Satellite Technology for Vegetation Drought Monitoring in Taiwan

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ABSTRACT

This study collected the climate data recorded by 355 precipitation stations all over the island of Taiwan from January of 1991 to October of 2002 and 54 satellite images of NOAA taken in the period of 1995-2001. The normalized difference vegetation index (NDVI), vegetation condition index (VCI), temperature condition index (TCI), and drought index (DI) were calculated from satellite data. The correlation between precipitation and DI was analyzed. Based on forest type, Taiwan may be divided into 4 regions, i.e., north, center, south, and east. The forest vegetations were recognized as hardwood forest, softwood forest, artificial softwood forest, grass, and mixed forest. The calculated value of NDVI in winter (November-January) was the minimum, whereas that in summer (May-July) was the maximum. Therefore, changes of NDVI may reflect the conditions of drought. There is no difference in DIs among various regions in all seasons, but the northern area showed a slightly higher DI in summer. DIs of central and eastern regions were higher than those of northern and southern regions in autumn. The values of DI calculated from eastern region showed the highest discrepancy between autumn and winter. Results suggest that satellite images of forest vegetation provide information about drought progression status and may be used to establish an early drought forecasting system.

Keywords: Satellite image, Geographic information system, Drought index.

衛星遙測技術應用於臺灣植群乾旱之研究

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摘要

本研究收集1991年1月至2002年10月約11年間分佈於全臺之355個雨量站氣象資料，以及1995-2001年間共54幅NOAA衛星影像資料，以地理資訊系統建立雨量資料庫，藉由資料庫的整合針對全臺灣地區的降雨模式進行分析，衛星影像分析方面，則利用於計算臺灣各地區之標準差植生(被)指標(數(normalized difference vegetation index, NDVI)、植生狀態指標(vegetation condition index, VCI)、溫度狀態指標(temperature condition index, TCI)及乾旱指標(drought index, DI)，並將降雨資料與乾旱指標結合探討其相關性，研究結果顯示，衛星影像於乾旱研究方面可提供不同角度的資訊，有助於對旱災方面的瞭解與防範。關鍵詞：衛星影像、地理資訊系統、乾旱指標，

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INTRODUCTION

The agricultural productivity in Taiwan is greatly affected by the precipitation and its temporal distribution, and heavy rain and drought would cause severe economic loss. The drought damage ranks the third place in the agro-economic loss caused by agricultural climatic disasters. The annual agro-economic loss caused by drought damage was about five millions US dollars per year during 1961-1982 (Shieh and Chen 1985). While much attention has been focused on meteorological and hydrographic models of drought in Taiwan area, relatively little work has been done on drought monitoring using the techniques of satellite remote sensing.

Chlorophylls in leaf absorb most visible light and spongy mesophyll cells reflect near-infrared light. Therefore, the irradiance discrepancy between red and near infra-red, named vegetation index, can reflect the vegetation growth information (Bouman 1992). The vegetation indices with various combinations of red and near infrared bands show different sensitivities to vegetation changes (Lillesand and Kiefer 1994). Drought-caused change of plant physiology can be monitored by the differences in reflectance of multiple satellite channels, such as normalized difference vegetation index (NDVI), vegetation condition index (VCI) and temperature condition index (TCI) (Leonard and Kogan 1998, McVicar and David 1998, Tokumaru and Kogan 1993, Dewez and Dautrebande 1993). McVicar and David (1998) defined drought as NDVI < 0.18 or VCI < 36%. Tokumaru and Kogan (1993) used NDVI to monitor drought status. Dewez and Dautrebande (1993) combined satellite images and GIS to allocate the drought. Bootsma et al. (1996) developed warning system for drought by combining remote sensing technology and hydrographic model, leading to the decrease of farmers’ loss. McVicar and Jupp (1998) developed a decision system to allocate and broadcast the drought, analyze vegetation damage and estimate soil water for Australia’s government using remote sensing data, GPS and GIS.

Yevjevich (1967) presented the theory of runs to define the drought (Fig. 1). When \( Q_1/Q_0 \) is deficient, where \( Q_1 \) is the continual \( n \) days cumulative precipitation and \( Q_0 \) is the cut baseline. When \( Q_1 > Q_0 \), it means that the precipitation is sufficient. Many drought studies applied this tool to clearly define when to happen, when to end, the length of drought period, and the severity of drought (Dracup et al. 1980, Shen 1976, Zelenhasic et al. 1987). Tabony (1977), Oladipo (1985) and Wilhite (1992) all pointed out that drought is a relative, not absolute,
phenomenon. Besides its physical characteristics, the drought research should take the effect of human society into account. Therefore, defining the meteorological drought status should consider the purpose and information transduction of definition. All patterns of drought are result from the decrease of normal precipitation. The appropriate definition of meteorological drought should immediately indicate the deficiency of precipitation under natural condition and offer precaution in the nick of time to prevent from damage.

The aim of this study was to combine the theory of runs, meteorological data, NOAA remote sensing data, GPS, and GIS in order to establish the interaction model between drought index extracted from NOAA and meteorological drought index collected on ground. The results were then integrated into a drought-warning system for forecasting drought status in different regions of Taiwan.

MATERIALS AND METHODS

STUDY AREA

Taiwan, with a total area of 36,002 km², is located in the Tropic of Cancer. Its topography and terrain are long, narrow and precipitous. In addition to the northeast monsoon type of rain and occasional drizzles, the water resources are from two major rain seasons. One is the Mei-Yu rain season in early summer (May and June) and the other is the heavy rain of typhoon season in summer. The averaged annual precipitation between 1950 and 1990 is about 2,515 mm, which is 2.6-fold of the world average. Although rainfalls are abundant, the precipitation is unevenly distributed in the island. It concentrates in the wet season from May to October, taking 78% of annual water income. The precipitation ratio of wet/dry season is 6:4 in the north, while it is 9:1 in the south, indicating that water resource is more limited for crop during dry seasons. More than 20 rivers in Taiwan are often flooded during wet seasons, yet they are always depleted in water during dry seasons (November-April).

The annual run off is about 668×10⁸ m³, of which the wet and dry periods occupy 77% and 23%, respectively. The run off is only half of the above value in the dry year, and the more toward the south the more depleted in river water. It is 38% in the north and is 9% in the south. Therefore, it is very important to regulate the water resources in the whole island between wet and dry seasons. In the past, the Taiwanese expert defined the non-precipitation days as the amount of rainfall that is less than 0.6 mm. The small-scale drought is the continuous of 50 days non-precipitation and the large-scale drought is the continuous of 100 days non-precipitation (Wang and Chao 1990). Yu et al. (1992) analyzed the continual period and frequency of daily precipitation which is less than or equal to 0.0, 0.6, 2.0, and 5.0 mm. The drought occurrence in Taiwan is periodically. Once it occurs, it affects the livelihood of community, the social activities of local people and the economical events of the industry.

SATELLITE DATA

Since drought does not occur in a small or single area, this study collected meteorological and satellite data of whole Taiwan area in 12 years to monitor the physiological status of different forest vegetations in large-scale. Fifty-four sets of NOAA AVHRR-14 satellite images, covered from 1995 to 2001, were collected to screen the proper images suitable for calculating the vegetation indices. The satellite images were purchased from the Center for Space and Remote Sensing Research of National Central University. A sample of the NOAA AVHRR-14 satellite image is graphed in Fig 2.

Fig. 2. A NOAA satellite image of Taiwan area.

The climate data cover a period from January 1991 to October 2002, including monthly mean temperature
and daily cumulative precipitation, were provided by the Central Weather Bureau. The data were recorded from 355 precipitation stations and 130 temperature stations.

**SATELLITE DATA PROCESSING ALGORITHM**

The original satellite data were processed and corrected by using Geometric Correction made of ERDAS Imagine software. Three wavebands, i.e., channels 1 (CH1), 2 (CH2), and 4 (CH4), were used to calculate the vegetation indices and drought index as follows.

1. **Normalized difference vegetation index (NDVI):**
   
   \[
   NDVI = \frac{CH_2 - CH_1}{CH_2 + CH_1}
   \]  
   
2. **Vegetation condition index (VCI):**
   
   \[
   VCI_i = \frac{100 \times (NDVI_i - NDVI_{\min})}{NDVI_{\max} - NDVI_{\min}}
   \]  
   
   The NDVI is the weekly change of NDVI at the year of i. NDVI_{\min} and NDVI_{\max} are the minimal and maximal NDVI per pixel per week, respectively, during the period of 1995-2001.

3. **Temperature condition index (TCI):**
   
   Values of CH4 of NOAA were transformed to brightness temperature (BT) to represent temperature on the ground.

   \[
   TCI_i = \frac{100 \times (BT_{\max} - BT_i)}{BT_{\max} - BT_{\min}}
   \]  
   
   The BT is the weekly change of BT at the year of i. BT_{\max} and BT_{\min} are the minimal and maximal BT per pixel per week, respectively, during the period of 1995-2001.

4. **Drought index (DI):**
   
   In order to immediately respond to the drought status, VCI and TCI were combined as the following.

   \[
   DI = 0.7 \times VCI + 0.3 \times TCI
   \]  

**ESTIMATION OF DROUGHT INDEX**

The chart below (Fig. 3) was designed to estimate the drought index calculated by NOAA satellite data, according to the model of Tokumaru and Kogan (1993).

![Fig. 3. The flow chart for the estimation of drought index.](image-url)
CLIMATE DATA PROCESSING

When the cumulative value of precipitation in 30 days is greater than 130 mm but is less than 10% of this value in the same period of different years, it is defined as drought. In Taiwan, it will become more absolute if the fix non-precipitation days were adopted as criterion to judge the occurrence of drought, since it will become too much or too less drought for the areas with short or long dry season and even-precipitation. Therefore, the cumulative precipitation in a period is used as the criterion to reflect the fact. However, exceptions occur in extreme weather conditions. Therefore, the probability distribution of precipitation was used and was represented by the probability distribution of cumulative precipitation in the same period.

The \( x_t \) is the cumulative precipitation for continuous \( n \) days including the \( n \) day before random \( t \) days per year. \( F(x_t) \) is the cumulative distribution function of cumulative precipitation from \((t-n+1)\) day to \( t \) day. As shown in Fig. 4, if \( p \) is the probability \((0<P<1)\) for cumulative precipitation less than or equal to \( x_p \), the equation becomes:

\[
F(x_t) = p
\]

(5)

Apparently, cumulative distribution function \( F(x_t) \) will change with time \((\Delta t)\), so there is significant difference in the distribution of continuous \( n \) days of cumulative precipitation between rainy and dry seasons. In addition, the amounts of precipitation recorded in various stations are different, and the precipitation distribution ranges in different periods at the same station and of different stations are also varied. Therefore, in this study precipitation probability \((p)\), in stead of cumulative precipitation \((x_p)\), was adopted to be the criterion of drought. The decimal system was used to demonstrate \( p \) value; for example, \( x_{0.1}, x_{0.2}, \ldots, x_{0.9} \) stand for the relative precipitation and called the 1st, 2nd, … 10th decimal fraction, equivalent to probability 0.1, 0.2, … 0.9, respectively. Taking local variance into account, the \( x_{0.1}, x_{0.2}, \ldots, x_{0.9} \) will be different among various stations and among various periods measured at the same station.

The start of drought is defined as if the continual \( n \) days cumulative precipitation of the day, prior to the day of \( t \) including \( t \) is less than \( x_p \). The end of drought is defined as if the continual \( n \) days cumulative precipitation of the day, before the day of \( t+1, t+2, \ldots, t+d-1 \) is less than \( x_{p+1}, x_{p+2}, \ldots, x_{p+d-1} \) and that of the day before the day of \( t+d \). This means that drought extended over \( d \) days. Therefore, the duration of drought can be defined as the continual period of continual \( n \) days cumulative precipitation reaching \( x_p \) at the same period.

Fig. 4. The distribution function of the continuous cumulative precipitation for \( n \) days.
The severity of drought is the deficiency of cumulative precipitation, or the discrepancy between cut baseline and real precipitation (Fig 1). Since the continuous n days cumulative precipitation was the criterion for judging the drought status in this study, the drought severity would be repeatedly calculated. Thus, the deficiency of cumulative precipitation in the drought extended period was accumulated and then divided by cumulative days (nd) to obtain average daily deficiency of precipitation. Finally, to find out drought severity, multiply the drought extended period (drought duration) and the days before the day of n (n+d-1), shown as the following equation:

$$\text{Drought severity} = \frac{\sum_{t=1}^{n} (x_t - x_{p})}{nd} (n + d - 1)$$

where $x_t$ is the continuous n days of cumulative precipitation, $x_p$ is the cut baseline, and d is the drought duration.

In each case of drought, duration, severity, and frequency are significant characteristics of drought. In the past, drought duration, i.e., non-precipitation days, was used as criterion for drought status in Taiwan area. In the above criterion of drought, the severity was neglected. For example, it is not considered the case of drought if non-precipitation period continues for n-1 days, followed by one day of raining and n-1 days of non-precipitation, according to the criterion of continuous n days of non-precipitation. However, the deficiency of precipitation in the above case is great and may cause disaster. Since the drought severity is the deficiency of precipitation, which is also the discrepancy between cut baseline and precipitation. The amount of precipitation always varies with seasons, it is not appropriate to apply the cut baseline as the definition of drought severity. The continuous n days of cumulative precipitation used in this study varies with season and location.

RESULTS AND DISCUSSION

NDVI

The agricultural drought damage is result from water utilization status of crop. Many factors affect agricultural damage, such as weather condition and crop ability to against water stress. The latter is expressed by the external leaf surface and internal physiological adjustment. Many studies reported that decrease in chlorophyll content and leaf turning color to yellow are common symptoms of drought (Rahman and Yoshida 1985) which affects the spectral sensitivity of plants to satellite remote sensing. This study used 54 satellite images of NOAA covering from 1995 to 2001. The area of Taiwan was divided into north, center, south, and east regions, and the forest vegetation was classified as hardwood forest, softwood forest, artificial softwood forest, grass, and mixed forest. The NDVI of each image plot in all seasons in all sections were calculated from original satellite digital data. It was shown that NDVI of the whole area of Taiwan (Fig. 5) and monthly mean NDVI of each region (Fig. 6) varied seasonally or periodically. In the large scale, the value of NDVI in winter (November-January) was the minimal, and was maximal in summer (May-July). In order to validate the results, a smaller scale area, Chiayi region, was examined in the same period and the same season (Table 1 and Fig. 7). In Chiayi region, values of NDVI in each month of 1994 were always greater than those in the same month of 1998, confirming the above phenomena. Precipitation is one of the environmental factors influencing the seasonal changes of NDVI. As a result, NDVI may be used as an indicator of drought status of a crop or covered vegetation.

Fig 5. The images of seasonal changes of NDVI in Taiwan.
Table 1. The monthly changes of NDVI in Chiayi region in 1994 and 1998.

<table>
<thead>
<tr>
<th>Month</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mean</th>
<th>95% Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan.</td>
<td>0.05</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03 ± 0.00</td>
</tr>
<tr>
<td>Feb.</td>
<td>0.04</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03 ± 0.00</td>
</tr>
<tr>
<td>March</td>
<td>0.07</td>
<td>0.05</td>
<td>0.06</td>
<td>0.06 ± 0.00</td>
</tr>
<tr>
<td>April</td>
<td>0.06</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03 ± 0.01</td>
</tr>
<tr>
<td>May</td>
<td>0.06</td>
<td>0.01</td>
<td>0.03</td>
<td>0.03 ± 0.01</td>
</tr>
<tr>
<td>June</td>
<td>0.14</td>
<td>0.09</td>
<td>0.12</td>
<td>0.12 ± 0.01</td>
</tr>
<tr>
<td>July</td>
<td>0.20</td>
<td>0.11</td>
<td>0.16</td>
<td>0.16 ± 0.01</td>
</tr>
<tr>
<td>1995</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan.</td>
<td>0.18</td>
<td>0.10</td>
<td>0.15</td>
<td>0.15 ± 0.01</td>
</tr>
<tr>
<td>Feb.</td>
<td>0.23</td>
<td>0.14</td>
<td>0.19</td>
<td>0.19 ± 0.00</td>
</tr>
<tr>
<td>March</td>
<td>0.12</td>
<td>0.02</td>
<td>0.05</td>
<td>0.05 ± 0.01</td>
</tr>
<tr>
<td>April</td>
<td>0.24</td>
<td>0.13</td>
<td>0.19</td>
<td>0.19 ± 0.01</td>
</tr>
<tr>
<td>May</td>
<td>0.13</td>
<td>0.03</td>
<td>0.07</td>
<td>0.07 ± 0.01</td>
</tr>
<tr>
<td>June</td>
<td>0.38</td>
<td>0.27</td>
<td>0.34</td>
<td>0.34 ± 0.01</td>
</tr>
<tr>
<td>July</td>
<td>0.27</td>
<td>0.08</td>
<td>0.18</td>
<td>0.18 ± 0.02</td>
</tr>
</tbody>
</table>
CHANGE OF NDVI AND VEGETATION MORPHOLOGY

When going further to a smaller scale, such as individual vegetation (e.g., hardwood forest, softwood forest, artificial softwood forest, grass, and mixed forest), they all exhibited the similar trend in periodical and seasonal changes (Fig. 8). Among them, the broad-leaf forest exhibited the greatest variation.

DROUGHT INDEX

In order to extract the satellite drought index, equations 2 and 3 were used to calculate the vegetation indices VCI, BT, and TCI, respectively. The DI of individual vegetation changed in seasons and months (Figs. 9 and 10). Among them, no significant difference was found in the DI of grass. The broad-leaf vegetation exhibited the most significant change. The DI of some vegetation exhibited significant difference among the various time scales. The phenomenon was apparently caused by the annual growth characteristic of grass. The growth cycle of grass is more sensitive to the time scale so that the DI of grass vegetation exhibited the most sensitive trend than others in the monthly scale.

![Fig. 8. The seasonal changes of NDVI in different vegetations.](image)

![Fig. 9. The seasonal changes of DI in different vegetations.](image)
On the other hand, the DI of grass vegetation showed little seasonal change, in contrast to the changes in broad-leaf vegetation. Consequently, for a longer time scale, broad-leaf vegetation is the best target to monitor the drought status and offers more information pertaining to drought. For a shorter time scale, such as monthly scale or daily scale, the grassland is the best target for monitoring drought status.

METEOROLOGICAL DATA

The precipitation data of fifteen counties collected by 355 stations throughout the island of Taiwan during the period of 1992-2002 were used to analyze the drought characteristics, such as annual drought frequency, maximal drought duration, mean drought severity, maximal drought severity, mean daily drought severity (Table 2), and the continuous 30 days of cumulative precipitation (Fig. 11). Taipei County had the highest drought frequency and Taitung County had the less. But the mean drought severity of the latter was relatively high.

Table 2. The drought characteristics of each county in Taiwan area.

<table>
<thead>
<tr>
<th>Location</th>
<th>Annual Frequency (no year⁻¹)</th>
<th>Mean drought prolong (day)</th>
<th>Maximal drought prolong (day)</th>
<th>Mean drought quantity (mm)</th>
<th>Maximal Drought Quantity (mm)</th>
<th>Mean daily drought quantity (mm day⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taipei</td>
<td>1.69</td>
<td>16.0</td>
<td>86</td>
<td>442.7</td>
<td>1576</td>
<td>27.66</td>
</tr>
<tr>
<td>Taoyuan</td>
<td>1.38</td>
<td>16.6</td>
<td>36</td>
<td>395.9</td>
<td>1443</td>
<td>23.84</td>
</tr>
<tr>
<td>Hsinchu</td>
<td>1.30</td>
<td>27.8</td>
<td>36</td>
<td>333.8</td>
<td>1783</td>
<td>12.72</td>
</tr>
<tr>
<td>Miaoli</td>
<td>0.92</td>
<td>19.0</td>
<td>38</td>
<td>548.5</td>
<td>1766</td>
<td>28.86</td>
</tr>
<tr>
<td>Taichung</td>
<td>0.76</td>
<td>21.2</td>
<td>50</td>
<td>876.8</td>
<td>2290</td>
<td>41.35</td>
</tr>
<tr>
<td>Changhua</td>
<td>0.84</td>
<td>12.8</td>
<td>19</td>
<td>319.1</td>
<td>1019</td>
<td>24.92</td>
</tr>
<tr>
<td>Nanli</td>
<td>0.61</td>
<td>21.3</td>
<td>79</td>
<td>496.5</td>
<td>2291</td>
<td>23.30</td>
</tr>
<tr>
<td>I-lian</td>
<td>0.69</td>
<td>11.8</td>
<td>26</td>
<td>334.4</td>
<td>535</td>
<td>28.33</td>
</tr>
<tr>
<td>Yulin</td>
<td>0.69</td>
<td>15.7</td>
<td>46</td>
<td>509.8</td>
<td>1365</td>
<td>32.36</td>
</tr>
<tr>
<td>Hualien</td>
<td>0.84</td>
<td>13.8</td>
<td>23</td>
<td>270.2</td>
<td>548</td>
<td>19.57</td>
</tr>
<tr>
<td>Taitung</td>
<td>0.46</td>
<td>11.4</td>
<td>15</td>
<td>483.0</td>
<td>913</td>
<td>42.36</td>
</tr>
<tr>
<td>Chiayi</td>
<td>0.69</td>
<td>25.1</td>
<td>49</td>
<td>269.0</td>
<td>510</td>
<td>10.71</td>
</tr>
<tr>
<td>Tainan</td>
<td>0.69</td>
<td>11.7</td>
<td>17</td>
<td>285.6</td>
<td>583</td>
<td>24.41</td>
</tr>
<tr>
<td>Kaohsiung</td>
<td>0.53</td>
<td>15.1</td>
<td>31</td>
<td>482.7</td>
<td>1144</td>
<td>31.96</td>
</tr>
<tr>
<td>Pingtung</td>
<td>0.69</td>
<td>14.6</td>
<td>35</td>
<td>566.0</td>
<td>1709</td>
<td>38.76</td>
</tr>
</tbody>
</table>
CONCLUSION

This study integrated the historical drought data, NOAA satellite images, meteorological data, and threshold to develop methodologies for evaluating cumulative drought severity and ranking. The approach can be used to establish a warning system to predict the start and end of drought damage, and to offer precise and quick information for farmers and government in decision-making.

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