years	Detected area of vegetation disturbance (km^2)
Fanele	2009	90	942	4.41	6931
Yasi	2011	110	930	4.16	6805
Gustav	2008	125	943	2.48	2666
Irene	2011	105	957	1.65	2446
Monica	2006	135	917	1.48	2258
Ike	2008	115	945	2.12	2195
Durian	2006	90	940	5.17	1756
Alex	2010	90	948	3.61	1756
Nesat	2011	80	950	>2.0	1348
Isaac	2012	70	966	2.22	1066
Sidr	2007	115	944	3.92	1004
Nalgae	2011	95	935	>2.0	878
Xangsane	2006	85	940	7.09	815
Nanmadol	2011	90	945	12.50	784
Megi	2010	125	885	3.60	753
Favio	2007	95	935	0.45	659
Dolly	2008	75	967	1.85	659
Jokwe	2008	85	962	0.97	596
Dean	2007	110	935	1.85	533
Felix	2007	135	939	4.17	502
Lua	2012	85	935	2.91	502
Fengshen	2008	85	955	3.00	470
Bingiza	2011	85	958	>2.0	470
Jim	2006	80	955	1.79	439
Shanshan	2006	80	950	0.67	408
Karl	2010	110	956	5.20	408
Richard	2010	85	977	3.27	376
Bolaven	2012	90	925	>2.0	376
Clovis	2007	55	983	6.60	345
Norbert	2008	95	954	0.50	345
Saomai	2006	100	935	1.62	314
Cimaron	2006	100	920	0.55	314
George	2007	110	902	1.02	314
Sepat	2007	90	940	4.29	314
Humberto	2007	80	985	0.48	314
Ivan	2008	95	935	1.33	314
Jade	2009	60	975	5.00	314
Kompasu	2010	80	960	2.61	314
Roke	2011	80	950	1.62	314
Clare	2006	75	960	0.63	282
Ului	2010	80	967	0.29	282
Phet	2010	65	980	1.29	282
John	2006	95	958	0.30	251
Fanapi	2010	80	950	>2.0	251
Wipha	2007	100	925	2.80	220
Nargis	2008	90	962	0.68	188
Paloma	2008	125	951	>2.0	188
Jimena	2009	95	965	0.16	157
Heidi	2012	65	971	15.00	157
Indlala	2007	95	935	0.63	125

(*Continued*)

Table 1. (*Continued*).

TS name	Year	WMO Wind speed (knots)	WMO Pressure (mb)	Ratio of QUICC points in year of TS to all other years	Detected area of vegetation disturbance (km^2)
Sinlaku	2008	80	960	1.14	125
Rene	2010	65	980	2.40	125
Giri	2010	105	950	0.80	125
Jelawat	2012	90	930	12.00	125
Glenda	2006	70	962	0.49	94
Lane	2006	110	954	1.06	94
Henriette	2007	70	972	>2.0	94
Ida	2009	70	985	0.67	94
Hubert	2010	55	985	3.60	94
Tomas	2010	80	990	1.00	94
Jova	2011	85	974	1.50	94
Ernesto	2012	80	979	>2.0	94
Larry	2006	100	945	0.02	63
Mala	2006	90	966	>2.0	63
Chebi	2006	95	930	0.60	63
Gonu	2007	77	970	1.00	63
Usagi	2007	80	960	0.44	63
Fame	2008	70	972	0.25	63
Hagupit	2008	90	935	0.39	63
Magda	2010	110	925	0.12	63
Vicente	2012	80	950	0.29	63
Jangmi	2008	100	925	0.55	31
Carlotta	2012	90	976	3.00	31
Jaya	2007	75	965	0.00	0
Giovanna	2012	85	945	0.00	0
Sanba	2012	90	935	0.00	0

Note: Ratio '>2.0' indicates that one or less QUICC points were detected on average along 50-km landfall buffer zones during years other than the year of the corresponding TS event.

sort of damage (including 9% mortality), and that understory and emergent trees experienced significantly higher mortality than canopy trees.

Cyclone Yasi, which made landfall in northern Queensland, Australia, in 2011 (Figure 2), was detected as the next most destructive TS event (2006–2012) in terms of the area of coastal vegetation affected (covering more than 6800 km^2). The Yasi storm surge was estimated to have reached 7 m high and destroyed many structures along the coast, including sugar cane and banana plantations (Sun 2011). Hurricanes Gustav (2008) and Irene (2011) both made landfall across several Caribbean islands and then in different locations on the southern coast of the United States, each causing more than 2400 km^2 of detectable damage to inland vegetation, according to the QUICC product results (Figure 2). Survey assessments reported by Negrón-Juárez et al. (2010) found that flooded forest areas in Louisiana were not severely damaged by Hurricane Gustav, whereas non-flooded forests and seasonally flooded hardwood (e.g. cottonwood and boxelder) bottomlands were heavily damaged by the extreme winds, with as high as 70% tree mortality. The Hurricane Irene timber damage survey carried out by aircraft in 2011 reported impacted forest areas as 21% with light damage and 6% with moderate-to-heavy damage, again mainly in hardwood stands (NCFS 2011).

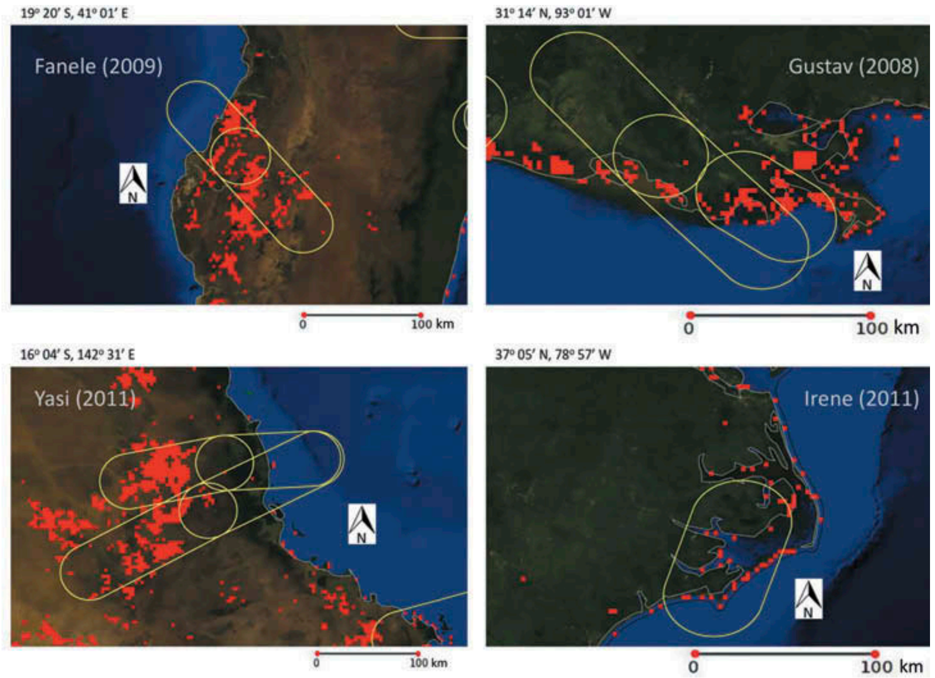

Figure 2. QUICC results (5600-m resolution pixels shaded in red for scales) along 50-km landfall buffer zones (as yellow-coloured polygons) associated with the most extensive vegetation disturbance areas of all major TS events recorded from 2006 to 2012. Geographic coordinates were shown for the northwestern corner point of each map.

The global relationship of MWS at landfall to area of vegetation disturbance from QUICC area summations (Table 1) showed a significant exponential correlation ($p < 0.01$), particularly at estimated MWS of greater than 100 knots at landfall (Figure 3). Given the fact that TS events can have varying wind speeds and direction patterns that would be influenced by local coastline geometry and inland topography (e.g. mountains, valleys, river courses), and that a 50-km buffer zone around the path of the storm may not cover the entire area of vegetation disturbance in every case, the strength of the relationship shown in Figure 3 may have been influenced by the inherent uncertainties in these two variables.

It is worth noting that the term forest or tree ‘damage’ refers to different levels of ecosystem disturbance in the numerous previous publications cited in this study, and consequently, the term is commonly ill-defined in many of these citations. For the purpose of clarity of the QUICC product evaluation, ‘damage’ is defined as a loss of the majority of canopy tree (leaf area) cover and loss (blow-down) of the majority of tree stems per unit forested area. This clear definition of terms should enable QUICC users to be informed of the potential advantages of the QUICC product, but also cautioned about the potential limitations to properly interpret the results.

Tree damage and mortality from intense storm events can result in measurable transfers of live standing wood biomass to down and dead carbon pools (McNulty 2002). If TS events increase in intensity or frequency in a warming climate, this shift in live to dead biomass stocks can reduce standing vegetation pools of carbon, accelerate ecosystem respiration fluxes of carbon dioxide and thereby represent a potentially significant positive feedback to terrestrial greenhouse gas emissions (Negrón-Juárez et al. 2010; Vargas 2012). Chambers et al. (2007), for example, estimated that Hurricane

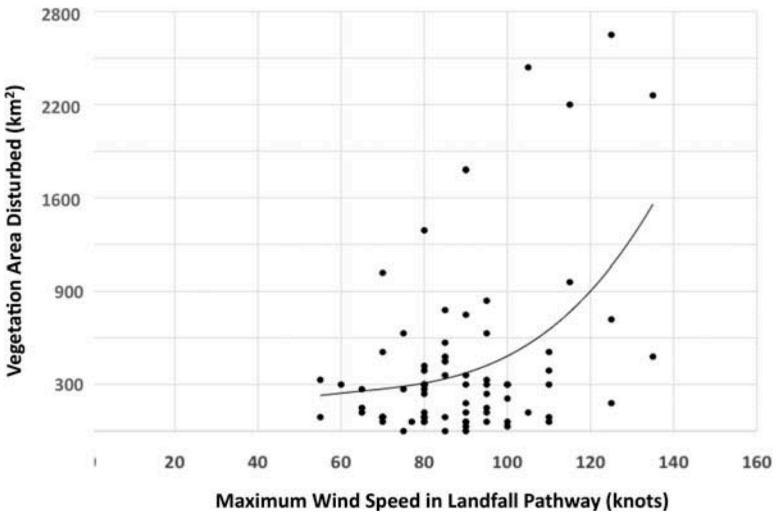

Figure 3. Total area (km^2) of QUICC 5600-m resolution pixels detected along TS 50-km landfall buffer zones versus MWS (knots) reported in landfall pathways in the IBTrACS database (as listed in Table 1). The two TS events detected with the largest areas of vegetation disturbance by QUICC image analysis were statistical outliers and therefore were not included in this plot, namely cyclones Fanele and Yasi. The positive exponential correlation was statistically significant at $p < 0.01$ ($n > 70$).

Katrina caused mortality or severe structural damage to 320 million trees, with a total biomass loss equivalent to 50–140% of the net annual US carbon sink in forest stands. Major changes in the land surface albedo can result from disturbed forest cover (Negrón-Juárez et al. 2008). There is also mounting historical evidence that strong hurricanes promote the subsequent occurrence of forest fires of higher than normal intensity (Myers and van Lear 1998; Liu, Lu, and Shen 2008). Therefore, validation of new methodologies that can quantify forest disturbance zones globally is a critical component in understanding the widespread impacts of large-scale TS disturbances.

The results of this worldwide assessment confirm that the MODIS QUICC product can reliably detect extensive tropical forest damage following extreme storm events. The QUICC methodology was conceived to be a computationally simple, early alert product, designed primarily to identify large areas of tropical forest disturbance. These features make timeliness the greatest advantage for QUICC users to identify possible new areas of deforestation and degradation. Subsequent accuracy assessments of QUICC products from human-caused deforestation must derive from site visits and surveys to verify the varied causes and consequences of tropical ecosystem change.

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