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Abstract.

The rise in global production of horticultural tree crops over the past few decades is driving technology-based innovation and research to promote productivity and efficiency. Although mango production is on the rise, application of the remote sensing technology is generally limited and the available study on retrieving mango phenology stages specifically, was focused on the application of optical data. We therefore sought to answer the questions; (1) can key phenology stages of mango be retrieved from radar (Sentinel-1) particularly due to the cloud related limitations of optical satellite remote sensing in the tropics? and (2) does weather have any effect on phenology? The study was conducted on a mango farm in the Yilo Krobo Municipal Area of Ghana. Time series analysis for radar vegetation index (RVI) values for 2018 – 2021 was used to retrieve three key phenology stages of mango namely; Start of Season (SoS), Peak of Season (PoS) and End of Season (EoS). Characteristic annual peaks (in April/May for the major season and October/November for the minor season) and troughs (in June/July for the major season and December/January for the minor season) in the phenology trend of mango were identified. Rainfall and temperature explained less than 2% and 14% of the variability respectively in mango phenology. The application of radar remote sensing provides a cutting edge technology in the assessment of mango phenology, particularly in the tropics where cloud cover is a big challenge. This study offers an opportunity for production efficiency in the mango value chain as understanding of the crop's phenology allows growers to manage farm and post-harvest operations.

Keywords.
Remote sensing, Radar Vegetation Index, Synthetic Aperture Radar, Mango (Mangifera indica), Phenology, Sentinel-1

Assessing the potential of Sentinel-1 in retrieving mango phenology and investigating its relation to weather in Southern Ghana

Introduction

Globally, the production of horticultural tree crops has seen a consistent rise over the past few decades (Dehnen-Schmutz et al., 2010; Gehrig et al., 2009). Among them is the mango, although not the major crop in production today, but has been venerated as the king of fruits due to its nutrition and health benefits, taste and smell among others. In order to boost mango production, there is the need for the application of technologies and approaches that are capable of promoting and predicting yields as well as providing insight into the life cycle trends of the crops during the growing season (Panda et al., 2010). Additionally, the approach must be robust enough to retrieve various key phenology stage information on the crop's growing cycle such as the start of season (SoS), peak of season (PoS) and end of season (EoS) (DEA, 2021). Knowledge of mango phenology is key to its proper management and yield improvement (Ramírez et al., 2014). It helps in farm management decision on the appropriate time and quantities of farm inputs such as fertilizer application and irrigation (Wang et al., 2019).

Traditional means of assessing crop phenology and other biophysical properties are often laborious, time consuming and limited in terms of area coverage (Usha & Singh, 2013). Remote sensing therefore provides a valuable option in assessing crop phenology at varying scales by covering large areas within a relatively shorter time and with less labour input (Usha & Singh, 2013). In spite of the promise shown by the remote sensing approach to conduct this kind of assessment, and the successful application of optical remote sensing in this field of study, it is often limited by cloud cover in tropical countries like Ghana (Mandal et al., 2020). This therefore results in the reduction in the number of satellite images that are available for time series analysis and leads to inaccuracies in the estimation of crop biophysical properties including phenology. Fortunately, synthetic aperture radar (SAR) data such as the free Sentinel-1 (S1), has the ability to penetrate through clouds and can acquire data over an area during the day and night (Aher et al., 2014; Mandal et al., 2020). However, radar backscatter signals are sensitive to viewing angle, surface roughness and moisture content (Kim & van Zyl, 2009). Previous studies to retrieve phenology using SAR focused mainly on forests and annual crops such as winter wheat, rapeseed, rice and mustard among others (Haldar et al., 2021; Nasrallah et al., 2019; Son et al., 2021; Tůma et al., 2021; Zeng et al., 2016 ; Zheng et al., 2016). The application of SAR in retrieving phenology of horticultural tree crops such as mango is a relatively new area of research.

Additionally, studies have shown that weather variables such as temperature and rainfall influence crop phenology in a variety of ways (Makhmale et al., 2016; Ramírez et al., 2014; Wiley, 1993). For example, optimal water supply from either adequate rainfall or irrigation is required after the dormancy period to influence flowering in mango (Wiley, 1993). According to Makhmale et al. (2016), monthly and annual rainfall are crucial to the growth and development of the mango fruit. However, rainfall during flowering is harmful since it can lead to total crop failure (Makhmale et al., 2016). The rise and fall in temperature have the potential to advance or retard the changes in the phenology of mango at both the vegetative and reproductive stages.

To overcome the limitations associated with the application of optical remote sensing in retrieving phenology, this study was conducted to assess the potential of Sentinel-1 radar data in retrieving key phenology stages of mango and to explore the effects of weather on phenology in the Yilo Krobo Municipal area of Ghana.

Materials and Method

Study area

The study was conducted on a 19-year-old, 45 ha mango farm near Somanya in the Yilo Krobo Municipal Assembly (YKMA) in the Eastern Region of Ghana situated between longitude 0° 2' E to 0° 3' W and latitude 6° 2' N to 6° 4' N. Production from the YKMA accounts for more than 50% of Ghana's total mango production (Akotsen-Mensah et al., 2017; Zakari, 2012). Ghana is a West African country bordered by Togo to the East, Cote D'Ivoire to the West, Burkina Faso to the North and the Gulf of Guinea to the South (Figure 1). The area is characterized by a bi-modal rainfall season with the major rains in May/June and the minor rains in September/October with annual rainfall ranging from 750 mm to 1600 mm. Temperatures range between 24.9°C and 30°C. The Pentacom farm, where the study was conducted is located on a relatively flat land with isolated undulating portions.

Data acquisition and analysis

Farm data on phenology and other management activities spanning the period 2018 – 2021 were obtained from the Pentacom Farms. The data consists of dates that different physiological changes of the mango crop such as flowering and fruitset (F/FS) around January/February, fruit development (FRD) between February and May, fruit maturity (around April/May when the fruit reaches its development peak and is ready for harvesting) and harvest (M/H) around June/July for the major production season. Additionally, flushing (FLU) of both leaves and flowers and finally, dormancy occur mainly after harvesting in a given season (around December/January). Furthermore, literature on mango phenology cycles in West Africa, including Ghana were reviewed (Vannière et al., 2013; Vayssières et al., 2014). In total, 238 Sentinel-1 images projected in the UTM Zone 30 N coordinate system, covering the Pentacom Farms and spanning the period 2018 – 2021 was acquired from the DE Africa platform for analysis (DEA, 2021). The data was subsequently aggregated into 2-week composites covering the four-year period for further analysis. Sentinel-1 is composed of two (S1A and S1B), synthetic aperture radar (SAR) satellite constellation operating at C-band (5.404 GHz), launched in April, 2014 and April, 2016 respectively, with a temporal resolution of 6 days (Frison et al., 2018; Haldar et al., 2021). The SAR data provided by the DE Africa platform is a Radiometric Terrain Corrected (RTC) gamma-0 SAR backscatter data that has been corrected for variations due to observation geometries (DEA, 2021).

The data was acquired in an interferometric wide swath (IW) mode with dual polarization, vertical-vertical (VV) and vertical-horizontal (VH) (DEA, 2021; Frison et al., 2018; Mandal et al., 2020). The dual polarization is useful for Forestry, Agriculture, Wetlands and land cover classification applications (Frison et al., 2018; Kussul et al., 2016; Mandal et al., 2020 ; Nguyen et al., 2016). The two bands (VV and VH) with a spatial resolution of 20 m were used to compute the radar vegetation index (RVI) in equation 1 below (Charbonneau et al., 2005 ; Kim & van Zyl, 2009):

$$RVI = \frac{4 \times \mathrm{VH}}{(VV + VH)} \tag{1}$$

Phenology stages retrieved in the study by Torgbor et al. (2022) were used as a guide for this study. The medians of a total of 105 RVI data points were obtained from the 2-week aggregation of the 238 raw data points. These points were subsequently grouped by months and averaged for all the years in the time series and plotted to reveal the phenology trends. The 105 data points were plotted as raw data and the monthly aggregates were plotted as smooth lines to show the consistency between the RVI peaks and troughs. Three key metrics were extracted from the RVI values across each annual time series. They include the start of season (SoS), peak of season (PoS) and end of season (EoS). Southern Ghana experiences a bi-modal production seasons (i.e. major and minor). The day of year (DOY) with the lowest RVI prior to fruit maturity was extracted as the SoS and plotted. In this case DOY 15, a period of flowering and fruitset was selected. Similarly, the DOY with the highest RVI value in a given season is extracted as the PoS.

This is usually expected to coincide with the months where fruit development and maturity occurs. Invariably, biomass levels at this stage are expected to be highest. Finally, DOY (in a given month) where RVI values are lowest after harvest in a given season is extracted as the EoS. This normally occurs within two weeks after the harvest period. Since the Sentinel-1 data provides information about the structure and volume of the tree canopy, harvest is expected to change its structure and volume thereby reducing the RVI values at the EoS. According to the growers, SoS, PoS and EoS for the major season occur around the months of January/February (J-F), April/May (A-M) and June/July (J-J) respectively. Similarly, the minor season's SoS, PoS and EoS around the months of August/September, October/November and December/January respectively, depending on when flower induction is done.

Monthly average rainfall data covering 48 months (January 2018 to December 2021) was obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) platform. CHIRPS is a platform that has leveraged on high resolution (approximately 5km) satellite-based precipitation estimates in combination with station data to build and deliver complete, reliable and up-to-date datasets on global precipitation for early warning drought monitoring systems. It has data spanning from 1981 to near-present. Minimum and maximum temperature (Tmin and Tmax) data covering 48 months was obtained from ERA5 which is the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data for the global climate and weather from 1979 to date (www.ecmwf.int, accessed on 11 February, 2022). It has an hourly temporal resolution. A simple linear regression analysis was conducted on the RVI versus rainfall and temperature to check for trends and possible relationships. Furthermore, the weather data (rainfall and temperature) was plotted together with the RVI metrics derived from the Sentinel-1 data to graphically display any possible relationships.

Results and Discussion

Retrieving key phenology metrics from Sentinel-1

Three key phenology metrics including SoS, PoS and EoS were retrieved from the Sentinel-1 data. Southern Ghana's mango production has an advantage over other countries in the sub-region due to the two seasons (major and minor) experienced. Figures 1 and 2 show the periods (DOY and corresponding months) in the major and minor seasons where all the key stages occur. For example, in 2018, SoS occurred in January (15th DOY) with an RVI of 0.770 and peaked on the 105th day with an RVI of 0.848 (PoS) and finally troughed on the 166th day with an RVI of 0.792 (EoS). Table 1 provides details on the various seasons and DOYs across the four-year time series when the key phenology events occurred. This result confirms the observation made by Zakari (2012) and Van Melle and Buschmann (2013) in studies conducted in Africa.

Table 1. Day of year (DOY) and corresponding RVI values retrieved for the key phenology stages for the major and minor mango production seasons of the Pentacom Farms in Ghana

RVI METRICS												
	MAJOR SEASON						MINOR SEASON					
YEAR	SOS_{sma}		POS_{pma}		EOS_{ema}		SOS_{smi}		POS_{pmi}		EOS_{emi}	
	DOY	RVI	DOY	RVI	DOY	RVI	DOY	RVI	DOY	RVI	DOY	RVI
2018	15	0.770	105	0.848	166	0.792	196	0.803	319	0.865	349	0.840
2019	15	0.823	46	0.841	135	0.762	166	0.770	288	0.798	349	0.758
2020	15	0.763	106	0.768	167	0.734	197	0.720	289	0.789	350	0.756
2021	15	0.738	105	0.775	166	0.732	196	0.749	319	0.787	349	0.763
AVERAGE	15	0.774	105	0.800	166	0.757	196	0.761	319	0.801	349	0.779

For the minor season, SoS, PoS and EoS usually occurred in the months of August/September (A-S), October/November and December /January of the ensuing year (D-J) respectively, in the annual time series (Figure 1 and 2). The Fruit development (FRD) and Flushing (FLU) stages as observed from the Sentinel-2 study, were assumed to occur between the SoS – PoS and PoS-

EoS continuum on the left and right sides of the bell-shaped curve respectively as shown in Figure 1. This is because, fruit development is a continuum and studies, as well as expert judgement in the industry, have shown that on the average, 3 - 5 months are required for mango fruits to reach maturity after fruitset. In view of that, fruitset occurring in January will eventually reach maturity by April/May and will be harvested in June/July. Thus, major season harvesting usually takes place around June/July and the minor season around November/December. There are times when the minor season harvesting enters January/February of the ensuing year, depending on the time of flower induction and fruitset as well as prevailing weather. Although the southern part of Ghana experiences bi-modal production around June/July and December/January each year, the study by Torgbor et al. (2022), generally showed a unimodal peak in some cases probably due to cloud. The current study however, which used Sentinel-1 data, was able to show the bi-modal production appreciably. This observation affirms Frison et al. (2018) position that SAR has the potential of producing more accurate results on phenology than optical data.

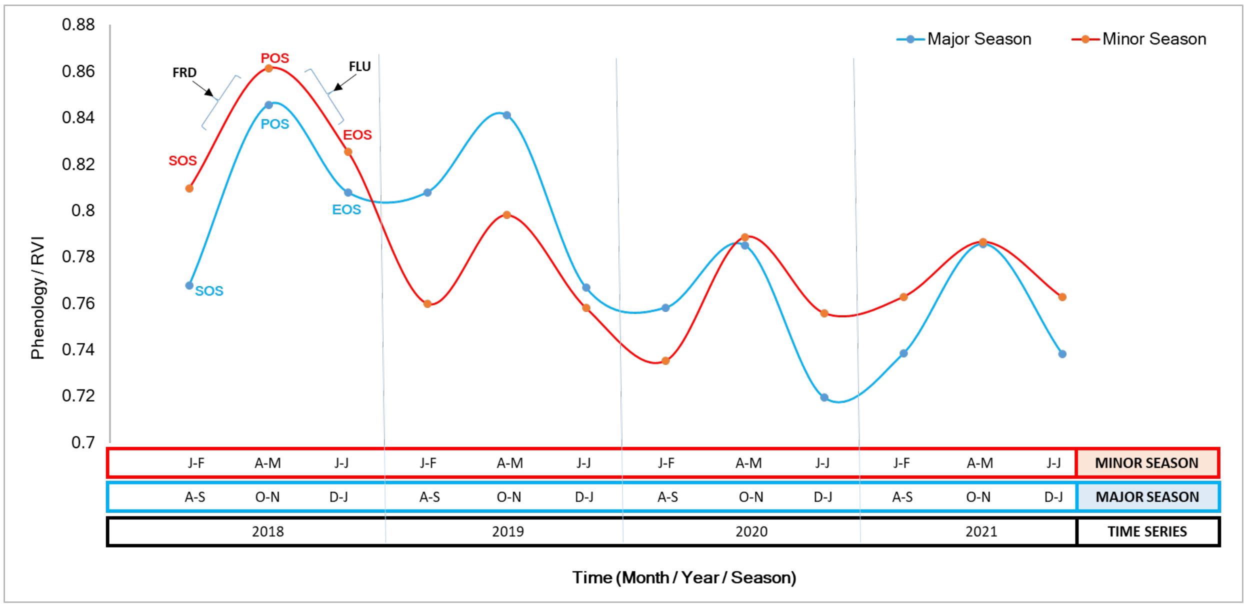

Figure 1. Mango phenology trend showing annual SoS, PoS and EoS metrics for the major and minor production seasons from 2018 to 2021. The fruit development (FRD) and FLU stages occurring on the left (SoS - PoS) and right (PoS – EoS) side of the bell-shape curve respectively.

Figure 2 shows a combined annual trend for both the major and minor mango season's phenology from 2018 to 2021. Generally, RVI values for SoS, PoS and EoS were higher in 2018 than all the other years in the time series. RVI values for 2020 and 2021 were quite similar and stable. Given also in Figure 2, is an unusual drop in the RVI values for 2019. This drop was the result of pruning that affected the vertical structure and drastically reduce the amount of biomass in the canopy. An interview with the Farm Manager of the Pentacom Farms revealed that the company undertook a massive pruning in the farm in 2019 to improve hygiene and also prepare the farm for a better production in the subsequent years. The trend in the phenology showing higher RVI values in 2018 could be a result of higher canopy volume of vegetative growth with less reproductive growth. The uncharacteristic trough around July, 2020 as shown in Figure 2 above, could be a result of variations in weather conditions in the area or the effect of the massive pruning event in 2019.

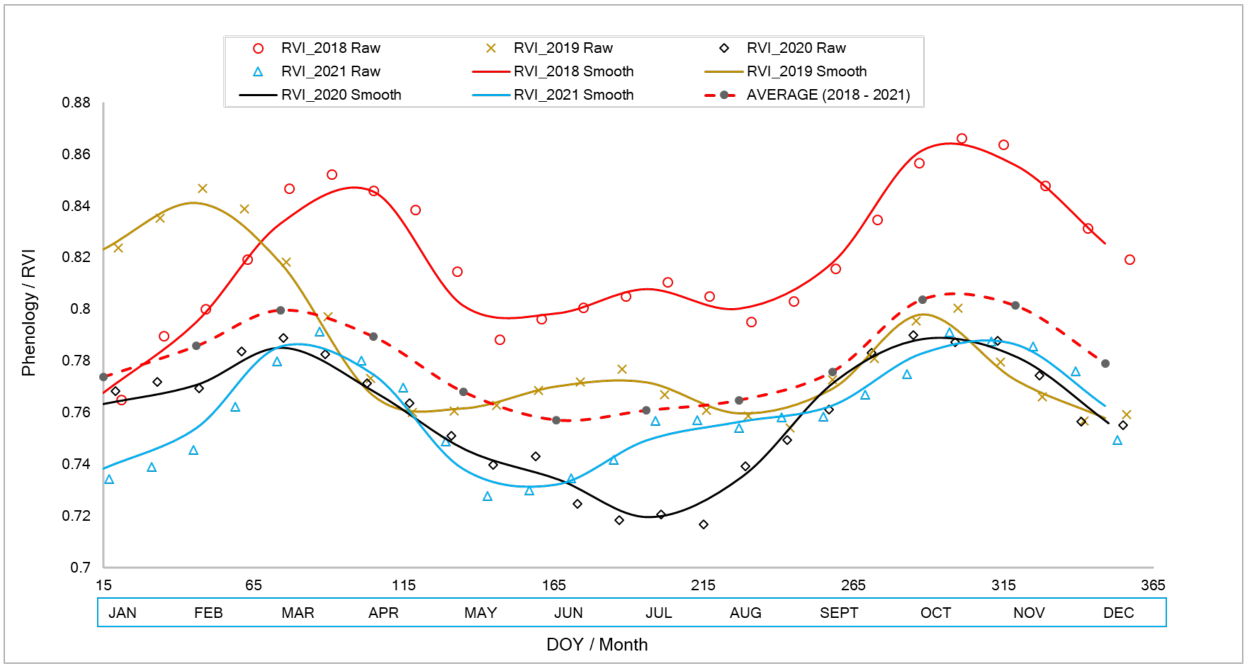

Figure 2. Annual phenology trends from 2018 to 2021 showing the relationship between the raw (coloured points) and their corresponding smoothened (coloured lines) data.

Effects of rainfall and temperature on mango phenology

The relationship between RVI, Rainfall and Temperature (Tmax and Tmin) was evaluated (Figure 3). The temperature generally peaks around February/March and November/December and troughs around June/July. This trend is similar to what happens in the phenology cycle of the mango plant as observed from the Sentinel-1 data. Makhmale et al. (2016) showed that relatively higher air temperatures is required during growth and fruit development phase of the mango phenology. Tmax and Tmin explained 14% and 0.23% respectively of the variability in the phenology of mango in the Pentacom Farms as shown in Figure 4(a – d). In view of this observation, temperature may not have caused the general drop in the phenology trend (RVI values) from 2019 to 2021. In effect, temperature alone may not explain the variability in the phenology of mango in the study area. Remote sensing therefore provides a huge opportunity for such phenology assessments as it has the potential to retrieve key phenology metrics of mango.

Additionally, it was observed that for the effect of temperature to be shown in the phenology of the mango crop, a period of approximately 1-month time lag is required. For example, the peak observed in the phenology in the months of April 2018, February 2019, March 2020 and March 2021 were generally preceded by a month of high temperatures (Tmax) of 35.7, 36.2, 37.7 and 36.1 degrees celsius respectively. The contribution of Tmax increased from 14% to 23% after the introduction of the time lag in the phenology data. It can therefore be argued that the physiological property of the plant that the radar system measures is the effect of the weather (Tmax) on the crop in the previous month. For example, the effect of rainfall or temperature in March may be felt in the following month, April.

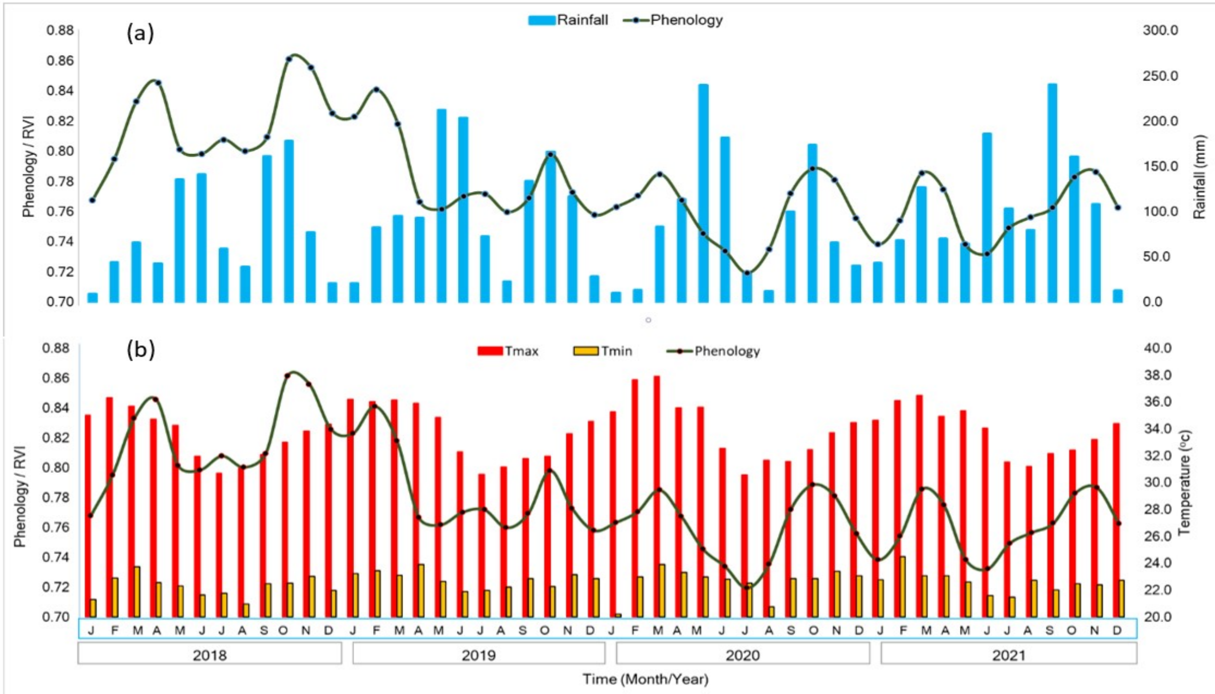

Figure 3. Temporal profile of mango phenology for the Pentacom Farm showing the interaction between phenology and weather variable (rainfall (a) and temperature (b)) across the four-year time series (2018 - 2021).

Although rainfall has an effect on the phenology of mango in the study area, it did not appear to influence the phenology much. It explained less than 2% of the variability in the data (Figure 4(d)). Peak rainfall appears to correlate at some points (Figure 3(a)) but does not have any regular trend as was found in Tmax. Since rainfall and temperature alone cannot explain or predict the phenology of mango, remote sensing has a huge potential in retrieving various phenology stages of the crop. This therefore provides an opportunity for yield prediction and timing of inputs application as well as harvesting of the crop. Frison et al. (2018) in a study to assess the potential of S1 data in monitoring temperate mixed forest phenology in France, concluded that S1 has a high potential for monitoring vegetation. Their results support the findings of this study that since the data is not sensitive to the atmosphere and the impact of weather on phenology is minimal, phenology estimates from S1 could be more accurate than using optical data.

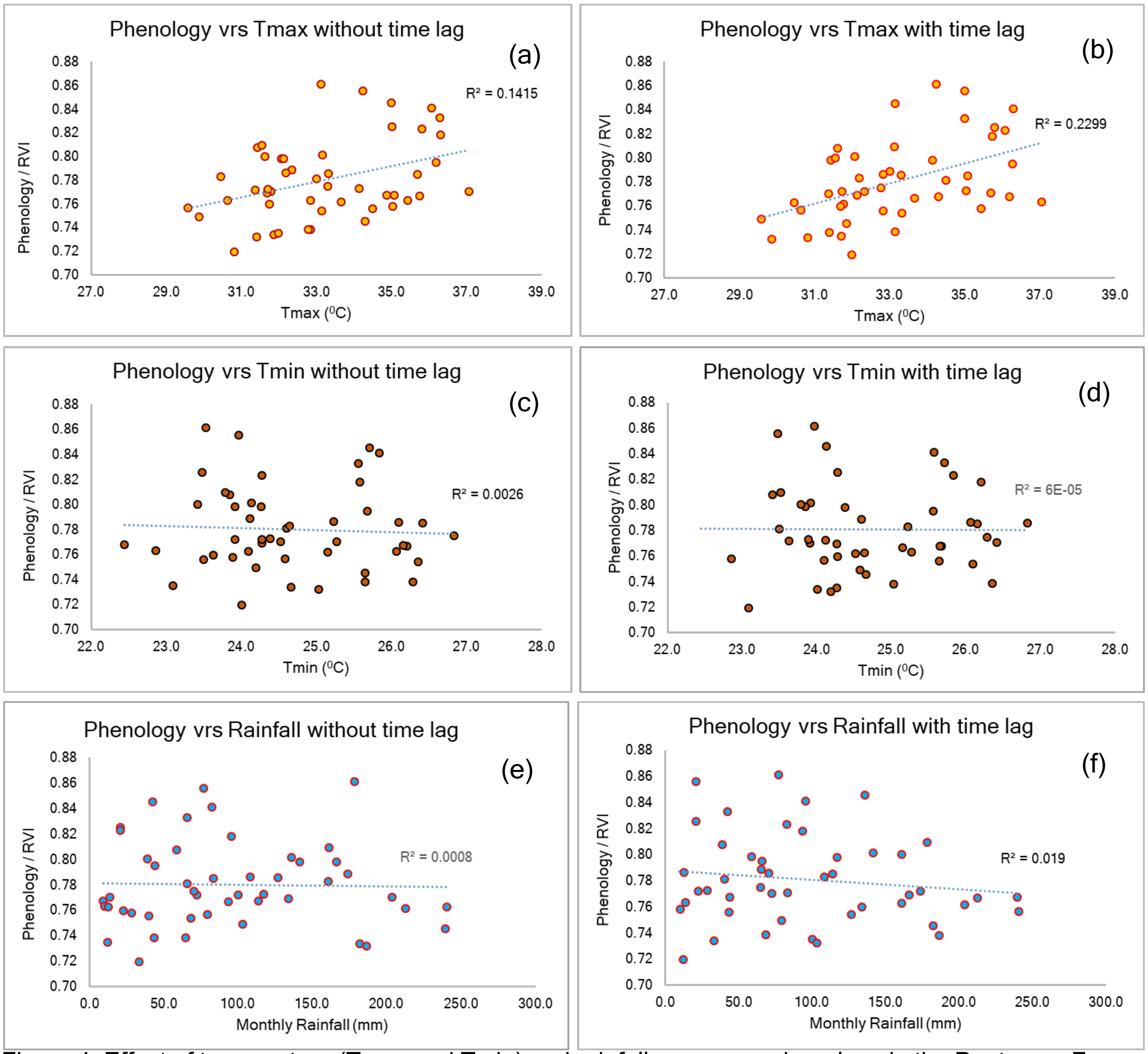

Figure 4: Effect of temperature (Tmax and Tmin) and rainfall on mango phenology in the Pentacom Farms. A 1-month time lag was introduced into the analysis to test the effect of Tmax/Tmin (which is observed during the day when photosynthetic and other physiological activities of the plant are high/low) and rainfall on phenology.

Conclusions

The study was targeted at assessing the potential of Sentinel-1 in retrieving phenology stages of mango and investigating the effects of weather on phenology at the farm level using time series data from 2018 to 2021. Three key phenology stages namely; SoS, PoS and EoS which corresponded with three main parts (i.e. F/FS, M/H and D) of the bell-shaped phenology curve. Our study has therefore demonstrated the feasibility of SAR to retrieve key phenology stages of mango. Although the study was conducted on one farm, it holds a huge potential in differentiating phenology of different horticultural tree crops and farms as well as its application at a regional scale. Our study has demonstrated the potential of Sentinel-1 in identifying the bi-modal production season in southern Ghana which was not possible using Sentinel-2 from the previous study. It has also created the path for the identification and contribution of different variables such as rainfall, temperature and management strategies among others that will serve as input to yield models. Finally, the study has shown the place of active remote sensing (Sentinel-1) in identifying various critical phenology stages that will aid in the timing of inputs application, maturity and harvesting periods to minimize wastage in the mango value chain.

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