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# Satellite observed positive impacts of fog on vegetation

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**Key Point:**

- The first observed positive impact of fog on vegetation using satellite remote sensing data.
- Fog can explain 10%–30% of variability in vegetation proxies.
- Optical and microwave remote sensing data showed continuous positive impact of fog on vegetation.

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This is the author's manuscript of the article published in final edited form as:

Qiao, N., Zhang, L., Huang, C., Jiao, W., Maggs-Kölling, G., Marais, E., & Wang, L. (n.d.). Satellite observed positive impacts of fog on vegetation. Geophysical Research Letters, n/a(n/a), e2020GL088428. https://doi.org/10.1029/2020GL088428

## Abstract

Fog is an important water source for many ecosystems, especially in drylands. Most fog-vegetation studies focus on individual plant scale, the relationship between fog and vegetation function at larger spatial scales remains unclear. This hinders an accurate prediction of climate change impacts on dryland ecosystems. To this end, we examined the effect of fog on vegetation utilizing both optical and microwave remote sensing derived vegetation proxies and fog observations from two locations at Gobabeb and Marble Koppie within the fog-dominated zone of the Namib Desert. Significantly positive relationships were found between fog and vegetation attributes from optical data at both locations. The positive relationship was also observed for microwave data at Gobabeb. Fog can explain about 10%–30% of variability in vegetation proxies. These findings suggested that fog impacts on vegetation can be quantitatively evaluated from space using remote sensing data, opening a new window for research on fog-vegetation interactions.

## Plain Language Summary

This study presents the first observed relationships between fog and vegetation function using satellite remote sensing data. Significant correlations were found between fog and satellite derived vegetation indices at two study sites within the Namib Desert. These findings suggested that satellite data can be used to assess and quantify the impacts of fog on vegetation at large spatial scales.

## 1 Introduction

Dryland ecosystems, defined as regions where the ratio of mean annual precipitation to potential evapotranspiration (aridity index) is smaller than 0.65, form about 40% of the global land area [*Lal*, 2004; *Wang et al.*, 2012]. Vegetation in drylands plays a major role in carbon sequestration as they contribute approximately 40% of global net primary productivity [*Grace et al.*, 2006]. Vegetation functions strongly rely on water resources in dryland ecosystems, so any form of water could positively affect vegetation greenness and productivity [*Dawson and Goldsmith*, 2018; *Tietjen et al.*, 2010; *Wang et al.*, 2010; *Wang et al.*, 2017]. Since rainfall is predicted to decrease in many drylands due to global climate changes [*Dore*, 2005], there is a great importance to understand the contributions of non-rainfall atmospheric water to vegetation dynamics. Fog is regarded as an important water source during rainless periods in some dryland ecosystems [*Hachfeld*, 2000; *Runyan et al.*, 2019].

Fog can maintain vegetation photosynthetic function and sustain biogeochemical dynamics during rainless periods [*Scholl et al.*, 2011; *Wang et al.*, 2017]. *Fischer et al.* [2009] found that fog provided supplementary water to reduce annual drought stress by 20-36% for plants off the coast of southern California. *Corbin et al.* [2005] reported that 28-66% of the water taken by California coastal prairie grasses via roots came from fog during the summer drought. These positive effects on plant growth induced by fog are supposed to stronger in drylands where fog water can exceed rainfall [*Weathers et al.*, 2019]. However, most previous investigations about the fog-vegetation relationship concentrated on individual plant scale, thus the impacts of fog on vegetation at larger spatial scales remains unclear. This hinders the understanding of large-scale vegetation dynamics in fog dependent ecosystems to future climate changes. Additionally, most field studies investigating the role of fog in vegetation function are based on discrete sampling due to logistic constraints in remote locations. Continuous observations of how plant function benefits from fog are still lacking.

With large spatial coverage and frequent observations, satellite remote sensing data plays an irreplaceable role in vegetation monitoring in global drylands [*Andela et al.*, 2013; *Yang et al.*, 2012]. Vegetation indices from optical remote sensing data (e.g., the Normalized

Difference Vegetation Index, NDVI and the Enhanced Vegetation Index, EVI), have been extensively used to monitor and analyze the vegetation greenness and productivity in drylands, such as desert grassland, woodland, savanna and shrub-steppe [*Fensholt et al.*, 2012; *Sjöström et al.*, 2009]. In addition to vegetation indices, the vegetation optical depth (VOD) derived from satellite passive microwave data, which is sensitive to vegetation water content of both leaf and wood components, has also been used to characterize aboveground vegetation biomass in southern Africa, semi-arid Sahel and global scales [*Liu et al.*, 2018; *Tian et al.,* 2016]. However, the impact of fog on vegetation utilizing remote sensing data has not been reported in literature. It is unclear whether vegetation proxies from satellite remote sensing data are sensitive enough to capture variations in the condition of vegetation induced by fog, which are supposed to be weak signals in drylands with low vegetation coverage [*Malo and Nicholson,* 1990].

The main objective of this study is to examine whether satellite derived vegetation proxies can be used to monitor the fog impacts on vegetation in drylands. Our testing bed was two locations in the Namib Desert where the system is characterized by frequent fog occurrence and has daily fog observations [*Kaseke et al.*, 2018; *Spirig et al.*, 2019]. We analyzed the relationships between fog and proxies of vegetation function represented by EVI and NDVI from optical data as well as VOD from passive microwave data at these two locations. We first explored the responses of daily EVI, NDVI and VOD to fog. Considering the potential lag and cumulative effects of water input (e.g., precipitation and fog) on vegetation in drylands [*Malo and Nicholson*, 1990; *Papagiannopoulou et al.*, 2017], we also analyzed the relationships between EVI/NDVI data and fog at an 8-day temporal resolution.

## 2 Materials and Methods

### 2.1 Fog observations

The fog observations were from customized automated weather stations (AWS) located at Gobabeb and Marble Koppie within the Namib Desert (Figure 1). The sites were selected based on the following criteria: (1) sites have observable vegetation cover within the pixel (0.1° × 0.1°) of the passive microwave remote sensing data used in this study; (2) sites have relatively high fog occurrence. The fog amount was measured by a cylindrical passive fog collector (Juvik fog collector) with a screen mesh. We used fog data recorded at hourly intervals from Gobabeb and Marble Koppie during the year of 2015 and 2017. The fog data in 2016 were excluded from the main text since there was an extremely large rainfall during the dry season in the study area. The fog-vegetation relationship analysis was conducted for the 2016 data and the results were shown in the supplementary materials. In addition, three fog records at the Marble Koppie site were removed since they are larger than three standard deviations of the mean value in the year of 2015 and 2017. Monthly fog time series at both study sites were shown in Figure 1 (a) and Figure 1 (b). The climate in the Namib Desert is arid and has one wet season (October to April) and one dry season (May to September) [*Li et al.*, 2016; *Lu et al.*, 2016]. Gobabeb (lat. −23.55° S, long. 15.04° E, and elv. 405 m) is 60 km from the South Atlantic Ocean on the banks of the ephemeral Kuiseb River and at the edge of the Namib Sand Sea (Figure 1 (a)). The mean annual temperature is 21.1°C and the average relative humidity is around 50% at Gobabeb. The banks of the Kuiseb River at Gobabeb are densely covered by a narrow strip of *Acacia erioloba*, *Euclea pseudebenus*, *Faidherbia albida*, *Salvadora persica*, and *Tamarix usneoides*. The dominant perennial plant species in the adjacent dunes of the Namib Sand Sea is isolated *Stipagrostis sabulicola* and *Acanthosicyos horridus* hummocks; with very sparse *Calicorema capitata* on the gravel plains north of the Kuiseb River [*Wang et* *al.*, 2019]. Marble Koppie (lat. −22.97° S, long. 14.99° E, and elv. 420 m) is located about 51.5 km from the Atlantic Ocean on the Central Namib gravel plains, with a mean annual temperature of 19.2°C and average relative humidity around 59%. The Marble Koppie area is dominated by low relief peneplains with shallow, dendritic drainage channels coalescing into a wide but shallow trunk channel (Figure 1 (b)). Isolated, small individuals of *Jamesbrittenia maxii*, *Pechuel-Loeschea leubnitziae*, *Orthanhtera albida* and rare *Tetraena stapffi* occur within the shallow channels on the gravel plains, with a sparse community of *Acacia reficiens* and *Tetraena stapffi* shrubs with *Pechuel-Loeschea leubnitziae*, *Jamesbrittenia maxii*, *Caroxylon* and other minor perennial and evergreen species in the trunk channel.

### 2.2 Vegetation indices from optical remote sensing data

This study used the daily nadir Bidirectional Reflectance Distribution Function (BRDF) adjusted reflectance product from MODerate-resolution Imaging Spectroradiometer (MCD43A4 V006, 500 m) and 8-day composite MODIS surface reflectance product (MOD09A1 V006, 500 m) to derive the EVI and NDVI data. The MCD43A4 dataset is produced using daily Terra and Aqua satellite overpasses within each 16-day window by the BRDF to model the reflectance at local solar noon. Only those data pixels identified as 'good quality' by the quality assurance (QA) flag were used. The MOD09A1 dataset was obtained by MODIS onboard the Terra satellite and the equatorial overpass is at about 10:30 local solar time. A pixel-based QA control was applied by removing the noise of low quality, clouds, and cloud shadows prior to calculating EVI and NDVI.

### 2.3 VOD from passive microwave remote sensing data

Daily VOD data at a 0.1° spatial resolution were derived from passive microwave remote sensing data from the Advanced Microwave Scanning Radiometer 2 (AMSR2), using the Land Parameter Retrieval Model (LPRM) [*Owe et al.*, 2008]. AMSR2 scans the Earth's surface in an ascending (day time) and descending (night time) mode. This study used the X-band data of the VOD daytime product downloaded from the Goddard Earth Sciences Data and Information Services Center (GES DISC).

### 2.4 Analyses of fog and remote sensing data

We utilized a combination of fog field observations, EVI, NDVI and VOD from remote sensing data to evaluate the impacts of fog on vegetation in the Namib Desert. First, we analyzed the relationships between daily fog and vegetation dynamics indicated by EVI, NDVI and VOD without the influence of rainfall at the Gobabeb and Marble Koppie sites. To select periods without the influence of rainfall on vegetation, we followed the method of *Li et al.* [2018] by utilizing soil moisture data from the Gobabeb AWS. Vegetation productivity and greenness are often reported to show delayed responses to precipitation pulses [*Malo and Nicholson*, 1990; *Papagiannopoulou et al.*, 2017], hence 8-day EVI and NDVI were also applied to evaluate and illustrate the potential lag and cumulative response of vegetation to fog occurrences similar to the method used for daily analyses. Hourly fog data were aggregated into daily and 8-day intervals in accordance with the temporal resolution of remote sensing data used in this study. Since fog in the Namib Desert mostly occurred at night (most from 21:00 to 9:00) and remote sensing data were observed in daytime, we computed daily fog by adding hourly fog data from 9 am to the previous 24 hours. Please note that the overpass time of Terra and Aqua satellites are at about 10:30 and 13:30 local solar time at the equator, respectively. The observation time of VOD daytime product was between 12:00 to 14:00 local solar time at the study sites. Fog would evaporate before the observation time of remote sensing data acquisition in this study. Thus, the influence of fog-related changes in soil moisture to EVI/NDVI/VOD is likely negligible.

The 500-m MODIS dataset were gridded in 0.05° × 0.05° windows in accordance with the geographic locations of study sites. The 0.05° grids were excluded if over 20% of the 500 m pixels within the grid were identified as low-quality observations by the QA flag for the MODIS dataset. The vegetation indices and VOD were derived using the average values in 0.05° grids and the value of pixels (0.1° × 0.1°) covered or near the study sites, respectively. For more information about the area selection of remote sensing data utilization, please refer to Figure S1. Additionally, we examined continuous EVI, NDVI and VOD dynamics during fog periods, and compared these proxies between fog periods and non-fog and non-rainfall periods.

## 3 Results and Discussion

Both EVI and NDVI showed significant correlations ($p < 0.01$) with periods of fog occurrences during 2015, 2017 and the entire study period at both study sites. VOD at the Gobabeb site also had significant correlation ($p < 0.05$) with fog occurrence in 2017 and the entire study period. With an increase in fog events, EVI and NDVI at both study sites, and VOD at the Gobabeb site showed an increasing trend (Figure 2). Similar relationships were observed for 2016 (Figure S2). The logarithmic relationships between fog and vegetation proxies also generated similar results (Figure S3). These relationships would be primarily driven by the fact that fog is a supplemental water source for plants in drylands [*Wang et al.*, 2017]. Several studies have demonstrated the mechanisms of fog water uptake of the Namib plants either through foliar water uptake or through shallow roots in the early morning before fog moisture evaporates [*Louw and Seely*, 1980; *Seely et al.*, 1977; *Wang et al.*, 2019]. EVI and NDVI have been extensively used to estimate the chlorophyll concentrations and leaf area index (LAI) [*Soudani et al.*, 2012]. Thus, both of them could be expected to characterize the vegetation greenness and productivity. As shown in Figure 2, fog had a positive impact on maintaining functional health in vegetation. In comparison to the positive relationship between NDVI and rainfall in the Sahel region from 1982 to 1985, where NDVI increased about 0.0009 per millimeter precipitation in the semi-desert grassland [*Malo and Nicholson*, 1990], the slopes between NDVI and fog for the Gobabeb site (0.0014) and the Marble Koppie site (0.0008) are in the same order of magnitude. This suggests that fog is an important factor to maintain vegetation greenness during non-rainfall periods. VOD, which is mainly sensitive to vegetation biomass and water content of both leaf and woody components [*Liu et al.*, 2015; *Tian et al.*, 2016], provides complementary evidence that fog is important for maintaining vegetation productivity during non-rainfall periods. These results indicated that fog enhances vegetation greenness and biomass in this desert ecosystem.

EVI and NDVI at the Marble Koppie site were significantly correlated with fog during 2015, 2017 and the entire study period. However, no significant correlation between VOD and fog was found at this site. This could be related to sparser vegetation and individually isolated low shrubs at Marble Koppie. Previous research indicated that NDVI was more sensitive to vegetation dynamics compared to VOD in regions with low vegetation coverage and dominated by herbaceous vegetation [*Andela et al.*, 2013]. Therefore, for the areas with sparser vegetation (the mean value of EVI for the Marble Koppie site is 0.0486, and it is 0.0760 for the Gobabeb site), the changes induced by fog on vegetation seems to be better captured by EVI and NDVI.

We also examined the temporal variations of vegetation proxies (EVI, NDVI and VOD) in relation to fog at both study sites during 2015 and 2017. As shown in Figure 3, fog mainly occurred from May to October at the study sites when rainfall is not common. Meanwhile, EVI and NDVI showed obvious vegetation responses to fog events and 44%-50% of the EVI and NDVI values during fog periods were higher than the average values during non-fog and non-rainfall periods. The values of EVI and NDVI at the Gobabeb site and EVI at the Marble Koppie site during fog periods were significantly higher ($p < 0.05$) than those average values during non-fog and non-rainfall periods based on one sample t-test. Although there was no significant correlation between VOD and fog at the Marble Koppie site (Figure 2(b)), about 43%-68% of VOD values during periods with fog were higher than the average values during non-fog and non-rainfall periods (Figure 3). The explanation could be related to the limitations of detecting very low VOD value ranges in a desert with sparse, isolated vegetation as at the Marble Koppie site [*Andela et al.*, 2013].

These results indicate that fog is the main water input in maintaining vegetation ecological functions at the study sites during rainless periods. Satellite based continuous observations clearly show plant communities over a larger area benefits from fog. This can be related to the positive impact of fog on plant water potential for dominant species in the Namib Desert [*Wang et al.*, 2019] and other fog harvesting mechanisms of different plant species in this fog dominated system [*Louw and Seely*, 1980; *Seely et al.*, 1977].

To account for the potential lag and cumulative effects of fog on vegetation function, we analyzed the correlations between fog and MOD09-based EVI and NDVI at an 8-day temporal resolution (Figure 4). Eight-day EVI and NDVI were significantly correlated ($p < 0.05$) with fog at both sites in each study period with the exception of 8-day NDVI at the Marble Koppie site in 2017. At the Gobabeb site, fog explained 30% of the EVI variations at an 8-day temporal resolution, and the explanatory power was approximately 7% higher than that for the daily scale (23%) for the entire study period. The coefficients of determination between 8-day vegetation indices and fog at the Marble Koppie site (EVI, $R^2 = 0.15$; NDVI, $R^2 = 0.15$) were similar to the results of daily vegetation indices (EVI, $R^2 = 0.16$, NDVI, $R^2 = 0.17$) for the entire study period. With increased fog, 8-day vegetation indices (slopes at the Gobabeb site: EVI, 0.0005, NDVI, 0.0007; slopes at the Marble Koppie site: EVI, 0.0002, NDVI, 0.0003) showed rising trends, which were consistent with the results of daily vegetation indices (slopes at the Gobabeb site: EVI, 0.0009, NDVI, 0.0014; slopes at the Marble Koppie site: EVI, 0.0006, NDVI, 0.0008) (Figure 2). The temporal variations of 8-day fog in 2015 and 2017, EVI and NDVI during non-rainfall periods are illustrated in Figure S4. About 38%-48% of the 8-day EVI and NDVI during fog periods were higher than the average values during non-fog and non-rainfall periods at both sites. This result is similar to the daily EVI and NDVI results (Figure 3). The relationships between 8-day vegetation indices and fog at both sites illustrate that fog has cumulative effects in maintaining vegetation function during rainless periods at both sites. This result can be related to the cumulative effects of water input on vegetation dynamics [*Papagiannopoulou et al.*, 2017; *Wen et al.*, 2019].

Since acquiring satellite remote sensing derived dryland vegetation proxies is challenging due to the low signal to noise ratio in sparse vegetated areas and there are limited number of sites used in this study, the use of remote sensing data to determine the impact of fog on vegetation dynamics needs to be further examined in other dryland regions. In addition, the robustness of the results are likely affected by the different spatial representativeness between observations of fog events on the ground and remote sensing data. Fog products from satellite data [e.g., *Andersen et al.*, 2019] could provide a potential approach to analyze the vegetation responses to fog in drylands at larger spatial scales in the future. With more field-based and satellite-derived fog observations, it would be feasible to examine the effects of fog seasonality on vegetation growth and identify possible fog impact thresholds.

## 4 Conclusions

We presented the first observed relationships between fog and vegetation dynamics using satellite remote sensing data. A combination of optical and microwave remote sensing data were used to investigate the effects of fog on vegetation at Gobabeb and Marble Koppie in the Namib Desert during a period without rainfall influences. At both study sites EVI and NDVI from optical data were significantly ($p < 0.05$) correlated with fog at both daily and 8-day temporal resolutions during the entire study period. A significant correlation ($p < 0.05$) was also observed for daily VOD from microwave data at the Gobabeb site in 2017 and the entire study period. These results indicate that the effect of fog on vegetation can be observed from space. Furthermore, about 40%-50% of EVI, NDVI and VOD values during periods with fog were higher than the average values during non-fog and non-rainfall periods at both sites. These results imply that fog plays an important role in sustaining vegetation functions at both sites during rainless periods. These findings can guide future research to use remote sensing data for monitoring and quantifying fog contributions to vegetation function in other fog-dominated ecosystems.

## Acknowledgments

The authors declare no financial conflicts or interests. Funding for this work was made available from the U.S. National Science Foundation (IIA-1427642 and EAR-1554894). We would like to acknowledge Gobabeb Namib Research Institute for access to the FogNet weather stations and logistical support and fieldwork assistance. This work was partially supported by the Major Science and Technology Projects of XPCC (2018AA00402) and the Innovation Team of XCPP's Key Area (2018CB004). Na Qiao sincerely thanks the China Scholarship Council (No. [2018]3101) for fellowship support. MCD43A4 and MOD09A1 data were available from the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/products/mcd43a4v006/, https://lpdaac.usgs.gov/products/mod09a1v006/). AMSR2 VOD product was obtained from the GES DISC (https://hydro1.gesdisc.eosdis.nasa.gov/data/WAOB/LPRM_AMSR2_DS_A_SOILM3.001/).We thank two anonymous reviewers and editor Dr. Valeriy Ivanov for their constructive comments, which significantly improved the quality of this manuscript.

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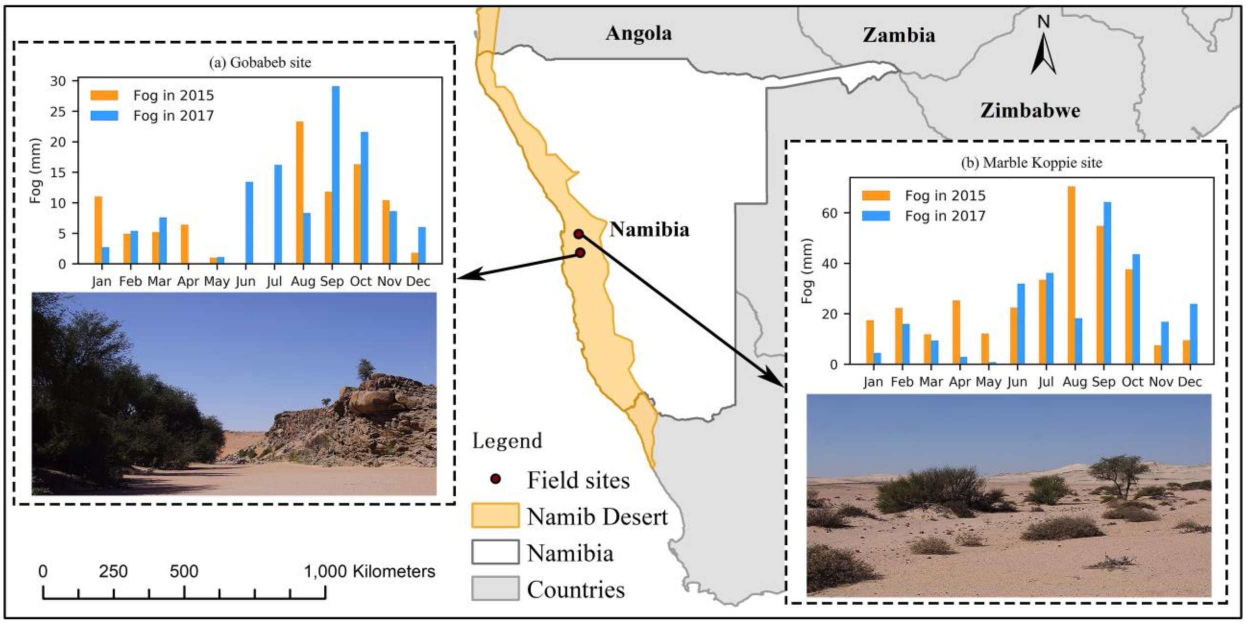


**Figure 1**. Map indicating the geographic locations of study sites within the Namib Desert, indicating the ephemeral Kuiseb River vegetation at Gobabeb (a) and sparse *Acacia reficiens* - *Tetraena stapffi* channel vegetation at Marble Koppie (b). Monthly fog time series at both study sites were shown in (a) and (b). Please note the 2015 monthly amount of fog in June and July at the Gobabeb site were excluded because of the lack of fog observations from June 17th to July 19th.

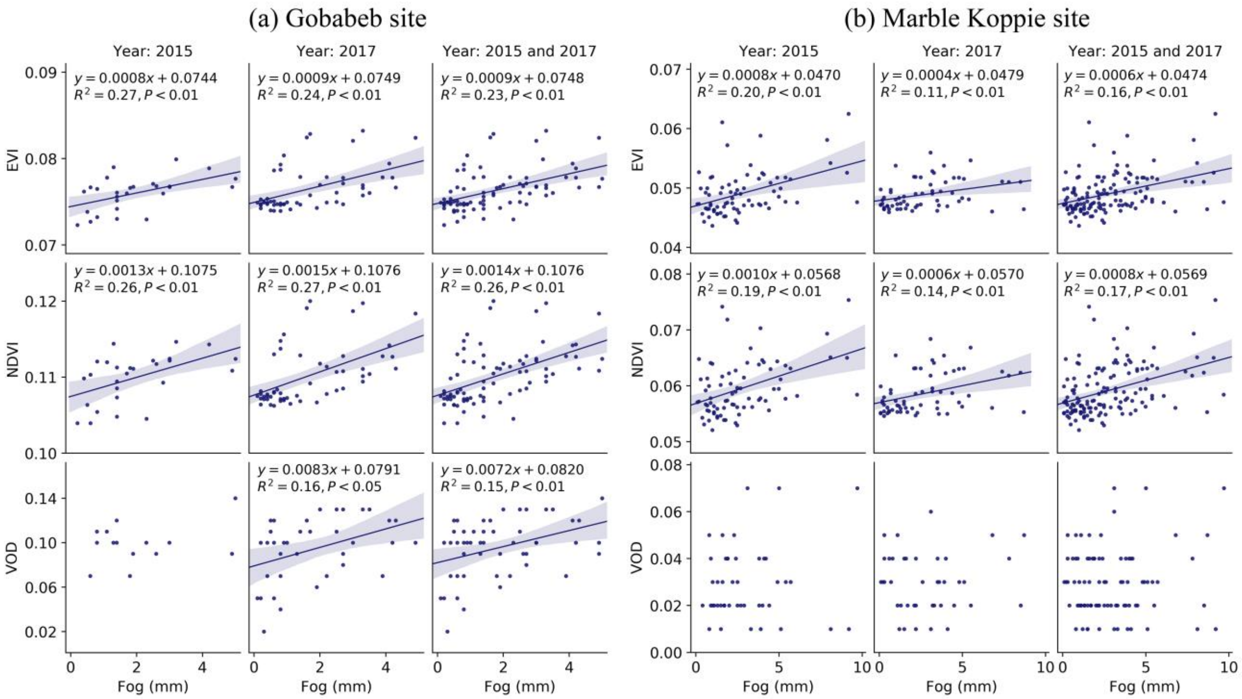
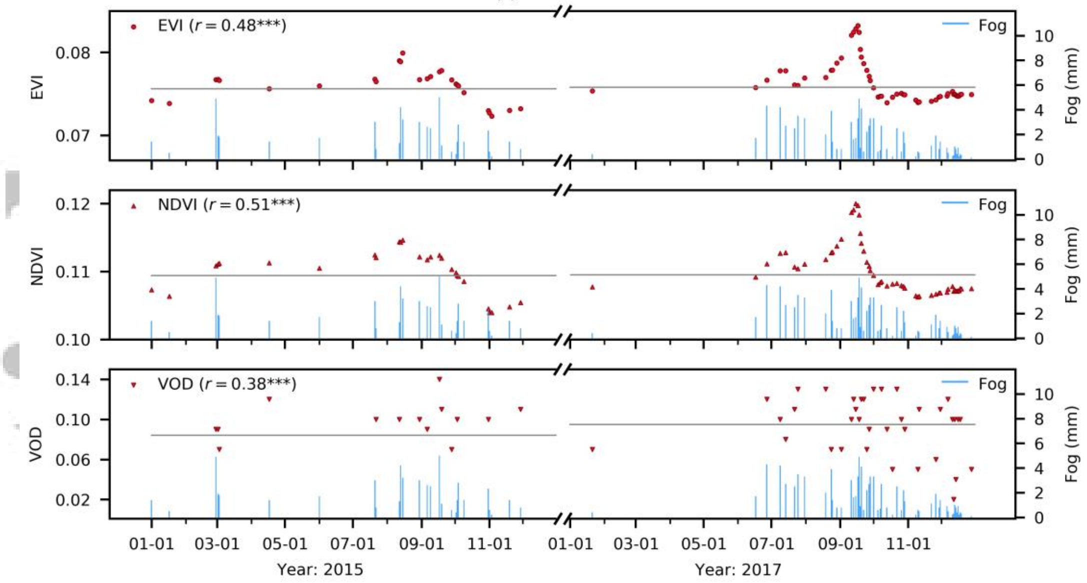


**Figure 2.** Relationships between daily fog and vegetation dynamics represented by EVI, NDVI and VOD at the Gobabeb (a) and Marble Koppie (b) sites during non-rainfall periods in 2015, 2017 and the entire study period. The shaded areas represent the 95% confidence intervals for the model.

(a) Gobabeb site



(b) Marble Koppie site

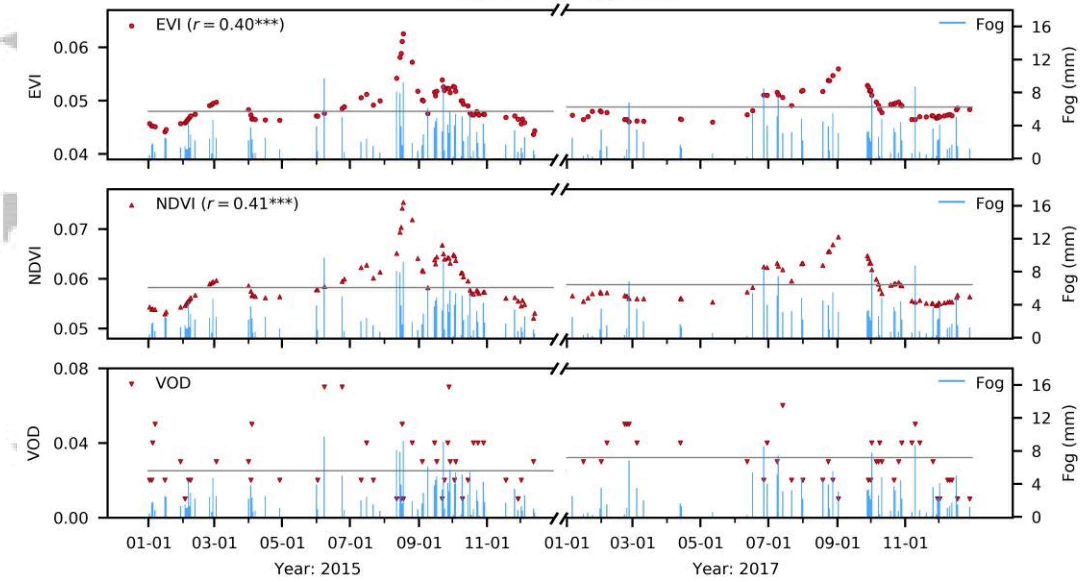


**Figure 3.** Dynamics of daily fog, EVI, NDVI, and VOD at the Gobabeb (a) and Marble Koppie (b) sites during non-rainfall periods in 2015 and 2017. The gray lines are mean values of satellite vegetation metrics (EVI, NDVI and VOD) during non-fog and non-rainfall periods. *r* represents the correlation coefficient between vegetation proxy (EVI, NDVI or VOD) and fog cross the entire study period. *** represents 0.01 significant level.

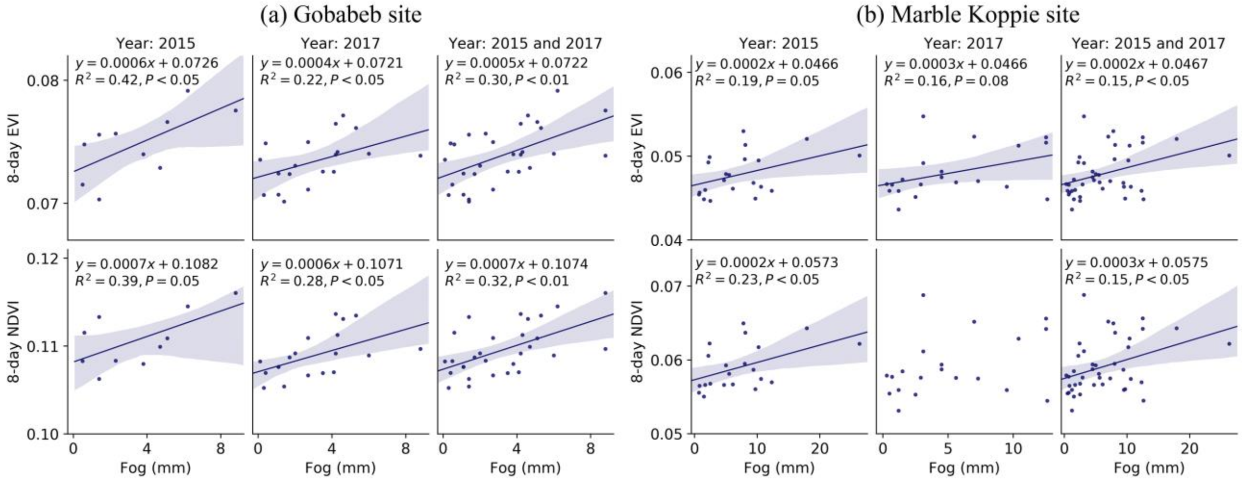


**Figure 4.** Relationships between 8-day fog and vegetation dynamics represented by EVI and NDVI for the Gobabeb (a) and Marble Koppie (b) sites during non-rainfall periods in 2015, 2017 and the entire study period. The shaded areas represent the 95% confidence intervals for the model.