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The spatial and temporal patterns of agricultural drought and their relationship with rice yield in Kupang Regency

Adi Jamaludin[1], Iqbal P.A. Shidiq*[1], Riza P. Syamsuddin[1], Tito L. Indra[1], Jarot M. Semedi[1], Rokhmatuloh Rokhmatuloh[1], Helmi Z. Mohd Shafri[2], Ramanatalia Parhusip[1]

[1] Universitas Indonesia, Faculty Mathematics and Natural Sciences, Department of Geography, 16424, Indonesia

[2] Universiti Putra Malaysia (UPM), Faculty of Engineering, Department of Civil Engineering and Geospatial Information Science Research Center (GISRC), 43400, Malaysia

* Corresponding author

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Highlights
- Authors chose vegetation health index (*VHI*) to represent drought in the arid area.
- Relationship between agricultural drought with 5 physical conditions and rice yield.
- Agricultural drought was related to elevation, slope, and precipitation.

Abstract: In Kupang Regency, Indonesia, drought occurs almost every year, affecting rice production, which requires a significant amount of water. Despite its frequent occurrence, limited studies have focused on agricultural drought in the region. Therefore, this study aims to analyse the spatial and temporal patterns of agricultural drought and their relationship with rice yield using the Vegetation Health Index (*VHI*). Spatial and temporal patterns were analysed based on physical conditions, while the relationship with rice yield was examined using the Spearman correlation test. The results showed that the most severe droughts occurred in 2015 and 2019, affecting 15,063 ha and 14,187 ha, respectively. The Receiver Operating Characteristics (*ROC*) analysis revealed that *VHI* had an Area Under the Curve (AUC) of 0.732. In addition, agricultural drought had a positive correlation with elevation. The majority of drought occurred in areas with an elevations of 0–25 m a.s.l., alluvial soil types, slopes of 0–8%, and within 0–229 m of water sources. The results also showed that patterns in Kupang Regency closely followed precipitation trends, with a one-month lag due to soil moisture. However, agricultural drought did not significantly impact productivity, as shown by significance values greater than 0.05.

Keywords: agricultural drought, Kupang Regency, Landsat 8, rice yield, vegetation health index

INTRODUCTION

Agriculture is a major sector that significantly contributes to the economy of Indonesia. Alongside forestry and fisheries, this sector accounted for 13.02% of the national total gross domestic product, making it the third largest contributor during the 2019–2022 period (BPS, 2023). Several studies have also shown that it is essential in sustainable structural transformation (Muta'ali, 2019) by contributing to economic growth through exports and employment opportunities as well as ensuring national food security. Within the agricultural sector, the food crop sub-sector is particularly significant, with rice being a major product

(Purnomo and Utami, 2019). According to previous studies, rice (*Oryza sativa*), a member of the grass family, exhibits distinct leaf characteristics, regarding both shape and parts (Sinaga, 2022). In addition, rice cultivated in irrigated fields is often harvested twice a year and requires a substantial amount of water to achieve optimal yields. As a major food crop, rice is highly dependent on natural conditions, specifically climate factors, making it especially vulnerable to production failures.

In 2023, an extended dry season led to widespread drought across various regions of Indonesia (Purwanto, 2023). Drought is defined as a condition in which the availability of water, including surface and groundwater, is insufficient to meet the needs of living organisms. This condition is largely attributed to the climate phenomenon known as the El Niño Southern Oscillation (ENSO) (Surmaini *et al.*, 2015). Historical data from 1830 to 1953 show that 93% of drought events in Indonesia occurred during El Niño periods (Quinn *et al.*, 1971). The phenomenon is also a primary cause of decreased precipitation, one of the most variable climatic factors over time. Droughts can be further classified based on their impacts; one such category is agricultural drought, which occurs when the water demand by crops exceeds the available supply from precipitation or irrigation (Bian *et al.*, 2023).

Previous studies have shown that drought significantly affects the agricultural sector, often rendering thousands of hectares of rice fields uncultivable (Purwanto, 2023). This issue is widespread across many regions of Indonesia, with Kupang Regency being particularly affected (Krisnayanti, Pasoa and Cornelis, 2023). Kupang Regency, located in the Nusa Tenggara region, experiences a dry climate with an average annual precipitation of 1,250 mm·y^{-1}, which is below optimal range required for rice crops (Krisnayanti, Pasoa and Cornelis, 2023). Rice can grow optimally in Indonesia in regions with an annual rainfall of 1500 mm to 2000 mm (Lestari, Simpen and Setiyoko, 2021).

From 1988 to 2017, the Kupang region experienced a decline in monthly rainfall of 0.933 mm and an increase in surface temperature of 0.025°C. Meanwhile, from 2008 to 2017, the area experienced a more significant reduction in rainfall of 9.2 mm per month and a rise in surface temperature of 0.06°C per month (Ledoh, Satria and Hidayat, 2019; Pattipeilohy, Beis and Hadi, 2022). This has led to a decline in crop yields, specifically in rice production, resulting in reduced supply and soaring prices. These trends align with previous research findings that indicate the high risk of drought in Kupang Regency and are supported by the Indonesian Disaster Risk Index (*IRBI*) published by the National Disaster Management Agency (Ind.: Badan Nasional Penanggulangan Bencana – BNPB). The data reveals that Kupang Regency drought risk index has consistently ranked the highest or been among the top two positions from 2015 to 2023. In 2019, a severe drought in Noelbaki Village, East Kupang Sub-district, resulted in crop failure across 70 ha of rice fields. Agricultural drought, a seasonal disaster, remains the main concern of the East Nusa Tenggara Provincial Government (Mauboy, Prasetyo and Fibriani, 2019). To address this issue, various approaches have been employed to detect and monitor agricultural drought, such as remote sensing (Bian *et al.*, 2023).

Several studies have shown that remote sensing provides various advantages compared to other approaches (Bian *et al.*, 2023). It enables the acquisition of coherent information in various regions that can replace or complement conventional meteorological measurement data collected from ground-based stations. Remote sensing has also been widely used to form various drought indices, using both univariate and multivariate analyses (Zhang X. *et al.*, 2017). The drought indices include the Vegetation Condition Index (*VCI*), Temperature Condition Index (*TCI*), Normalised Difference Water Index (*NDWI*), and the Vegetation Health Index (*VHI*). Indices based on a single variable are often considered insufficient for capturing the complexity of drought evolution and its impacts, which are influenced by multiple uncertain factors (disease and land management) (Aghakouchak, 2014). In contrast, indices derived from a combination of Normalized Difference Vegetation Index (*NDVI*) and Land Surface Temperature (*LST*) have proven to be more effective than single-factor indices, especially in dry regions like Kupang Regency (Sun *et al.*, 2020; Krisnayanti, Pasoa and Cornelis, 2023). Consequently, this research aims to investigate the spatial and temporal patterns of agricultural drought and their correlation with rice yield by employing the Vegetation Health Index (*VHI*).

STUDY MATERIALS AND METHODS

STUDY LOCATION

This study was conducted in Kupang Regency, East Nusa Tenggara Province, located in the western part of Timor Island. Geographically, Kupang Regency lies between 9.015'11.78" to 10.022'14.25"S and 123.016'10.66" to 124.013'42.15"E (Fig. 1). The regency is classified as dry, due to the dominance of limestone formations, which are characteristic of the karst area (Sandy, 1997). Timor Island along with Kupang Regency lie in the uplift area because they are located in the subduction zone north of the Bonaparte Basin and the Browse Basin. Karst areas are typically characterised by groundwater system dominated by fractures formed through the dissolution of rock (Khotimah, Supardi and Antriyandarti, 2019). The dissolved limestone contributes to the prevalence of dry land rice farming, which relies heavily on rain-fed irrigation systems.

STUDY METHODS

The *VHI* offers an improvement over *NDVI*-based drought monitoring as it provides a representation of vegetative conditions relative to long-term changes by combining *VCI* and *TCI* (Kogan, 1994). This study used Landsat 8 from 2013 to 2021, specifically using Landsat data from November and December. These months were selected based on the average period of the rice planting in Kupang Regency, which starts in November or December (Naisumu and Manek, 2022). The first stage of image processing involved calculating the *TCI,* which is derived from the *LST* using the following formula (Kogan, 1995a):

$$TCI = 100(T_{\max} - T)/(T_{\max} - T_{\min}) \tag{1}$$

where: $T_{\max}$ = maximum temperature (°C), $T_{\min}$ = minimum temperature (°C).

The next, the *VCI* was derived from the *NDVI*. The decreasing *NDVI* value reflected the occurrence of drought (Wang *et al.*, 2020). Processing of *NDVI* was performed using the following formula:

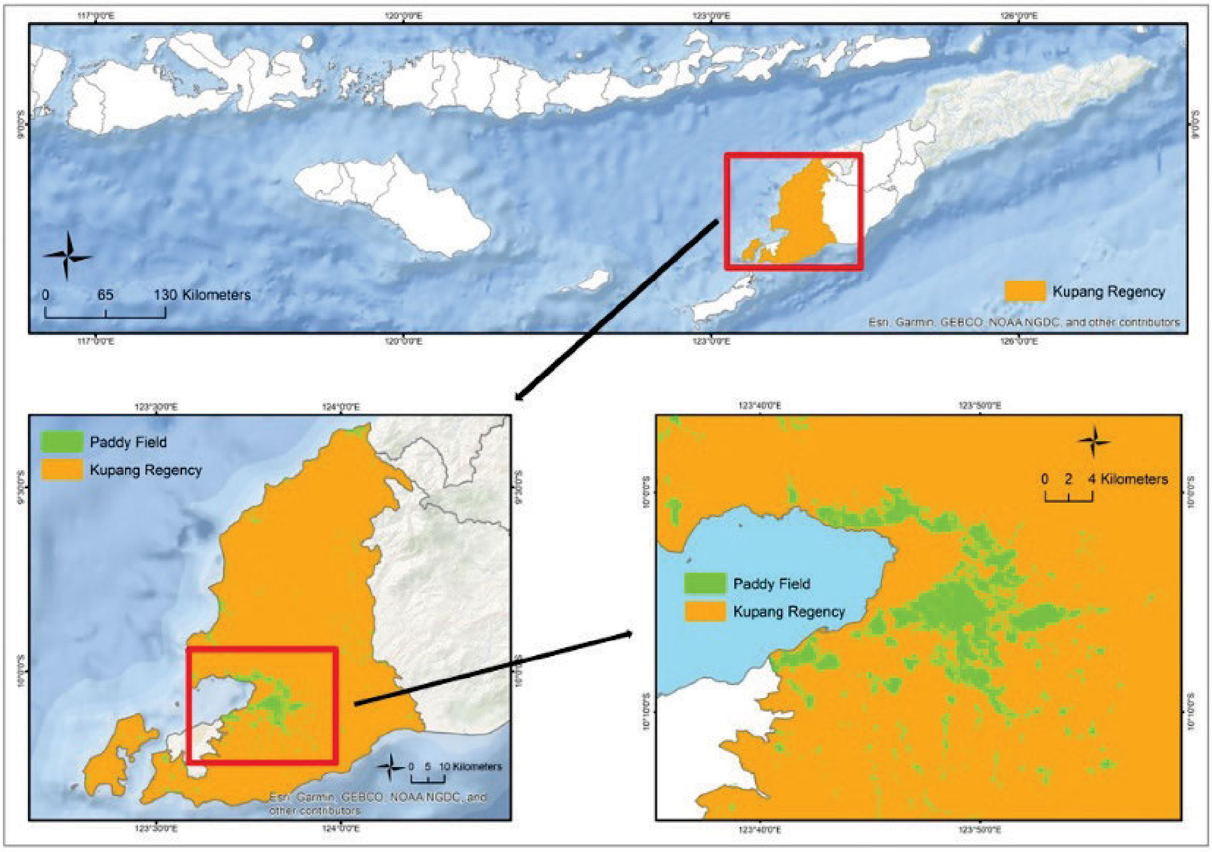


Fig. 1. Study area map; source: own elaboration

$$NDVI = (R_{\mathrm{NIR}} - R_{\mathrm{RED}})/(R_{\mathrm{NIR}} + R_{\mathrm{RED}}) \quad (2)$$

where: R_{NIR} = near infrared band value, R_{RED} = red band value.

After obtaining the *NDVI* value from the Landsat 8 image, *VCI* processing from the *NDVI* value was then performed. processing of *VCI* was carried out using the Equation (3) (Kogan, 1995b):

$$VCI = 100(NDVI - NDVI_{\min})/(NDVI_{\max} - NDVI_{\min}) \quad (3)$$

Drought index used in this study was *VHI*, which was a combination of *TCI* as a temperature variable and *VCI* as a plant health variable to identify agricultural drought more accurately. Processing of *VHI* was performed using the following formula (Kogan, 1994):

$$VHI = 0.5VCI + 0.5TCI \quad (4)$$

After the *VHI* value was successfully obtained, the value of each pixel was subsequently classified according to Zhang L. *et al.* (2017). Values of *VHI* ranging from 0–10 were classified as extreme drought, 10–30 as severe drought, 20–30 as moderate drought, 30–40 as mild drought, and >40 were classified to indicate no drought.

This study used the Spearman correlation test to analyse agricultural drought based on slope, area elevation, soil type, and distance from water sources. These values were extracted using zonal statistical tools on a 30×30 m grid. The analysis was carried out by overlaying agricultural drought maps, generated from *VHI* processing for 2013, 2015, and 2021, with physical condition maps, including the elevation, to represent a normal year (2013), an El Niño year (2015), and a La Niña year (2021) (Andri and Priantoro, 2020). Subsequently, a temporal descriptive analysis was used to assess patterns of agricultural drought based on precipitation data from 2013 to 2021. The Spearman correlation coefficient also was used to analyse the relationship between agricultural drought and rice yield in Kupang Regency, using rice yield data by elevation for 2013, 2017, 2021, 2022, and 2023, along with agricultural drought data obtained from *VHI* processing.

In this study, data validation was carried out to test the level of accuracy of the agricultural drought model using the *VHI* method for May 2024. The validation was based on drought points in rice fields obtained from surveys. Testing the level of accuracy of agricultural drought model was conducted using the area under the curve (*AUC*) value from the receiver operating characteristics (*ROC*) curve. The *AUC* value obtained from the validation ranges from 0 to 1 (Kumbula *et al.*, 2019; Fand *et al.*, 2020; Perlambang, Suharyadi and Jatmiko, 2021). Values of *AUC* in the range of 0.5 to 0.7 were categorised as poor, while those in the range of 0.7 to 0.9 were classified as good and >0.9 – as very good.

RESULTS AND DISCUSSION

AGRICULTURAL DROUGHT

A trend of drought occurrences during El Niño years, namely 2015 and 2019, is showed in Figure 2. This condition occurs because the El Niño phenomenon causes an extreme decrease in precipitation, with 2015 identified as a strong El Niño year (Andri

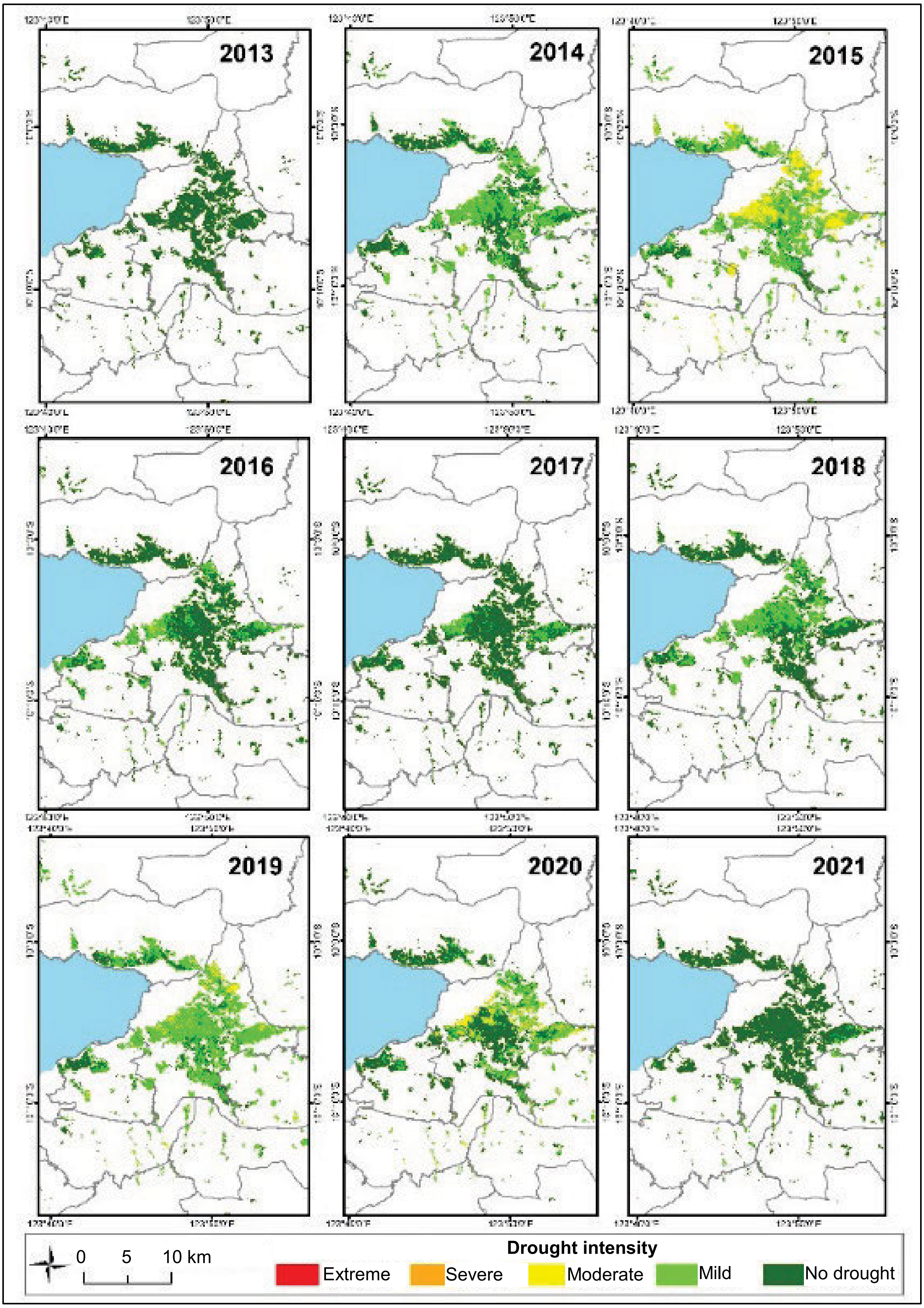


Fig. 2. Kupang Regency agricultural drought map for 2013–2021; source: own study

and Priantoro, 2020). The shortage of rainwater led to a decrease soil moisture content, preventing rice plants from receiving adequate water for their optimal growth.

Based on *VHI,* agricultural drought data validation was conducted using 30 drought samples with a multistage sampling method. The resulting map was validated against the 2024

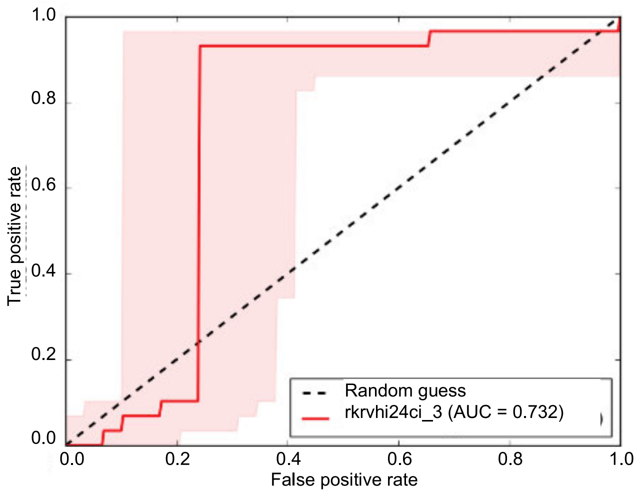


Fig. 3. Results of agricultural drought map accuracy test; rekrvhi24cl_3 = the agricultural drought map for 2024; *AUC* = area under curve; source: own study

agricultural drought map. The accuracy test was conducted using the *ROC* curve. The results are presented in Figure 3.

The *ROC* curve analysis showed the *AUC* value of agricultural drought map of 0.732. This value was higher than the *AUC* threshold for random prediction, showing that the model performs better than random prediction (Perlambang, Suharyadi and Jatmiko, 2021). The *AUC* value depicted moderate predictive accuracy because it was in the range of 0.7–0.9 (Kumbula *et al.*, 2019). When compared to previous drought related studies using the *ROC* accuracy test, this study, which produced an *AUC* value of 0.732, was in the middle between the results reported by Yildirak and Selcuk-Kestel (2015). This had an *AUC* value of 0.8389 and the results of the study by Luqman, Wiyono and Hidayah (2022) had an *AUC* value of 0.7189. The results of the accuracy test show that this model is acceptable for predicting agricultural drought, but further study and development were needed before applying it to other regions.

PHYSICAL CONDITIONS AND SPATIAL AND TEMPORAL PATTERNS OF AGRICULTURAL DROUGHT

This study used Spearman's correlation analysis to examine the relationship between agricultural drought, as derived from *VHI* processing, and physical factors, such as elevation, slope, soil type, and distance from water sources. The *VHI* value and the elevation of the statistical test area were extracted using the fishnet grid and zonal statistic tools. Subsequently, the values were subjected to Spearman's correlation analysis, with results presented in Table 1.

Table 1 shows a correlation between agricultural drought and both elevation and slope, while no significant relationship was observed between agricultural drought and soil type or distance from water sources. Relationship between *VHI* values and elevation had positive correlation coefficient, indicating that higher elevations were associated with higher *VHI* values, or the less severe drought conditions. However, in 2021, the correlation coefficient was negative, suggesting that higher elevations experienced lower *VHI* values and thus appeared drier. The different result is likely due to the presence of extensive cloud cover in the 2021 imagery, which affected the *VHI* values. Clouds block reflectance and thermal emissions, skewing *NDVI* and *LST* values, critical for *VHI*. This led to underestimated or distorted *VHI* values, masking true ecological conditions like drought severity or vegetation stress. Similar issues have been reported in previous studies (Bento *et al.*, 2020; Kloos *et al.*, 2021). To minimise these effects, this study applied cloud masking and utilised composite imagery techniques during image processing.

The positive correlation in 2013 and 2015 aligns with findings by Wang *et al.* (2021), who stated that there was a relationship between elevation and agricultural drought, implying that agricultural drought occurred more often in highland areas compared to lowland regions. This patters may be explained by differences in precipitation and temperature: lowland areas typically receive less rainfall than higher elevations. Additionally, higher air temperatures in lowland areas lead to increased evapotranspiration rates, making these areas more susceptible to drought.

Similar to elevation, the results of the statistical tests showed a direct relationship between agricultural drought and slope in Kupang Regency, suggesting that steeper slopes corresponded to higher *VHI* values, or less severe drought. These results differed from those of Kimball *et al.* (2017), who reported that agricultural drought was more likely to occur in steep areas than in flatter regions. However, the geological context of Kupang Regency differs significantly. Unlike volcanic regions, Kupang is composed primarily of limestone characteristic of a karst region (Sandy, 1997). This makes Kupang difficult to cultivate land for agricultural production as limestone does not have good water storage capacity. Karst regions are known for thin soil layers, hence, water penetrates the underground layer and allows the surface to dry (Cahyadi, Ayuningtyas and Prabawa, 2013). Therefore, the thin soil layer in Kupang Regency makes slopes exposed to surface runoff. This differs from the conditions of the Santa Ana Mountains in Orange County, California, United

Table 1. Correlation between agricultural drought with physical conditions in Kupang Regency

Year	Elevation		Slope		Soil type		Distance from water sources	
	significant	correlation coefficient	significant	correlation coefficient	significant	correlation coefficient	significant	correlation coefficient
2013	<0.001	0.047	<0.001	0.018	0.405	−0.144	<0.001	−0.137
2015	<0.001	0.069	<0.001	0.047	0.240	−0.178	0.505	0.023
2021	<0.001	−0.095	0.006	0.007	0.313	0.171	0.346	−0.034

Source: own study.

States, where volcanic formations and thicker soils promote different hydrological behaviours (Kimball *et al.*, 2017). In Kupang Regency, drought tends to be more prevalent in flat areas, likely due to greater water evaporation rates over expansive, exposed surfaces.

When associated with soil type, the results of statistical tests showed no relationship between agricultural drought and soil type in Kupang Regency. This contrasts with the statement by Wu, Qian and Chen (2017), which suggested soils with higher sand content are more prone to drought due to their lower water-holding capacity. This discrepancy may be attributed to the karst characteristics of the Kupang region, dominated by thin soil layers. This limits soil moisture, reducing amount of water available to rice plants during drought periods. Subsequently, the variability in soil texture within the same soil type may have contributed to the lack of correlation observed. Such variations can occur due to differences in physical, chemical, and biological properties of the soil at a given location (Kushartono, 2009). Furthermore, low precipitation over a long period could deplete the presence of water in the soil beyond levels accessible to plants.

Similar to soil type, statistical test results showed no correlation between agricultural drought and the distance from water sources in Kupang Regency. This contrasts with the results of Dimyati *et al.* (2024), who reported that the rice fields located closer to water networks were less likely to experience drought. However, this condition could occur because rivers in the region were also experiencing drought, rendering river water unusable for agricultural purposes. Decreasing precipitation, combined with the region's karst geology, likely contributed to the drying of river systems. In karst landscapes, water tends to quickly penetrate the underground layer. The results of the study were also supported by field observations that despite their proximity to the river network, rice fields did not get enough water due to the closure of dam outlets in several areas, including Kupang Tengah and Kupang Timur Regencies (Hayong, 2019).

The spatial patterns of agricultural drought were observed in relation to regional elevation and are shown in Figure 4. The extent of agricultural drought in 2013, 2015, and 2021, classified by elevation zones, is presented in Table 2.

Based on Figure 4 and Table 2, the rice field areas in the lowland districts that experienced the most extensive drought were predominantly located in flat slope areas with gradients ranging from 0–8%. This contrasts with previous studies, which reported that agricultural drought was more likely to occur in steep areas than in flat zones (Kimball *et al.*, 2017). This discrepancy can be explained by geological conditions of Kupang Regency, which is characterised by karst terrain. The most drought-affected areas were also dominated by alluvial soil types, which were dominated by clay or loamy soil textures. Although clay or loamy soil textures have higher water storage capacity, prolonged periods of low precipitation combined with the thin layer of soil contributed to drought conditions. In terms of the distance from water sources, the largest drought-affected areas were located 0–269 m of a river. This pattern was because the rivers also experienced drought conditions, rendering them unusable for irrigation by farmers.

Figure 5 shows a tendency for the *VHI* values to follow the precipitation patterns. Regarding precipitation, the discrepancy between the decline in precipitation and the decrease in *VHI* values was consistent with the results of Ding *et al.* (2021), who reported that a series of drought events typically begins with a decline in precipitation, leading to meteorological, hydrological, and finally agricultural drought. During the absence of rain, plants could obtain water from soil moisture, or water bound to the soil that could be used by plant roots. This condition is likely due to the decrease in precipitation and *VHI* values (Ayu, Prijono and Soemarno, 2013). Notably, low *VHI* values occurred in 2015 and 2019 which were El Niño years coinciding with significant reductions in precipitation. The 2015 El Niño was a phenomenon with an extremely strong intensity and was associated with drought (Andri and Priantoro, 2020).

Table 2. Area of agricultural drought in Kupang Regency in 2013, 2015, and 2021

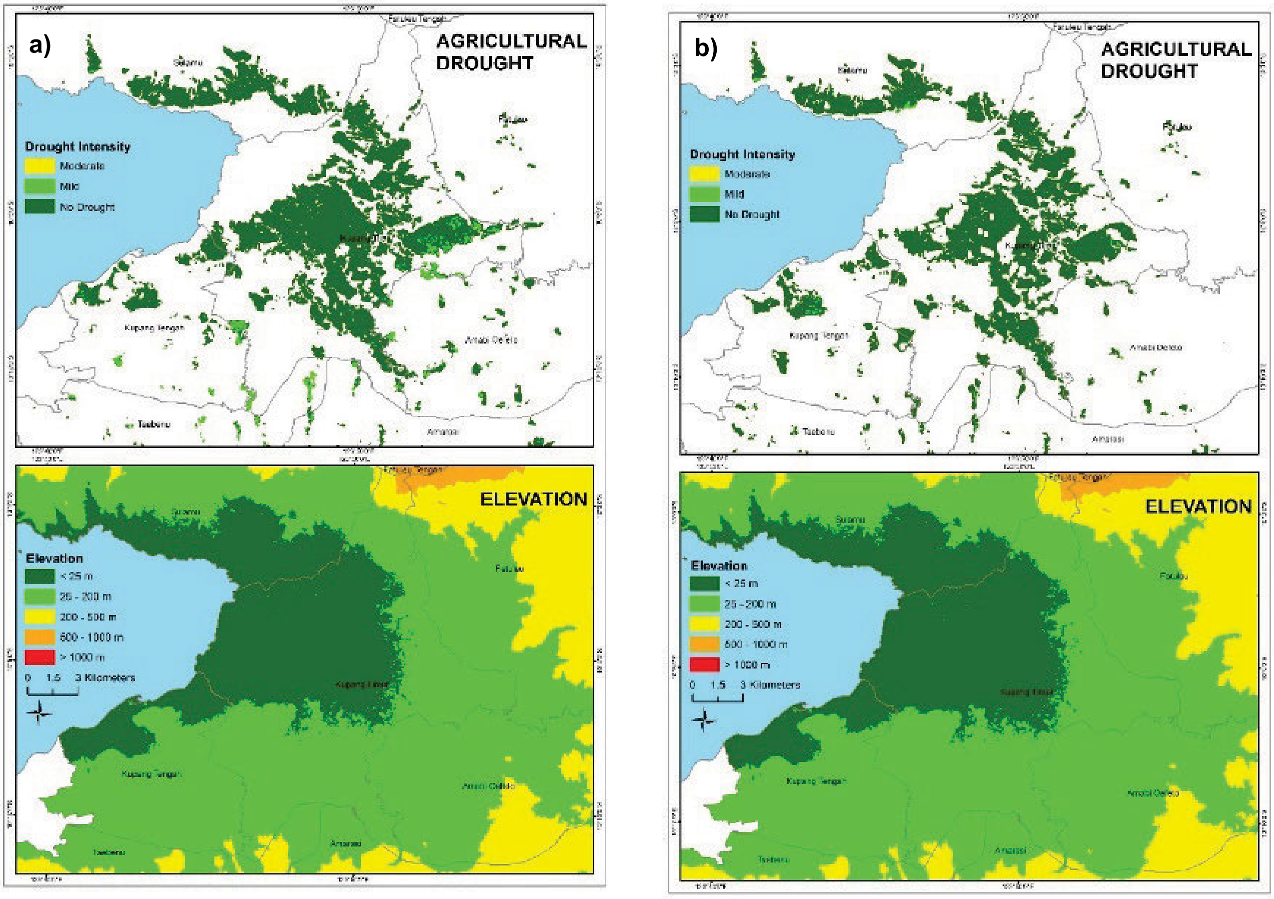
Drought level	Area height	Area (ha) in		
		2013	2015	2021
Moderate drought	low	2	2,005	0.18
	medium	2	1,080	2
	slightly high	0	70	0
	high	0	6	0
	very high	0	2	0
Mild drought	low	611	6,078	532
	medium	367	4,566	872
	slightly high	22	870	111
	high	0	293	14
	very high	0	83	0.71
No drought	low	7,891	1,683	8,944
	medium	5,259	1,159	5,327
	slightly high	1,110	526	1,048
	high	405	144	408
	very high	95	9	94

Source: own study.

RELATIONSHIP BETWEEN AGRICULTURAL DROUGHT AND RICE YIELD

No relationship was found between two variables, namely agricultural drought obtained from *VHI* processing with rice yield based on elevation, in Kupang Regency in 2013, 2017, 2021, 2022, and 2023 (Tab. 3). However, the statistical test in 2021 showed relationship between agricultural drought and rice yield. The difference in the results in 2021 with other years was due to the large number of clouds in the 2021 image.

The results of the correlation test obtained differ from the study by Chere *et al.* (2022) which stated that there was a positive relationship between agricultural drought based on *VHI* and crop yield. This condition was due to temporal differences in crop yield data. Furthermore, the *VHI* value which was initially in pixel units was generalised into regional height units, hence, it lost detail. In addition, the presence of grass and secondary crops planted by farmers as substitutes for rice contributed to high *VHI* values, which would otherwise have been low due to drought conditions. One of the crops replacing rice is corn, which serves



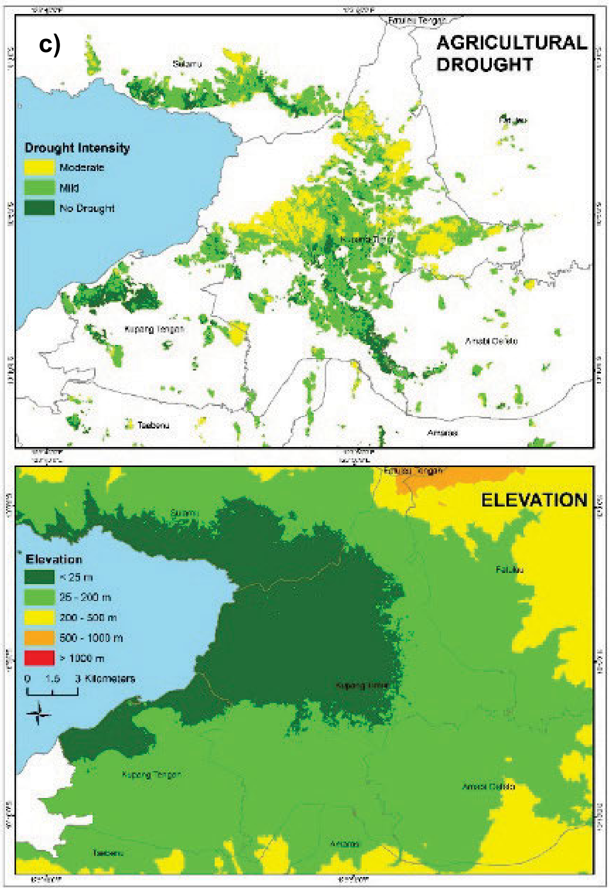


Fig. 4. Spatial patterns of agricultural drought in Kupang Regency in: a) 2013, b) 2015, c) 2021; source: own study

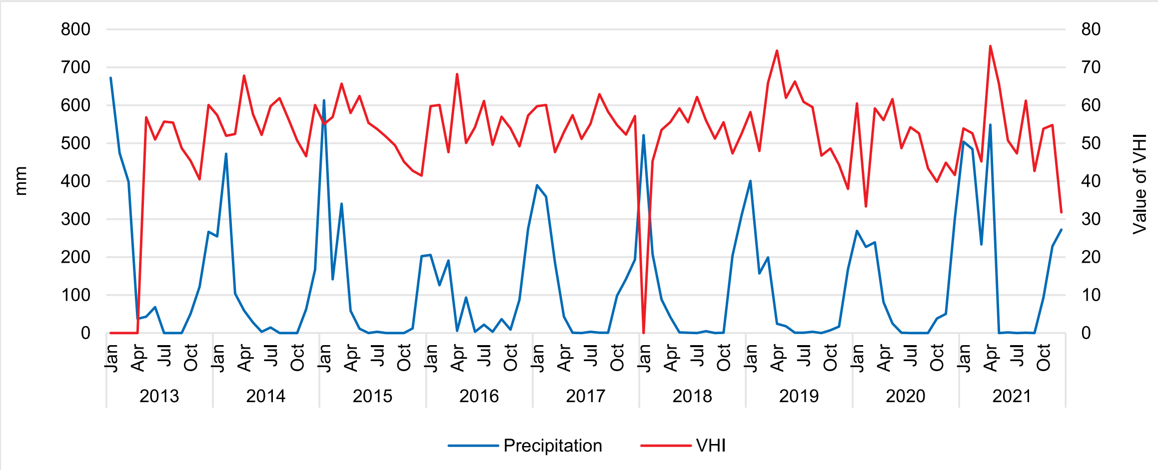


Fig. 5. Comparison chart of precipitation and vegetation health index (*VHI*) values; source: own study

Table 3. Results of correlation test of agricultural drought with rice yield in Kupang Regency

Year	Significance	Correlation coefficient
2013	0.303	0.140
2017	0.712	−0.050
2021	0.417	0.111
2022	0.015	−0.321
2023	0.240	−0.158

Source: own study.

as an alternative crop due to its ability to thrive in regions with an annual rainfall of 800 to 1200 mm. The cultivation of these alternative crops has led to high pixel values in paddy fields, which would typically indicate drought conditions. The lack of relationship between agricultural drought and rice yield was due to the complexity and challenges in measuring and comparing the impacts of drought temporally and spatially (Lu, Carbone and Gao, 2017; Virtriana *et al.*, 2022). This complexity occurred because crop yields and production were controlled by many factors including advances in science and technology. Limited data was a challenge because there was no rice yield data based on a more detailed level from the sub-district over a long period.

CONCLUSIONS

In conclusion, agricultural drought in Kupang Regency, as determined by vegetation health index (*VHI*) values, is closely related to regional elevation, with lower-lying areas (0–200 m a.s.l.) experiencing more frequent drought. These areas are characterised by alluvial soil, gentle slope gradients (0–8%), and proximity to water sources (0–229 m). The Spearman's correlation test confirmed a direct relationship between agricultural drought and elevation and slope gradient, but no significant relationship with soil type or distance from water sources. Drought patterns in Kupang Regency align with precipitation trends, intensifying during El Niño events. A one-month time lag between reduced precipitation and increased drought levels was observed, attributed to soil moisture retention. Analysis of receiver operating characteristics (ROC) demonstrated the reliability of *VHI* with an area under curve (*AUC*) of 0.732. However, statistical tests revealed no direct relationship between agricultural drought and rice yield, likely due to the complexity of factors influencing yield, such as data limitations, remote sensing biases, and other environmental variables.

To address the identified drought risks, this study recommends the integration of *VHI*-based monitoring with active mitigation measures. These measures include optimising irrigation systems, promoting drought-resistant crop varieties, and implementing soil conservation practices. By combining monitoring with proactive strategies, this approach aims to enhance drought resilience, mitigate adverse impacts on agricultural productivity, and support ecosystem health in Kupang Regency.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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