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Effects of climate and land cover on the relationship of satellite derived vegetation water content and greenness

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Abstract The relationship between vegetation water content and greenness has been quantified for various vegetation types over a range of contrasting climate regimes. NDVI and vegetation water content (VegWC) are derived from MODIS and AMSR, respectively. Three study areas were selected: North America Monsoon System (NAMS) region, International H2O Project (IHOP) region, and a region in Georgia. Both NDVI and VegWC are higher in the more mesic IHOP region than in the arid NAMS region. Although NDVI is even higher in the humid Tifton region, VegWC does not also increase. The VWC of natural ecosystems exhibits greater spatial and temporal variability than in crop regions. Overall, the differences in VegWC between regions and land cover types are small compared to that for greenness. This observation is reasonable given the adaptations of plants to cope with the soil water limitations that are common in dry climates.

Key words normalized difference vegetation index; soil water limitation; vegetation water content

INTRODUCTION

Vegetation responds to meteorological and climatological changes on a variety of time scales (Rodriguez-Iturbe *et al*., 1999; Nicholson, 2001). The characteristics or nature of variations at any point depend on a number of factors. Of primary importance is the vegetation type (e.g. forests *vs* cropland) and general climatic condition (e.g. humid *vs* dry). These fundamental controls of vegetation type and climate are modified by soil texture and depth and slope, aspect and topography (Lane *et al*., 1998).

Satellite-derived vegetation indices, such as NDVI (Normalized Difference Vegetation Index), have been used to characterize the variability of vegetation greenness (Tucker, 1979). In a more detailed modelling context, reflectance measures like NDVI can be used to derive other information, such as NPP (Net Primary Productivity), ET (Evapotranspiration) and LAI (Leaf Area Index) (Roujean & Breon, 1995; Ambast *et al*., 2002; Anderson *et al*, 2004). The temporal and spatial variability of either greenness or NPP can be explained by observed meteorological conditions, for example accumulated rainfall over some period (Austin *et al*., 2004). However, this information gives a general picture of plant–climate interactions. For example the NPP response to precipitation variability is greatest in sub-humid ecosystems relative to that observed in drier or wetter ecosystems (Roujean & Breon, 1995; Schuur & Matson, 2001; Austin *et al*., 2004).

Detailed information on physical linkages at the land surface can be derived by comparing two vegetation variables measured from space: vegetation water content and vegetation greenness or NDVI. Microwave instruments such as AMSR (Advanced Microwave Scanning Radiometer) allow us to monitor the changes in vegetation water content (VegWC) (Njoku & Li, 1999; Njoku *et al.*, 2003). This allows for a new approach to evaluate linkages between the hydrological state of vegetation and greenness at continental scales. The vegetation water content has been derived but not compared to other aspects of vegetation state, such as greenness. Here we compare the vegetation water content to vegetation greenness and propose a hypothesis to explain the observed relationship between water content and greenness across climatic gradients and land cover types.

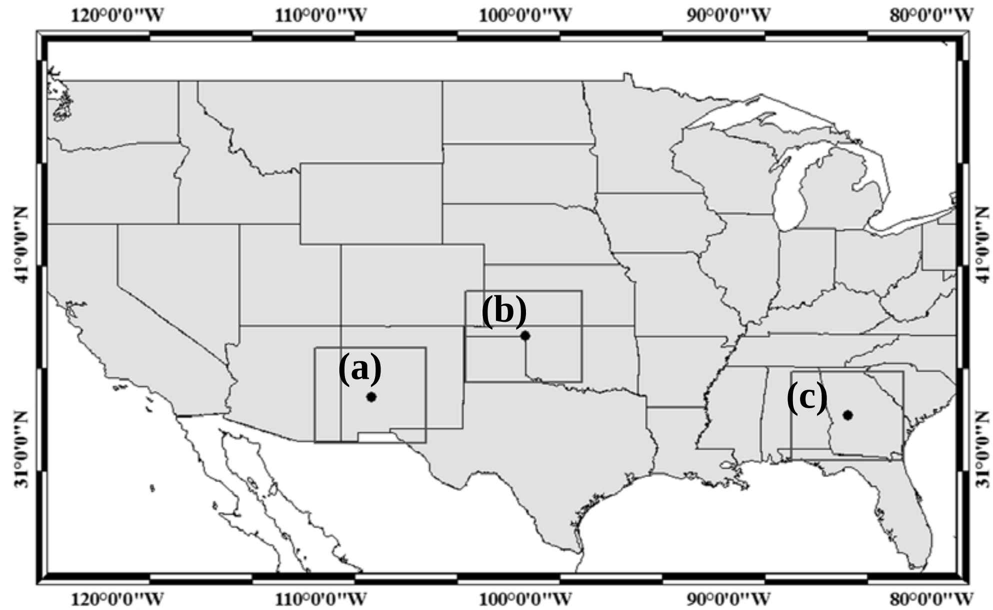
DATA AND METHODS

In this study, we used MODIS (Moderate Resolution Imaging Spectroradiometer) (Justice *et al*., 1998) Terra (10:30 h equator overpass) 16-day aggregated data sets in 1-km spatial resolution for NDVI. Data retrieved from AMSR-E are used for VegWC analysis. VegWC is retrieved from a radiative transfer model in which vegetation opacity is used to derive VegWC (area averaged water content in vertical column of vegetation) at low frequency (Njoku & Li, 1999). We have re-sampled/remapped all data to a 25-km spatial grid and the AMSR projection as this is the lowest spatial resolution. All 1-km MODIS data are converted to 25-km resolution as AMSR-E data, and different spatial projection types between MODIS and AMSR-E are changed to the same AMSR geographical projection. The nearest neighbour method has been used for those processes of changing spatial resolution and projection types. Then each data set has been time-averaged (for 16 day composites) for the 3-month summer season (9 June–12 September) for 2003 and 2004.

Three regions, which have climatically contrasting characteristics, have been selected for this study (Fig. 1): NAMS (North American Monsoon System) region, IHOP (International H2O Project) region, and Tifton, Georgia (GA) region. The mean annual precipitation in each region is approximately 300, 600, and 1000 mm, respectively. The relatively arid NAMS region has sparse vegetation with maximum rainfall in July and August, whereas the sub-humid IHOP region, which is in the Southern Great Plains, is relatively wetter with more vegetation than the NAMS region. The rainfall in the IHOP region mainly occurs in spring. Tifton, Georgia is humid and has frequent summer rainfall with higher vegetation than the NAMS or IHOP regions. In this study all three regions have the same spatial size of 500 × 500 km with centre points of 33.5N/107.5W, 36.5N/100.0W, and 32.4N/84.0W in latitude/longitude for NAMS, IHOP, and Tifton, Georgia, respectively (Fig. 1).

RESULTS AND DISCUSSION

NDVI and VegWC vary over a broad range, both within and between the three regions studied (Fig. 2 and Table 1). Both the mean NDVI and VegWC are twice as high in



F ig. 1 Study regions (500 × 500 km) (a) NAMS Region: centre points in lat/long: 33.5ºN and 107.5ºW, (b) IHOP Region: 36.5ºN and 100.0ºW, and (c) Tifton, Georgia: 32.4ºN and 84.0ºW.

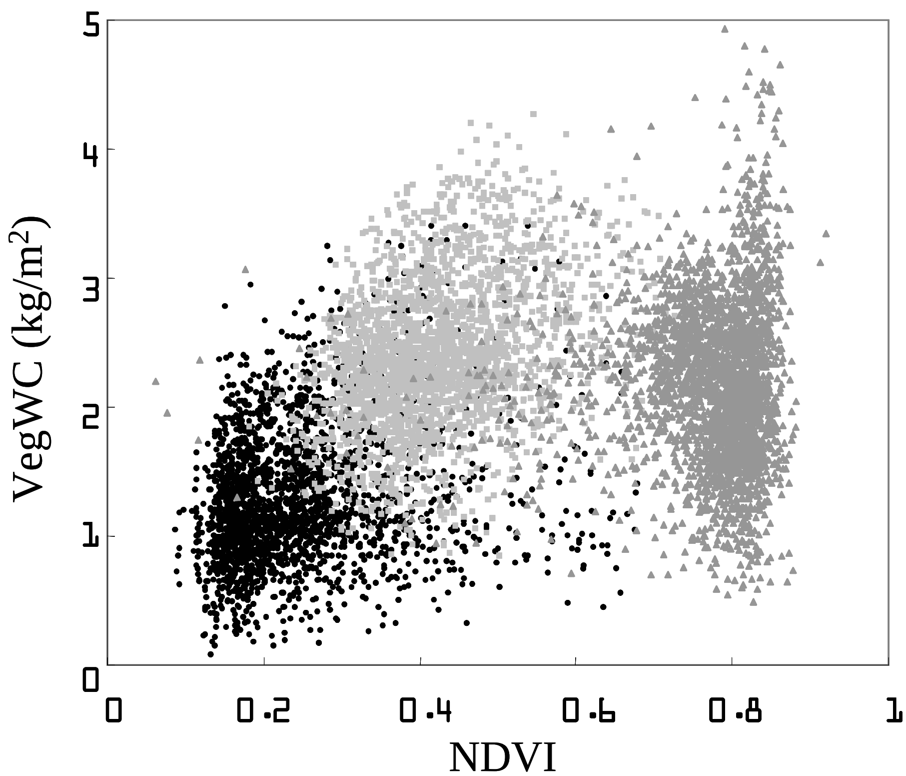


Fig. 2 Variation of vegetation water content *vs* NDVI for the three study regions. Each point represents a biweekly data for the growing season, (June to September 2003) and a single 25 × 25 km pixel corresponding to various vegetation types.

Table 1 Spatial mean (Mean), standard deviation (Std.), coefficient of variation (CV), maximum (Max) and minimum (Min) averaged over June to September for VegWC and NDVI over dominant land cover types in all three regions considered in the study. The column N(%) denotes the number of pixels (percentage of total); as there can be almost 400 pixels (500km domain and 25km pixel size) in each study area.

			N(%)	**NDVI**					**VegWC**				
				Mean	Std.	Max	Min	CV	Mean	Std.	Max	Min	CV
2003	**NAM**	Shrubland	169(43)	0.23	0.08	0.45	0.13	0.35	1.20	0.28	2.32	0.32	0.23
		Savanna	101(26)	0.22	0.06	0.37	0.12	0.27	1.23	0.33	2.32	0.42	0.27
	IHO	Grassland	142(34)	0.41	0.08	0.63	0.28	0.20	2.36	0.50	3.71	1.27	0.21
		Cropland	105(25)	0.43	0.06	0.59	0.34	0.14	2.51	0.33	3.36	2.04	0.13
	GA	Deciduous	42(9)	0.81	0.04	0.85	0.65	0.05	2.27	0.92	4.97	0.95	0.41
		Cropland	59(13)	0.72	0.05	0.80	0.57	0.07	2.43	0.25	2.98	1.91	0.10
2004	**NAM**	Shrubland	53(13)	0.32	0.07	0.45	0.17	0.22	1.44	0.38	2.20	0.74	0.26
		Savanna	19(5)	0.28	0.06	0.41	0.19	0.21	1.18	0.28	1.78	0.55	0.24
	IHO	Grassland	42(10)	0.47	0.09	0.71	0.30	0.20	2.37	0.47	3.61	1.26	0.20
		Cropland	205(50)	0.50	0.06	0.64	0.40	0.12	2.38	0.35	3.19	1.85	0.15
	GA	Deciduous	26(8)	0.82	0.04	0.86	0.69	0.05	2.46	1.01	4.37	1.00	0.41
		Cropland	27(8)	0.73	0.02	0.79	0.67	0.03	2.64	0.32	3.27	1.47	0.12

IHOP as in NAMS: NDVI increases from 0.21 to 0.42 and VegWC increases from 1.2 kg m^2 to 2.4 kg m^2 between the regions. When these two regions are considered together, VegWC tends to increase (roughly linearly) as NDVI increases from 0.1 to 0.55. This result is consistent with basic relationships between climate and vegetation: regions with more precipitation have more productive and abundant vegetation (e.g. Huxman *et al*., 2005).

Although we have not explicitly compared vegetation properties to precipitation, our results show that both vegetation greenness (NDVI) and water content (VegWC) increase from the arid southwest to the more mesic Great Plains. This relationship between NDVI and VegWC does not extend to the GA region, which is substantially wetter than IHOP and NAMS. A large majority of pixels (25 × 25 km) in GA exhibit NDVI between 0.65 and 0.85, and the mean is 0.75 (Fig. 2). This is nearly twice as high as in IHOP (Table 1). However, the vegetation water content is not higher. Instead, VegWC is slightly lower in GA than in IHOP: 2.35 kg m^2 *vs* 2.4 kg m^2, respectively. This is the case for both the summer seasons i.e. 2003 and 2004, which we have examined in this study.

To understand the relationship between NDVI and VegWC observed in the three regions, we have examined temporal variations of both variables throughout the summers of 2003 and 2004, for the dominant land cover types in each region (Fig. 3). Two cover types predominate in the NAMS region, open shrubland and woody savanna. The NDVI of shrubland in the NAMS region was nearly constant during the summer of 2003. However, the average VegWC of shrubland pixels nearly doubles (from 0.8 to 1.8 kg m^2) during this same interval. We found an equally large variation of shrubland VegWC in 2004, and for NAMS savanna VegWC in both summers. We have found a different result in IHOP, where the dominant land cover type is grassland. The average NDVI of grassland in IHOP varies from 0.35 to 0.50 throughout the summer. This is a relatively large variation given the range of NDVI observed at pixels in the region (Fig. 2). In contrast, the VegWC of IHOP grassland varies much less, only between 2.0 and 2.5 kg m^2. Cropland in IHOP exhibits VegWC variations that are very similar in magnitude to the natural grassland, only shifted to higher NDVI values.

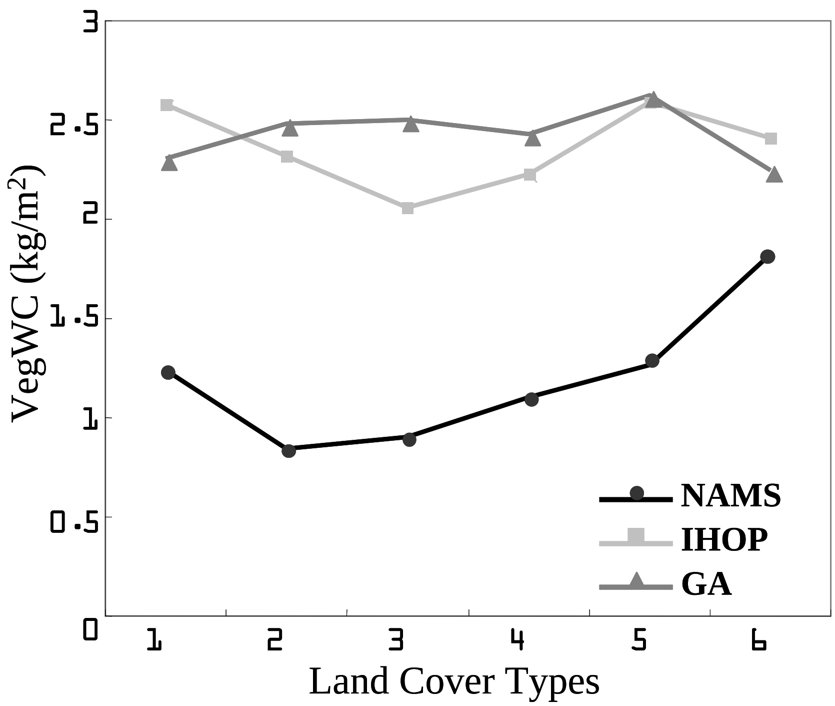


Fig. 3 Biweekly variation between June and September, 2003 for vegetation water content corresponding to NAMS (crop type—open shrublands), IHOP (grassland) and GA (cropland). The figure looks similar for 2004.

The dominant natural cover type in GA is deciduous broadleaf forest. The variations of NDVI and VegWC observed for this cover type are more like those in the NAMS region, than in IHOP. NDVI of the deciduous broadleaf forest in GA was nearly invariant throughout both summers (Fig. 3), varying by only ~0.05, while VegWC varied by almost 1 kg m^2. Cropland in GA exhibited behaviour unlike the natural ecosystems in any of the regions. Both NDVI and VegWC were nearly invariant throughout the summer. Average NDVI only varied between 0.70 to 0.75 and average VegWC between 2.4 to 2.6 kg m^2. Similar results were found from summer 2004 data.

These results suggest that the continental scale patterns of vegetation greenness and water content, and their temporal fluctuations, are not simply a function of spatial variations in climate. Instead, the influence of humans, via management of croplands and probably other factors, has a noticeable impact. The shrubland vegetation of the arid to semiarid NAMS region exhibits the greatest temporal variations of VegWC, both in terms of absolute magnitude and on a percent basis. We expect that the observed fluctuations reflect the vegetation's response to the seasonal increases in soil moisture associated with the onset of monsoon precipitation. The lack of fluctuations in NDVI are reasonable, given the abundance of evergreen shrubs (e.g. Creosote bush) and small trees (e.g. Juniper) that maintain a relatively constant leaf area even under drought conditions (Rambal, 1993). In contrast, the vegetation water content of cropland in GA was nearly constant. We expect that this is primarily the result of the human controls on the water status of these managed ecosystems. The cropland in IHOP, which is not as strongly engineered, varied more like the natural grassland ecosystem in the same climatic zone.

Summary statistics of VegWC from all pixels in the three regions further show the dominant influence of agricultural practices on vegetation water content. Two features of cropland pixels in both IHOP and GA are outstanding. First, the minimum VegWC values are higher than the minima observed in any of the natural ecosystems, in any of the three regions (Table 1). In 2003, minimum cropland VegWC was 2.08 and 1.9 kg m^2 in IHOP and GA, respectively. In contrast, the minima from natural ecosystems varied from 0.32 to 1.27 kg m^2. Second, the spatial variability of VegWC was lower for cropland pixels in both IHOP and GA (CV = 0.13 and 0.10) than in any of the natural ecosystems (CV = 0.21 – 0.41). Values were similar in 2004. We cannot assess whether cropland in NAMS is also outstanding with regards to these two features of the VegWC distribution because there are no 25 × 25 km areas where cropland predominates in this region and hence does not allow us to compute this statistic.

CONCLUSIONS AND DISCUSSION

In this paper we have shown that VegWC increases with NDVI between semiarid and somewhat wetter climates. However, VegWC is not still higher in humid regions that exhibit even greater greenness. In addition, the vegetation water content of natural ecosystems shows considerable spatial and temporal variability compared with crop regions. Overall, the NDVI differences between regions are large (NAMS: 0.1~0.4, IHOP: 0.3~0.7, Tifton, Georgia: 0.6~0.9) whereas the region-to-region differences of VegWC are relatively small (NAMS: 0~3 kg m^2, IHOP: 1~4 kg m^2, Tifton, Georgia: 1~4 kg m^2). This can be explained as follows: vegetation greenness or amount varies significantly with the regional climatic conditions. However, water content varies much less because vegetation tends to conserve water. Under water stress, the photosynthesis process is limited to conserve water. In response, leaf water potential decreases, stomata close and transpiration is lowered (Tanguilnig *et al*., 1987; Cohen *et al*., 2005). Plants in arid regions are particularly adept at maintaining high water content, even when plant water potential is very negative (Kramer, 1983). Here we have shown that continental scale patters of VegWC are consistent with this basic adaptation of plants to water-limited environments.

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