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Quantifying deforestation and forest degradation with thermal response

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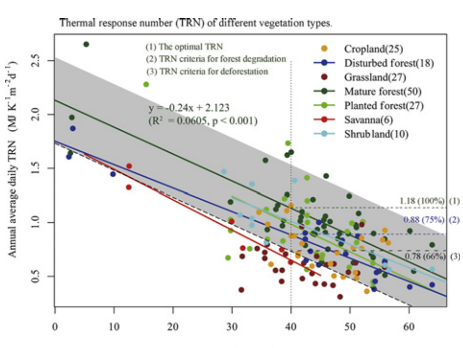
HIGHLIGHTS

- Deforestation and forest degradation reduce thermal buffer capacity of forests.
- A clear difference in thermal response exists between forests and non-forests.
- Thermal response allows quantification of forest degradation and deforestation.
- Forests are important for stabilizing local thermal environment.

GRAPHICAL ABSTRACT



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ABSTRACT

Deforestation and forest degradation cause the deterioration of resources and ecosystem services. However, there are still no operational indicators to measure forest status, especially for forest degradation. In the present study, we analysed the thermal response number (TRN, calculated by daily total net radiation divided by daily temperature range) of 163 sites including mature forest, disturbed forest, planted forest, shrubland, grassland, savanna vegetation and cropland. TRN generally increased with latitude, however the regression of TRN against latitude differed among vegetation types. Mature forests are superior as thermal buffers, and had significantly

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higher TRN than disturbed and planted forests. There was a clear boundary between TRN of forest and non-forest vegetation (i.e. grassland and savanna) with the exception of shrubland, whose TRN overlapped with that of forest vegetation. We propose to use the TRN of local mature forest as the optimal TRN (TRN_{opt}). A forest with lower than 75% of TRN_{opt} was identified as subjected to significant disturbance, and forests with 66% of TRN_{opt} was the threshold for deforestation within the absolute latitude from 30° to 55°. Our results emphasized the irreplaceable thermal buffer capacity of mature forest. TRN can be used for early warning of deforestation and degradation risk. It is therefore a valuable tool in the effort to protect forests and prevent deforestation.

1. Introduction

Deforestation and forest degradation are global environmental problems. Deforestation implies the transformation of a forest into another land cover type, whereas degraded forest has lost some of the ability to provide ecosystem services and resources (Sasaki and Putz, 2009). Both of these processes remove or reduce the multiple benefits of forest, such as the provision of biomass (including timber and non-timber products), food, and carbon sequestration as well as environmentally protective functions (Thompson et al., 2013; Trumbore et al., 2015). Many international organizations and programs focus on these issues. The FAO Global Forest Resource Assessment evaluates forest health and vitality based on areas of forest affected by various stresses (FAO, 2005, 2011). A UN *Programme on Reducing Emissions from Deforestation and Forest Degradation* (UN-REDD) was initiated in 2008 and the UN *Convention to Combat Desertification* (UNCCD) focuses on degradation in dry lands, while the UN *Framework Convention on Climate Change* (UNFCCC) concentrates on recovering degraded forests to mitigate climate change. All of these programs rely on operationally defining and monitoring deforestation and forest degradation.

Forest degradation is generally defined as "a reduction of the capacity of a forest to provide goods and services" (Simula, 2009). However, this definition is inadequate for decision-making. Many alternative criteria and indicators have been proposed, based on productivity, biological diversity, unusual disturbances, carbon storage, and the protective function of forests (Thompson et al., 2013). Among these indicators, canopy cover is often used because it is easily and accurately quantifiable (IPCC, 2003a; ITTO, 2002; UNFCCC, 2001). Carbon emissions or standing biomass are two other commonly used indicators that relate to ecosystem protective function (IPCC, 2003b, 2003c). However, area-based indicators can only detect deforestation or serious forest degradation when these processes already caused visually explicit impacts on forest structure. For example, LandTrendr, which is a time-series analysis of Landsat data, showed a range of errors especially where disturbance is subtle (Kennedy et al., 2010). Quantitative estimates of standing biomass or carbon emissions are affected by large uncertainties (Goetz et al., 2015) and might neglect other aspects of forest function, e.g. nutrient cycling (Trumbore et al., 2015).

Considering the abovementioned issues, a holistic indicator is needed to assess forest status. Canopy temperature is a proxy for interactions between physiological and physical processes (Niu et al., 2012). Previous research reported that land surface warming generally decreased with the increase of Normalized Difference Vegetation Index (NDVI): desert areas have the highest rates of increasing temperature (0.4 K/decade), tropical forests can maintain a stable canopy surface temperature, and areas of intermediate vegetation show moderate rates of increasing temperature (0.1–0.3 K/decade) (Lim et al., 2008). This implies that dense forests can therefore stabilize the local thermal environment. The thermal response to solar radiation is not only directly related to local thermal effects but also holistically reflects the status of forest by showing how energy is partitioned and used within a forest. From an energy balance perspective, the less energy is used for canopy heating, the more energy can be used for evapotranspiration and photosynthesis by forest (Gates, 2003; Kim et al., 2016; Schneider and Kay, 1994). It has been demonstrated that the thermal response of forest is associated with age, recovery and succession of vegetation (Lin et al., 2017; Luvall and Holbo, 1989). Canopy surface temperature and related indicators (e.g. crop water stress index and water deficit index) have been widely used to monitor drought stress and health in agricultural crops and forests (Christ et al., 2016; Jackson et al., 1981; Jimenez-Munoz et al., 2016; Kim et al., 2016; Maes and Steppe, 2012; Rashid et al., 1999), but its application to identify deforestation and forest degradation is still under study (Aerts et al., 2004; Gonzalez-Dugo et al., 2012; Kay et al., 2001; Kutsch et al., 2001; Lin et al., 2017; Maes et al., 2011). Temperature can change with variations in the amount of incident radiation, so the thermal buffer capacity (TBC, rate of temperature change) and thermal response number (TRN, the amount of energy required to change the surface temperature) were developed as surrogates for surface temperature.

In the present study, we use long-term meteorological data to analyse the thermal response to radiation of different vegetation types, and try to find criteria that can quantitatively distinguish deforestation and forest degradation.

2. Materials and methods

2.1. Data sources

Energy and carbon flux and meteorological data were retrieved from the FLUXNET database (http://fluxnet.ornl.gov/) for 163 sites (Fig. 1 and Appendix A). We classified seven vegetation types according to *International Geosphere-Biosphere Programme* (IGBP) classes and their status: mature forest (natural and healthy forests undisturbed for more than 50 years), disturbed forest (natural forest with recent disturbance, e.g. logging and fire, and young natural forest), planted forest, shrubland, savanna, grassland, and cropland (Appendix A).

FLUXNET coordinates global observations from worldwide distributed micrometeorological towers, using standardized quality control and gap-filling methods (Moffat et al., 2007; Papale et al., 2006; Reichstein et al., 2005). Radiation and air temperature are measured above the canopy, usually at or near the level of the eddy covariance sensors, and recorded as half-hour means. Observations began in different years so the temporal coverage of the data did not match exactly. To include as many sites as possible and reduce the possible impact of trends in climate, we used data in the time span between 2003 and 2006 (Appendix A).

2.2. TRN calculations

The thermal response number is defined as the amount of net radiation required to change one unit of surface temperature (Luvall and Holbo, 1989), calculated as:

$$TRN = \frac{\sum_{t_1}^{t_2} R_n}{\Delta T} \quad (1)$$

where R_n is net radiation summed from t_1 to t_2 and ΔT is the range in canopy surface temperature (T_c) over time period t_1 to t_2. In this study, we used the time interval from 0:00 to 24:00. In present study, we used T_a above the canopy instead of T_c due to the unavailability of T_c data at most FLUXNET sites. The whole analyses were based on

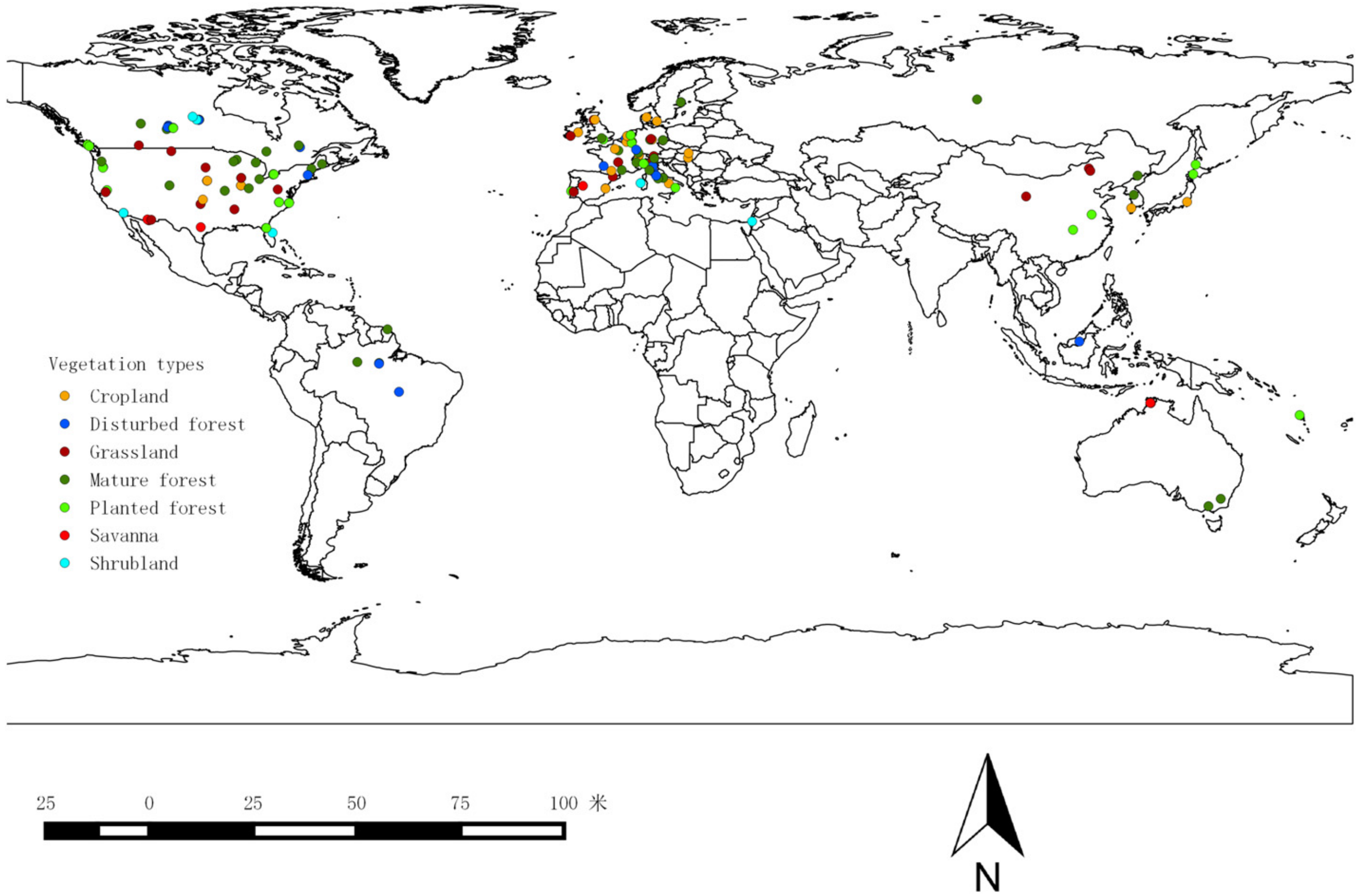

Fig. 1. Distribution of the 163 study sites.

annual average daily TRN which reduced the impact of weather (Lin et al., 2011).

2.3. Comparison of TRN among different vegetation types

Although TRN removed the influence of the amount of net radiation on surface temperature, the shape of the diurnal radiation curve (mainly determined by solar angle) still has an impact on surface temperature. For example, even given the same amount of daily net radiation, a radiation curve with a higher peak generates larger ΔT, and thus smaller TRN, than a curve with a lower peak. As latitude is the main factor that determines diurnal radiation curve, we plotted TRN against the absolute latitude, then compared TRN of different vegetation types at the same latitude. The impact of weather on the radiation curve is small for the annual average value.

Differences in the regression lines of TRN against latitude among vegetation types were tested using analysis of covariance (ANCOVA) with the R 3.1.1 software package. TRN was the response variable, latitude was the independent variable and vegetation type was the covariate. Slopes were assumed to be different as the covariate had a statistically significant impact on the responsible variable. Intercepts were assumed to be different when the independent variable had a significant impact on the responsible variable. All tests were performed at a significance level of $p = 0.05$.

2.4. Establishment of indicators for deforestation and forest degradation

Optimal TRN (TRN_{opt}) was defined as the TRN of the mature forest at a given latitude (L_s) and was calculated by the regression of TRN against latitude. We then found the regression line that separated non-forest vegetation and forest vegetation; the intersection point between this regression line and L_s was the TRN for non-forest vegetation (TRN_{def}) at L_s. Similarly, the intersection point of the regression line of TRN of disturbed forest against L_s and L_s was the TRN for degraded forest (TRN_{deg}) at L_s. If the decrease in forest TRN exceeded TRN_{deg}/TRN_{opt} (shown as a percentage), we assumed the forest was significantly disturbed, and if it exceeded TRN_{def}/TRN_{opt}, we considered this to be a warning sign for deforestation.

2.5. The relationship between Net Ecosystem Exchange (NEE) and TRN

We de-trended TRN to statistically subtract the influence of latitude by removing the regression fit of the TRN of the mature forests against latitudes from TRN, and then used a linear regression model to determine whether there was a relationship between NEE and TRN. The de-trended TRN (TRN.detrend) was the independent variable, and NEE was the dependent variable. If the p-value of the regression procedure was below 0.05, we assumed there was a linear relationship between NEE and TRN. We excluded croplands from this analysis, because of their peculiar behaviour, being subjected to management practices such as irrigation, fertilization and cultivation.

3. Results

3.1. Comparison of TRN among different vegetation types

TRN linearly decreased with increasing latitude, except in grasslands and croplands. TRNs of the mature forests were significantly higher than those of other vegetation types across all latitudes, except for those of shrublands, whose TRN overlapped with those of forest vegetation

(Fig. 2). TRNs of the grasslands and savannas showed the lowest level. The regression lines of TRN against latitude for planted forest, disturbed forest, and shrublands had no significant differences, and featured an intermediate level between TRNs of mature forests and grasslands across all latitudes (Fig. 2). Irrigated croplands have high TRN, varying between that of mature and disturbed forests and thus providing better thermal buffer capacity than grassland or savanna vegetation and comparable to that of plantations.

3.2. Establishment of indicators for deforestation and forest degradation

There were no significant differences in the slopes of the regression lines of TRN of the mature forests, the disturbed forests against latitude and the lines separating forest and non-forest vegetation; thus the selection of L_s had a very small influence on TRN_{deg}/TRN_{opt} and TRN_{def}/TRN_{opt} (Fig. 2). The average absolute latitude of all the study sites was 42.9°, so we used $L_s = 40°$. At the representative latitude of 40°, TRN_{opt} was 1.18 MJ K^{-1} $m^{-2}d^{-1}$,TRN_{deg} was 0.88 MJ K^{-1} $m^{-2}d^{-1}$, and TRN_{def} was 0.78 MJ K^{-1} $m^{-2}d^{-1}$. Compared with TRN_{opt}, TRN_{deg} showed a net decrease of 25% while TRN_{def} decreased by 34%.

We checked the TRN for 10 age and succession sequences. Forests with TRN below 66% of TRN_{opt} were all plantations of saplings, except for an Alaskan forest (US-Bn2) whose overstory was dominated by short aspen and willow (Liu and Randerson, 2008). Two shrublands (CA-NS6 and CA-NS7) and one grassland (US-Dk1) had TRN higher than 75% of $TRN_{opt.}$ TRNs at these two chronosequences had very narrow ranges. TRNs of the recently disturbed and young planted forests (within 16 years) were all smaller than 75% of the local TRN_{opt} with two exceptional sequences of US-Dk and US-NS (Table 1). Therefore, the criterion is applicable for 90% of deforested vegetation and 80% of the degraded forests for the 10 sequences. As 79% of the studied sites were located between 30° and 55° absolute latitude, we recommend using 75% of the TRN_{opt} as the possible threshold for significant disturbance (i.e. forest degradation), and 66% as the warning point for deforestation within the absolute latitude from 30° to 55°.

3.3. The relationship between NEE and TRN

Statistical results showed that TRN.detrend had no relationship with latitude after removing the latitudinal trend of TRN. A significant increase of NEE with decreasing latitude was found above 40° absolute latitude (Valentini et al., 2000), while the relationship between NEE and latitude across all latitudes was not significant. We therefore only detrended TRN in this analysis. NEE significantly decreased with increasing TRN.detrend (Fig. 3).

4. Discussion

4.1. Thermal responses by vegetation types

Mature forests had the largest TRN of all the natural vegetation types across any given latitude, which stresses the importance of the thermal buffer function by mature, intact, and healthy forests. Larger TRN implies a slower rate of increasing temperature and a consequential smaller daily temperature range under a given amount of radiation. Vegetation types with a high TRN are more resilient to global warming and drought, and can thus mitigate local climate change (Lim et al., 2008). Mature forests achieve a high thermal buffer capacity mainly by means of high standing biomass (Gu et al., 2007), active transpiration and access to deep soil water (van Gorsel et al., 2016), and long roughness length (Zhang et al., 2012). Leaves have a higher specific heat capacity than soil (Jayalakshmy and Philip, 2010). Vegetation with a high leaf area index (LAI) can protect soil from being directly heated by solar radiation, thereby reducing soil evaporation and increasing transpiration to a larger proportion of total evapotranspiration. The energetic consequences of high TRN in forests highlight the complementary dependence between physical and physiological processes due to their complex canopy structure (Cleverly et al., 2015, 2006; Lin et al., 2017).

Disturbance induces biomass loss and depression in transpiration, hence decreases thermal buffer capacity. A record-breaking warming trend in the Amazon forest was found during the extreme drought (Jimenez-Munoz et al., 2016, 2015), which was accompanied with

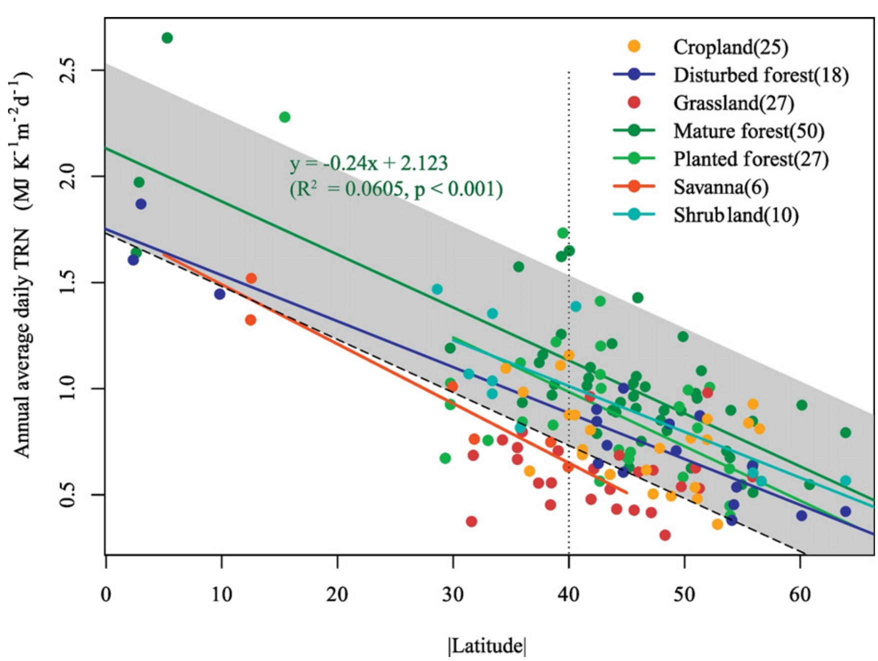

Fig. 2. Thermal response number (TRN) of vegetation at different latitudes. Solid lines are regression lines of annual average daily TRN against the absolute value of latitudes. The number of sites for each vegetation type is given in parentheses. The long dashed line is the boundary separating TRN of forest (including shrubland) and non-forest ecosystems. The shading area is the TRN range of forest vegetation. 1.18 MJ K^{-1} $M^{-2}d^{-1}$ is the optimal TRN (TRN_{opt}), 0.88 MJ K^{-1} $M^{-2}d^{-1}$ is the TRN for degraded forest (TRN_{deg}), and 0.78 MJ K^{-1} $M^{-2}d^{-1}$ is the TRN for non-forest (TRN_{def}) at absolute latitude 40°. The given equation was the regression of TRN of mature forests against latitude.

Table 1
The comparison of thermal response number (TRN) for the age and succession sequences of forests. Shading TRNs are the local optimal TRN (TRN_{opt}). Ratio = TRN / TRN_{opt}. The reference for each site is given in Appendix A. TRN_{opt} for CA-SF and CA-SJ was TRN_{opt} of the neighbour site CA-NS.

Site	Veg type	Description	Latitude(o)	Longitude(o)	TRN(MJ $K^{-1}m^{-2}d^{-1}$)	Age	Ratio
BR–Sa1	Mature	Primary forest	–2.857	–54.959	1.973		
BR–Sa3	Disturb	Logged forest	–3.018	–54.971	1.870		94.8%
CA–Ca1	Mature	Mature forest	49.867	–125.334	1.246	54	
CA–Ca3	Plant	Young plantation	49.535	–124.900	0.915	15	73.5%
CA–Ca2	Plant	Clearcut site	49.870	–125.291	0.584	3	46.8%
CA–NS1	Mature	1850 burn site	55.879	–98.484	0.631	153	
CA–NS2	Mature	1930 burn site	55.906	–98.525	0.601	73	
CA–NS3	Mature	1964 burn site	55.912	–98.382	0.641	39	
CA–NS4	Mature	1964 burn site wet	55.912	–98.382	0.511	39	
CA–NS5	Disturb	1981 burn site	55.863	–98.485	0.635	22	99.06%
CA–NS6	Shrub	1989 burn site	55.917	–98.964	0.604	14	94.22%
CA–NS7	Shrub	1998 burn site	56.636	–99.948	0.564	5	87.99%
CA–SF1	Disturb	Fire 1977	54.485	–105.818	0.536	27	83.6%
CA–SF2	Disturb	Fire 1989	54.254	–105.878	0.454	14	70.8%
CA–SF3	Disturb	Fire 1998	54.092	–106.005	0.381	5	59.4%
CA–SJ3	Plant	1975 harvest Jack pine plantation	53.876	–104.645	0.623	28	97.2%
CA–SJ1	Plant	1994 harvest Jack pine plantation	53.908	–104.656	0.448	9	69.9%
CA–SJ2	Plant	2002 harvest Jack pine plantation	53.945	–104.649	0.401	1	62.6%
CA–TP4	Plant	Mature white pine plantation	42.710	–80.357	1.412	66	
CA–TP3	Plant	Middle–aged white pine plantation	42.707	–80.348	1.067	31	75.5%
CA–TP2	Plant	Young white pine plantation	42.774	–80.459	1.002	16	71.0%
CA–TP1	Plant	Seedling white pine plantation	42.661	–80.560	0.565	3	40.0%
US–Bn1	Mature	1920 burn site	63.920	–145.378	0.793	83	
US–Bn2	Disturb	1987 burn site	63.920	–145.378	0.422	16	53.2%
US–Bn3	Shrub	1999 burn site	63.923	–145.744	0.566	4	71.4%
US–Dk2	Mature	Hardwoods	35.974	–79.100	0.935	74	
US–Dk3	Plant	Loblolly pine	35.978	–79.094	0.844	19	90.3%
US–Dk1	Grass	Open field	35.971	–79.093	0.797	1	85.2%
US–Me2	Mature	Intermediate aged ponderosa pine	44.452	–121.557	0.935	57	
US–Me3	Plant	Second young aged pine	44.315	–121.608	0.712	17	76.1%
US–SP1	Mature	Natural regenerated since 1965	29.738	–82.219	1.190	66	
US–SP3	Plant	Planted in 1989–1990	29.755	–82.163	0.925	13	77.7%
US–SP2	Plant	Planted in 1999	29.765	–82.245	1.026	4	86.2%

carbon loss (Doughty et al., 2015) and hydraulic deterioration (Rowland et al., 2015). TRN of disturbed forests were at the lowest level of forest ecosystems. Wildfire burnt 90% of the standing vegetation and litter at the grassland US-Aud (Krishnan et al., 2012) in 2002, which was reflected by a very low TRN (0.37 MJ K^{-1} $m^{-2}d^{-1}$). Planted forests usually have simple canopy structure, root system, and smoother canopy than mature forests, and are logged regularly, so they generally have lower TRN. However, old plantations with dense understory plants, e.g. JP-Tom (around 45 years of age) (Takagi et al., 2015), NL-Loo (about 100 years of age) (Dolman et al., 2002), or fertilized plantations, e.g. VU-Coc (Roupsard et al., 2009) can have comparable TRN with respect to mature forests (see Appendix A for site details). Shrublands are characterised by a range in canopy vertical structure, from simple and open in arid environments to multi-layer woodlands and short forests in semi-arid environments, therefore they covered a wide range of TRN. Croplands have high TRN due to artificial inputs of water and fertilizer, in relation with management practices by farmers, which leads to increased biomass and evapotranspiration.

Grasslands and savannas have low LAI and shallow root system. Compared with forests, their simple vertical canopy structures and shorter roughness lengths make them different in canopy thermal process (Raupach, 1994). Therefore, they have weaker thermal buffer capacities than forests. An increase of evapotranspiration in grasslands may have a positive effect on leaf surface temperature over the long term, which contrasts with the cooling effect from transpiration in forests. For example, enhanced transpiration by grasslands in Europe during the 2003 heatwave and drought suppressed surface heating until soil water had been depleted (Teuling et al., 2010; van Heerwaarden and Teuling, 2014). However, this was very short-lived, and forests were found to have much higher thermal buffer capacity over the long term during drought and heatwave (Teuling et al., 2010; van Gorsel et al., 2016). The clear TRN distinction between forests and non-

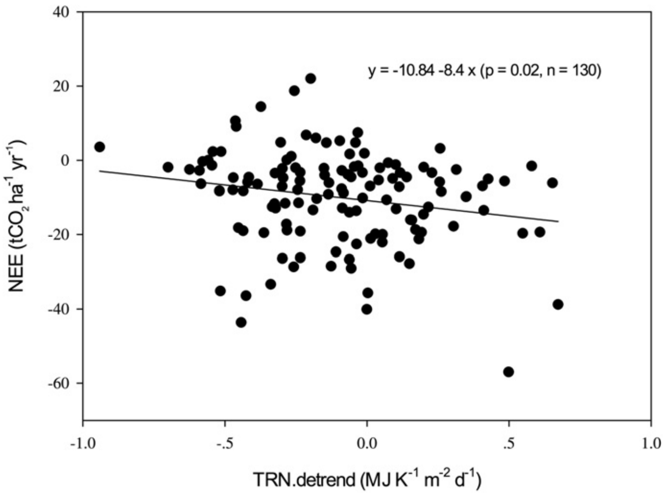

Fig. 3. The relationship between Net Ecosystem Carbon Exchange (NEE) and TRN.detrend. TRN.detrend removed the regression fit of mature forests' TRN against latitude from TRN. Croplands were excluded from this analysis.

forests along latitude further emphasizes that deforestation has a serious impact on local thermal stabilization.

4.2. Criteria for degradation and deforestation

Deforestation is easy to identify due to significant physiognomic changes; however, forest degradation is hard to detect, especially in its early stages (Guariguata et al., 2009). The following definition of forest degradation was adopted by the ninth meeting of the conference of the parties to the UNFCCC: "direct human induced long-term loss (persisting for X years or more) of at least Y% of forest carbon stocks (and forest values) since time (T) and not qualifying as deforestation (Penman et al., 2003)". The operational problem of this definition is that it is difficult to determine X and Y (Penman, 2008). Current methods and data cannot provide the desired precision for the estimation of CO_2 emissions (Bustamante et al., 2016; GOFC-GOLD, 2008). In a previous study, we found that TRN increased along vegetation growth, recovery and succession (Lin et al., 2017). TRN continuously changes with vegetation development, so that a decrease in TRN indicates that the vegetation is under stress or being disturbed.

In this study, we identified TRN thresholds for predicting forest degradation and deforestation by comparing TRN across vegetation types at a representative latitude. According to our results, the average TRN of the disturbed forests was 75% of TRN_{opt} and 66% of TRN_{opt} was the critical transition point from forest to non-forest at 40° latitude (shrublands excluded). We therefore recommend using 75% of the local TRN_{opt} as the baseline for forest disturbance, and 66% as the early warning of deforestation within the absolute latitude from 30° to 55°. This criterion was verified by the age and succession sequences (Table 1), and the accuracy is acceptable.

TRN is a comprehensive indicator being driven by biophysical processes of vegetation surfaces. It provides more information about energy partition than biomass and the CO_2 exchange of an ecosystem (Fig. 3). Compared with CO_2 emission, TRN can be measured precisely, due to the high accuracy of radiation and air temperature measurements, and mean annual daily TRN tempers the impact of weather conditions (Lin et al., 2017). Moreover, ground-based thermal remote sensing provides the possibility of upscaling measurements from the community to the landscape scale, which makes it more convenient to compare instantaneous TRN among different land surfaces (Maes et al., 2011; Maes and Steppe, 2012). In the early study, Luvall and Holbo (1989) have successfully used TRN to discriminate various types of coniferous forests with Thermal Infrared Multispectral Scanner (TIMS).

As TRN is influenced by the shape of diurnal radiation curve, i.e., solar angle, it must be detrended before it can be used to compare the status of vegetation under different radiation environments. For example, the TRN of savanna vegetation in a tropical region can be higher than that of a mature temperate forest without detrending (Fig. 2). Terrain slope inclination and aspect also have impacts on the angle of solar radiation. We did not adjust for the slope and aspect effect in the present study due to lack of information. Because the measurement height of air temperature above the canopy may have an impact on TRN, using canopy temperature could enhance the accuracy of the criterion. Further study is required to identify the range of seasonal variations in TRN as they vary with both phenology and solar angle. The criteria for TRN identified in the current study are thus not applicable on any specific day. In view of this, separating the impact of solar angle on TRN is a critical approach that requires further research. In the present study, sites were mainly located between 30° and 55° (absolute latitude), therefore, the availability of further data at different latitudes could improve the accuracy of the criteria for the assessment of deforestation and forest degradation and extend the criteria to broader range of latitude.

5. Conclusions

Our results revealed the difference in thermal response of different vegetation types. Mature forests had the highest thermal buffer capacity compared to other vegetation types. Within the absolute latitude ranging between 30° and 55°, degraded forest had lower values of TRN (75% of TRN_{opt}) due to their higher surface temperature and larger daily temperature range for a given amount of incident radiation. Grasslands and savannas had lowest thermal buffer capacity. Based on the statistic results, 66% of TRN_{opt} represents a tipping point for deforestation. TRN was responsive to the complementary effects of physical and physiological processes on canopy temperature, solar heating and evapotranspiration. TRN is an operational indicator capable of quantifying forest status and applicable for identifying forest degradation and for providing an early warning of incipient deforestation. It is therefore a valuable tool in the effort to protect forests and prevent deforestation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.07.062.

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