REMOTE SENSING-BASED DROUGHT MONITORING TO DETECT FLASH DROUGHT USING THE EVAPORATIVE STRESS INDEX IN EAST ASIA

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ABSTRACT: Remote sensing-based reliable indicators of rapid-onset of extreme drought conditions can help to improve the effectiveness of drought early warning systems. Flash drought refers to relatively short periods of warm surface temperature and anomalously low and rapid decreasing soil moisture. Further, flash droughts induce large impacts on agriculture and can stress short-term water resources through rapid deterioration of vegetation health and rapid depletion of soil moisture. Flash droughts are difficult to identify using traditional precipitation-based drought indices such as the Standardized Precipitation Index (SPI). The satellite-based Evaporative Stress Index (ESI) defined as the standardized anomaly of the ratio of the actual evapotranspiration (ET) to the potential evapotranspiration (PET). The relationship between rapid drought development and changes in ESI showed that the rapid change index derived from temporal changes in the ESI can provide early warning of agricultural flash drought. In this study, we examine the characteristic evolution of meteorological conditions and ESI drought indicator response associated with several flash drought events in recent years that have impacted agricultural areas over the East Asia region including east China, south-east Russia, Taiwan, Japan, North Korea and South Korea.

INTRODUCTION

Extreme drought events in recent decades have caused extensive damage to natural ecosystems and have contributed to lower agricultural productivity across all over the world. Because droughts collectively impact more people than any other type of natural disaster and can lead to extensive economic losses, the development of drought monitoring technology for rapid drought response is needed (Otkin et al., 2014). Droughts are apparent after a long period of time due to a lack of precipitation, but it is difficult to pinpoint the beginning, extent and end. It is also difficult to objectively quantify each characteristic in strength, size, duration, etc (Vicente-Serrano et al., 2010). Therefore in determining drought, the occurrence and distribution of temporal and spatial droughts should be identified (Nam et al, 2012), and it is important to quantify the droughts and identify and reflect the characteristics of drought areas (Wilhite and Glantz, 1985).

Various indices have been developed and used to determine drought. Typical drought indexes are standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), Palmer Drought Severity Index (PDSI) and so on. SPI is an index that quantifies drought by identifying soil moisture and ground water resources according to the time series using only precipitation. Also, due to its intrinsic probabilistic nature, the SPI widely used to carrying out drought risk analysis. The SPEI takes into account both temperature and precipitation; hence, considered to be a better approach for studying the effects of climate change on drought occurrence. The PDSI was created by Palmer (1965) with the intent to measure the cumulative departure (relative to local mean conditions) in atmospheric moisture supply and demand at the surface. It is an index that quantifies drought by entering data such as precipitation, temperature, solar time and effective soil water volume and comparing the actual amount of rainfall required for climates. However, there are some limitations to the drought index based on these existing ground observation data. First, since these indices analyze the spatial distribution by interpolating the point data, they have to use interpolated values rather than actual values when checking information. These interpolation values cannot take into account the terrain characteristics and may vary in accuracy depending on the density of the measuring points. The second is that it can't be used in areas without accurate weather data.

Remote exploration techniques can compensate for the shortcomings of these point-based data-based drought indices. Using satellite images, data can be acquired for areas that are inaccessible, as well as for a wide range of areas. The availability of satellite images in drought monitoring fields has been verified through a number of studies (Groten, 1993). Some of the typical indices for determining droughts using satellites are Normalized Difference Vegetation Index (NDVI), EVI, LAI and VHI. The NDVI is a graphical indicator used to assess whether the target being observed contains live green vegetation. It is derived from the visible and near-infrared reflectance (VIS–NIR) that it is associated with the fraction of solar radiation absorbed by plants during photosynthesis. Enhanced Vegetation Index (EVI) developed by improving NDVI has been shown to be well correlated with LAI, biomass, canopy cover, and the fraction of absorbed photosynthetically active radiation, and therefore is useful for monitoring seasonal, inter-annual, and long-term variation of the vegetation structure. The LAI reflects the biochemical and physiological processes of vegetation, thereby indicating the productivity of vegetation, and it serves as an input variable in land surface process models. Therefore, understanding the LAI of a crop and its dynamics is very important for a wide range of agricultural studies, such as crop growth monitoring and crop yield estimation (Fang et al. 2011). The VHI is created through calculations of VCI and TCI. It is a drought index that takes into account vegetation and temperature, has been applied for different applications, such as drought detection, drought severity and duration, early drought warning. As such, the indices for determining droughts vary, and the factors used by each index are also very diverse.

This study used ESI, a drought index based on evaporation volume, to determine drought. Evaporative Stress Index (ESI) is a drought index using the ratio of potential evapotranspiration to actual evapotranspiration. There are studies that this index is suitable for drought judgment and is sensitive to flash drought compared to other indices (Otkin et al., 2013), and used the ESI to produce a map of drought across the US (Anderson et al., 2011), and compared it with the existing precipitation-based drought index to confirm its applicability in the detailed drought determination. The research area was conducted on the East Asian countries of South Korea, North Korea, China and Taiwan, and compared each factor to analyze drought sensitivity and trend.

MATERIALS AND METHODS

Evaporative Stress Index (ESI)

ESI is established as a new drought index in which evapotranspiration is compared to potential evapotranspiration using geostationary satellites. ESI represents standardized anomalies in a normalized clear-sky evapotranspiration (ET) ratio where a reference ET scaling flux used to minimize impacts of non-moisture related drivers on ET (e.g., seasonal variations in radiation load). We use the FAO-96 Penman–Monteith (FAO PM) reference ET. There compared use of several different scaling fluxes over the continental U.S. and found the FAO PM equation provided best agreement with drought classifications in the US Drought Monitor and with soil moisture-based drought indices. When considering ETref rather than only using ET, it helps minimize the impact of the seasonal cycle in net radiation at the land surface when assessing anomalies in ET. Comparison of the observed ET flux to a reference ET flux provides a more meaningful depiction of moisture related stress than ET alone because it places changes in actual ET in context with observed changes in the evaporative demand and solar radiation forcing.

ESI is based on Atmosphere-Land Exchange Inverse (ALEXI), a remote sensing model. The ALEXI model computes the ESI through a two-source energy balance model established and factors (surface temperature, plants distribution, solar radiation estimates, and etc.) in the thermal infrared image acquired through the Geostationary Operational Environmental Satellite (GOES). The ESI image provided by the GOES is an 8-day cycle of the world image and provides a composite image of 4-week and 12-week data. Images of acquired indices were processed at intervals of 7 days, 8 days, and 16 days. In this study, data were compared based on ESI acquisition time. For each index, we used a date image with a difference of 1-3 days. Four indices were used to confirm drought trends in each East Asian country.

Extreme drought events in East Asia

Drought can't be explained by simple exponentiation or computation. In this study, instead of using any numerical value representing drought, the actual drought status and press release data of 2017 were used as a drought judgment criterion. Because the size of all drought events for East Asian countries is too large to be investigated, this study has made a judgment on the major drought periods. The season and areas of drought are shown in Table 1. In the case of Japan, there was no press release about the drought situation. Based on the ESI that has been validated by other countries, Japan has determined the drought in 2017 and recorded in the result chapter.

Table 1. Historical extreme drought events in East Asia during recent years

Country	Drought Periods	Drought area
China	April 2017 to June 2017	Northern and Northeastern China
North Korea	June 2017	Southwest North Korea
South Korea	May 2017 to September 2017	Overall area of South Korea (especially the southern region)
Taiwan	January 2017 to February 2017	Overall area of Taiwan

RESULTS AND DISCUSSION

Identification of drought trends using ESI

In South Korea, there is relatively accurate data on the actual drought situation, so Before other countries, it confirmed ESI's drought judgment in South Korea. In South Korea, the drought began in early May, and it was resolved by the rainfall in July and then deepened again in the southern region. Figure 1 shows the spatial distribution of major periods of drought on the Korea in 2017. The drought trends were confirmed in ESI and VHI, and tended to start from April 16th and May 28th respectively. In EVI and LAI, the drought trend couldn't be confirmed. The ESI showed a drought trend two weeks earlier than the actual press release and also accurately reflects the period and administrative district when compared to the actual drought trend in 2017. VHI also showed drought tendencies, but they were later than ESI. ESI and VHI showed extreme drought depths in the central and southern regions, which are major drought regions, and also reflected the resolution of drought. On the other hand, in the case of LAI and EVI, the index value tended to decrease, but it was difficult to judge accurately the drought.

The major drought period in North Korea was in June, and the main damage areas were the western and southern regions. ESI and VHI showed severe drought trends in June and July. And local trends were also the same. As a result of comparing the trends of South Korea and North Korea with relatively accurate data on the status of drought, ESI has been found to be sensitive to the identification of temporal and spatial distribution of drought and VHI was able to identify drought trends, but did not respond quickly and sensitively. EVI and LAI were difficult to identify drought trends, and showed only a tendency to increase or decrease depending on the vegetation growth period.

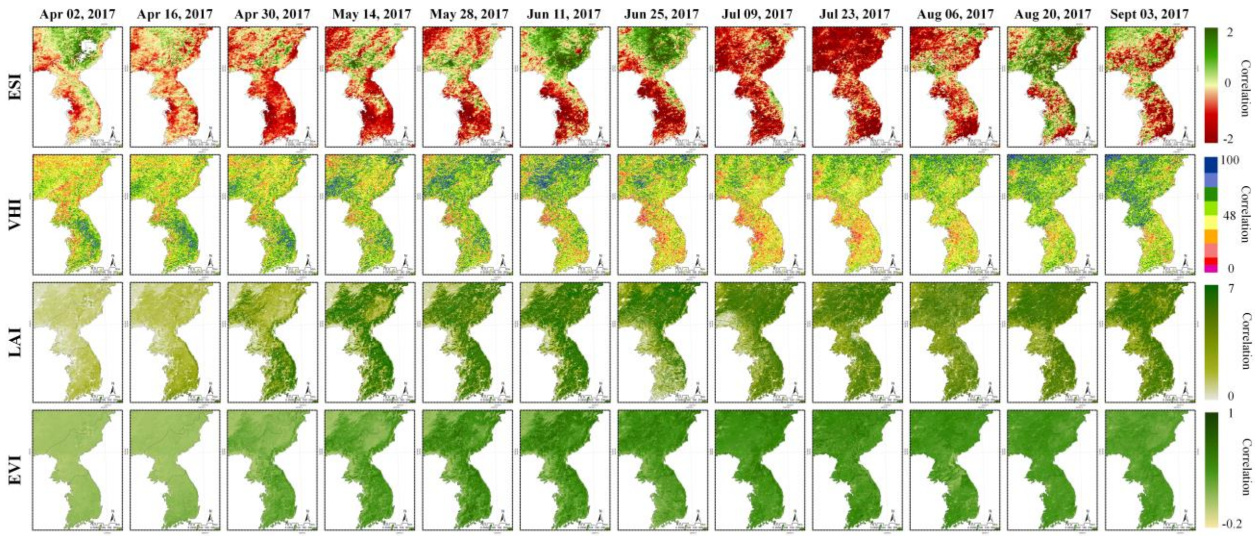

Figure 1. Comparison of trends in each index for South Korea and North Korea.

Table 2. Comparison of monthly mean extreme drought rates by drought indices in South Korea, 2017 (%)

Country	Major area	Indices	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
South Korea	(a)	ESI	7.2	8.9	12.3	**43.0**	**84.3**	**74.4**	**40.4**	7.0	12.5	6.6	1.4	3.4
		VHI	2.1	3.6	13.2	8.4	8.4	**18.6**	**16.5**	4.1	4.9	3.4	1.0	-
		EVI	65.6	72.1	70.3	28.1	13.5	14.5	2.2	2.3	1.9	4.8	39.7	65.9
		LAI	99.7	99.7	99.8	93.6	58.2	57.6	48.1	34.7	42.9	74.8	99.2	99.7
	(b)	ESI	1.9	4.3	0.3	0.7	13.8	17.4	**60.2**	**59.7**	**67.4**	**47.7**	1.3	0.8
		VHI	2.2	2.8	3.1	1.1	3.2	9.5	5.2	4.1	9.5	5.9	1.1	0.5
		EVI	43.7	40.5	33.9	8.1	3.7	7.0	2.5	2.6	2.2	3.9	18.6	34.9
		LAI	96.6	96.3	96.7	75.6	30.0	36.9	37.5	33.3	26.7	43.4	89.0	96.3

(a) : Chungcheongnam-do, (b) : Gyeongsangnam-do

Table 3. Comparison of monthly mean extreme drought rates by drought indices in North Korea, 2017 (%)

Country	Major area	Indices	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
North Korea	(a)	ESI	12.6	13.0	0.4	3.2	**14.7**	**56.9**	**57.7**	**32.7**	3.4	3.4	-	1.4
		VHI	0.3	0.4	5.8	**18.3**	**22.6**	**35.9**	**21.2**	0.7	0.2	1.4	0.4	0.2
		EVI	85.2	86.7	88.6	70.1	41.2	24.6	4.0	3.0	3.0	20.3	67.0	76.9
		LAI	99.9	99.9	100.0	99.5	81.0	78.7	64.0	42.6	63.9	96.1	99.9	98.6

(a) : Hwanghaenam-do

China experienced droughts in May, June and July. In addition, since China's drought was concentrated in the north and the northeastern region, identified drought trends for the region. As can be seen in Figure 2, ESI and VHI showed a tendency for drought from early April in the northeastern part of China. Severe drought trends were observed in both indices until May, June and July, and ESI showed a tendency of temporary drought relief at the end of June. As with previous results, ESI and VHI showed the same results with actual drought in 2017 for the overall drought trends and regions.

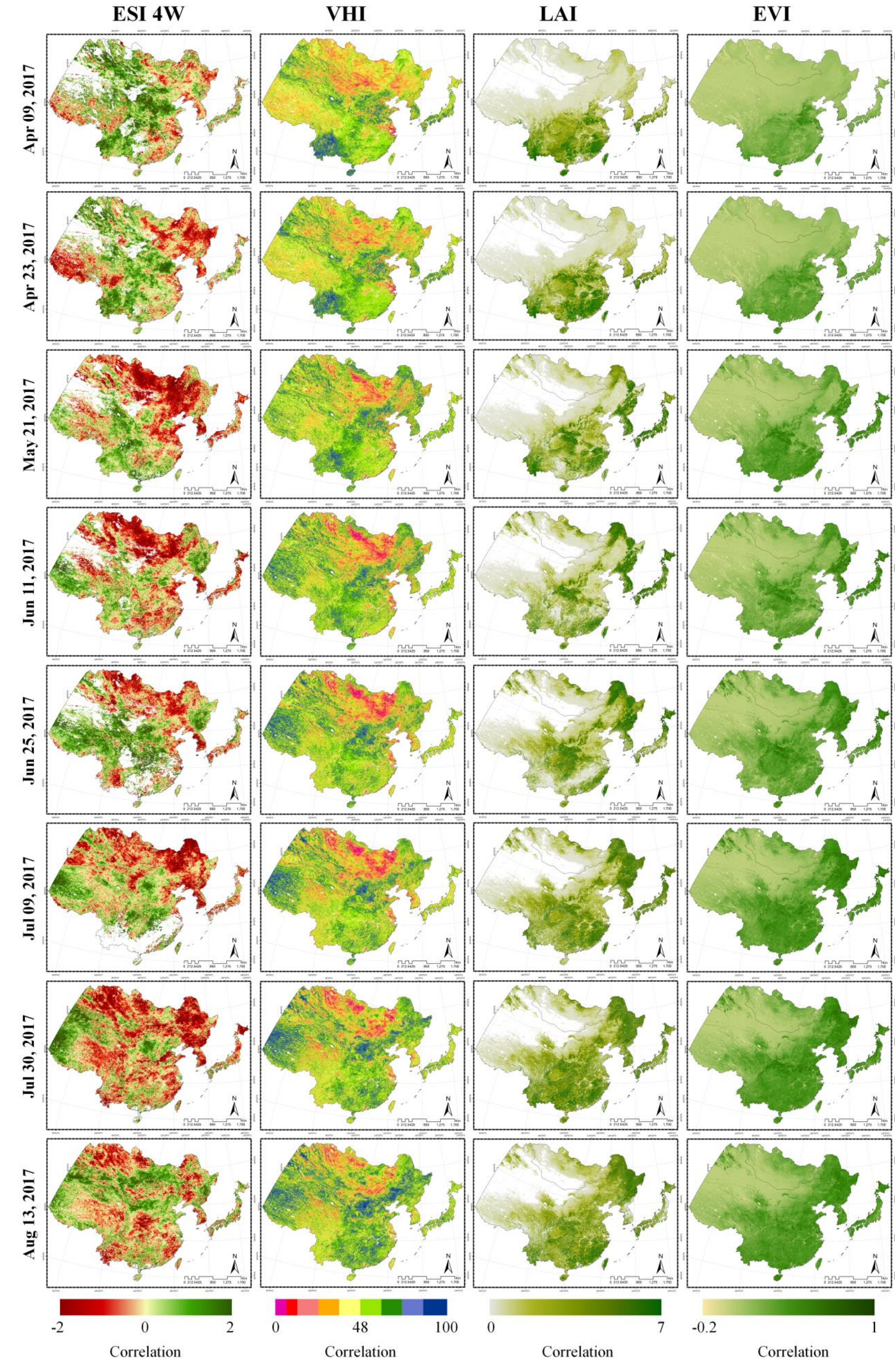

Figure 2. Comparison of drought trends in each index for Mongolia and China

Drought analysis through regional data extraction

The spatial distribution map only identifies the general drought trend. For this reason, the study determined local droughts by extracting only values below severe droughts to identify drought characteristics. This analysis can identify the onset of drought, drought depth and so on for each region. The analysis was conducted by each country, and South Korea, which has accurate data on actual droughts in 2017, was divided into eight administrative regions, while other countries were divided into regions such as eastern, western, northern and southern.

Figures 3 and 4 show extreme drought rates for each country's regions. For EVI and LAI, the drought rate has decreased since March (spring) when vegetation growth began, and has shown a tendency to rise again since October (late fall). The two indices are most affected by vegetation growth than drought. Nevertheless, in the case of LAI, there were some differences in extreme drought rate reductions in some areas. However, it was difficult to say that the LAI represented a regional difference because it did not deviate significantly from the overall increase and decrease trend. On the other hand, in the case of VHI and ESI, differences in specific regions have been identified. For South Korea and North Korea, the ESI showed the same drought region and timing as it really was, and VHI also explained drought in certain areas well. On the other hand, China and Taiwan have not been as apparent as South Korea and North Korea, although they have indicated drought trends during the period they wanted to study. In the case of South Korea and North Korea, the region was divided into administrative regions, showing a more fragmented tendency, while China and Taiwan were divided into large areas, such as northern, western, eastern and southern, with overall results.

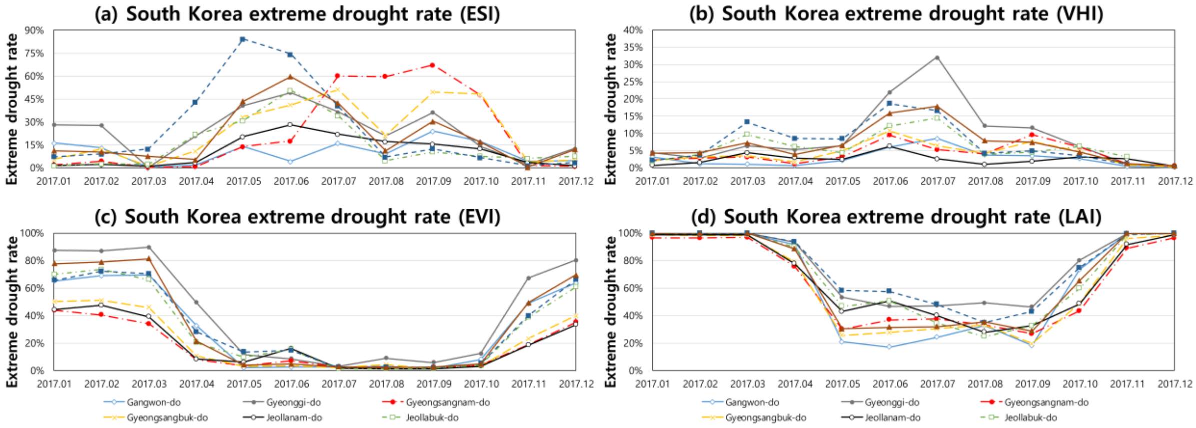

Figure 3. Comparison of extreme drought rates by drought indices in South Korea, 2017

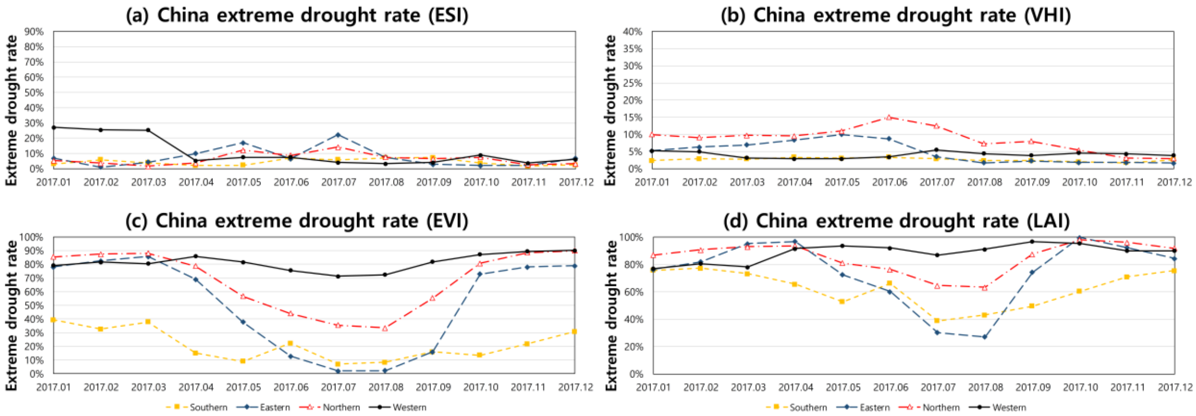

Figure 4. Comparison of extreme drought rates by drought indices in China, 2017

CONCLUSION

This study confirmed the applicability of satellite image-based drought indices to complement point observation data-based drought indices. ESI based on evaporation was used as a droughts index for satellite image. Drought indices using satellite images were compared with EVI, VHI and LAI to identify the drought sensitivity of the ESI. First of all, Drought applicability was confirmed for South Korea, where actual drought status data are present. It then assessed the drought in North Korea, Taiwan and China. For the ESI, all four countries have well reflected the trend for drought periods as defined in this study. Compared to the fact that the ESI reflected both the timing and depth of the drought, the VHI showed the drought trend, although the timing was a little late. EVI and LAI did not show a particular drought trend. The lack of drought trends in EVI and LAI is expected to be due to the fact that vegetation accounts for the largest portion of each index's calculations, which has been heavily affected by vegetation growth. Similarly, these indices are expected to be more suitable for drought analysis if analysed in conjunction with other factors such as land cover and local characteristics.

After checking overall drought trends through spatial distribution maps, only severe droughts in each index were extracted to identify the trend. Analysis using only severe drought values provides a clearer picture of regional differences. As a result, ESI showed drought trends in the same region, in the same period as the study selection period in all four countries. In the case of the VHI, the trend of drought was slightly later than it actually was in South Korea and North Korea, and it was difficult to determine that EVI and LAI showed a drought trend. There has been no apparent drought trend in Taiwan and China, and if analyzed separately in administrative or more subdivided areas, it is expected that there would have been a more pronounced trend like South Korea and North Korea.

In this study, drought tendency was confirmed by looking at the trend of each index which is simply mapped. However, the most important part of the judgment of drought is whether it is possible to judge the area where the crops are growing or the area affected by the actual drought. Therefore, future studies will require accurate drought timing data and information on crop cultivation areas. Also, it will be necessary to calculate the drought index through higher resolution images. Finally, the most encouraging fact confirmed by this study is that the overall drought determination through satellite imagery is highly reliable. Among them, ESI has shown its strengths in sensitivity, which is the most important part of forecasting drought, and therefore it was also advantageous to judge short-term drought. The use of satellite imagery capable of obtaining the same wide range of data across the globe will play a more important role in determining future droughts, and it is expected that the conjugation of ESI, which can make quick and accurate judgments, will increase further. It is also expected to be a great help in establishing measures to prevent disasters such as national drought, small area and local drought judgment, and prompt and accurate warning of drought damage.

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