Projecting Spatiotemporal Shifts in Phenology of Southeast Asian Commodity Crops Through A Simple Growing Degree Day Model For Near and Midterm Climate Change Scenarios

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Abstract
Understanding the impacts of climate change on crop phenology is vital for regional agricultural planning. This is especially pertinent to agricultural regions like Southeast Asia (SEA) dominated by small-holder modes of production. This study projected the Days to Maturity (DTM) trends for key commodity crops across the region over different future emission scenarios. A simple Growing Degree Day (GDD) model was used with data from ERA5 and CMIP6 projections (2026 - 2045, 2046 - 2065) in order to estimate trends in crop phenology until the mid-century. The results demonstrate that crop maturity across the region has already begun advancing due to rising temperatures, a trend projected to accelerate into the future. The magnitude of these shifts exhibits significant spatial heterogeneity and varies considerably based on crop species as well as seasonal timing. The majority of SEA will experience varying degrees of phenological acceleration, while some special sub-regions will remain unaffected. These findings underscore the necessity of continued emission mitigation and adaptation strategies. The gradual onset of temperature-driven shifts provides a critical temporal window to implement measures such as climate control technologies, agroforestry, and resilient crop varieties. Ultimately, urgent action is imperative to safeguard the smallholder-dominated agricultural systems that form the agricultural backbone of SEA.

Key Words: Phenology, Agriculture, Climate Change, Southeast Asia, CMIP6

Introduction

Southeast Asia (SEA) is one of the most agriculturally productive regions on earth. Notably, the majority of agricultural work is done through small holder farms and informal farmers (Boughton et al. 2024; Briones 2021; NIS-MAFF 2024; Lim and Kaur 2025; OECD 2025). Despite this, the region maintains an impressive position in global agriculture. For instance, six of the ten largest rice producers of 2024 belong to SEA (Food and Agriculture Organization [FAO] 2024a). The region is also home to net importers that rely on their more productive neighbors for agricultural needs such as Brunei, Singapore, and Philippines (Azffri et al. 2022; Dawe 2024; Diehl et al. 2020). Nonetheless, shocks to agriculture in the region are sure to manifest not only regionally but also in the global supply.

Modelling studies that predict diverse climate change-induced impacts for crop cultivation and yield in the SEA region exist. For instance, sugarcane yield has been projected to rise along with increasing precipitation in Vietnam (Lee & Dang 2018). Conversely, Tan et al. (2021) projected a decline in Malaysian rice yields due to higher maximum temperatures and an increase in main-season yields alongside a decrease in off-season yields stemming from shifts in minimum temperatures (Tan et al. 2021). Areas that can adequately support cultivation are also projected to decrease, notably in important rice regions like the Mekong Delta (Dang et al. 2020). This decline is also expected to occur for tree crops, with a greater magnitude in the maritime continent than the mainland (Appelt et al. 2023).

Being poikilothermic organisms, the internal temperature of plants is dependent on their immediate external environment. Because their biophysical processes are thermally dependent, the timing of plant phenological stages is inextricably linked to ambient temperatures (Trudgill et al., 2005). In fact, the onset of phenological stages has been used to reconstruct historical temperature records through the use of the Degree Days/Growing Degree Days (GDD) concept (Aono & Kazui 2008). GDD utilizes daily accumulated heat units to estimate the phenological timing of crops and has been widely used for its practicality (Paredes et al. 2025a). Models such as FAO's Aquacrop, which simulates crop yields and plant responses to environmental variability (Raes et al., 2023a), utilize the simple GDD model. Specifically, Aquacrop describes the duration or time required to reach developmental stages in GDD units instead of days (Raes et al., 2023b).

The Intergovernmental Panel on Climate Change (IPCC), has reported a clear increasing trend for global mean surface temperatures (Gulev et al. 2021). Consequently, climate change-induced temperature trends have begun to accelerate plant phenological development. Famously, an acceleration in the full flowering dates of cherry blossoms in Japan has been observed and attributed to anthropogenic climate change (Christidis et al. 2022). Similar advancing phenology attributed to increasing temperatures has also been recognized with Maize (Abbas et al. 2017), Rice (Liu et al. 2019), and Wheat (Ahmed et al. 2026).

Optimizing agricultural adaptation in SEA requires a deeper understanding of the possible effects of warming on regional crops. This presents a need to examine the incremental phenological changes driven by rising temperatures in SEA to inform adaptation efforts. Thus, the present study projected long-term warming induced shifts in the growing duration of important SEA commodity crops. Specifically, the projections (i) estimated the rate of maturity acceleration for near-term and mid-term scenarios and (ii) identified which agricultural zones are expecting the greatest phenological shifts up to the subnational level. Investigating phenological acceleration may prove useful to guiding regional adaptation priorities, especially since anticipatory adaptation is pertinent to small holder-dominated field cultivation settings such as those found in Southeast Asia.

Materials and Methods

Study Area

The study area covers Southeast Asia [92.0E, 11.0S, 141.0 E, 28.0N], namely the eleven member states of the Association of Southeast Asian States (ASEAN). These are Brunei Darussalam, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor Leste, and Vietnam. These nations span a combined 4.5 million km^2 of land area split between peninsular or mainland Southeast Asia and the maritime continent or maritime Southeast Asia. Collectively an estimated 676.6 million people inhabit the region (ASEAN 2024). The majority of the region is within the tropics with northern Myanmar stretching into the subtropics. The Asian monsoon regimes dominate the climate of the region (Chang et al. 2005).

Growing Degree Day

Complicated mathematical approximations of phenophase development exist for more precise modelling (Aono & Kazui 2008; Zhang & Liu 2022). However, the simple GDD model was sufficient given this study did not attempt to predict harvests to a precise date. Rather, the study sought to project and analyze general trends in maturity timing due to temperature shifts. While literature suggests that photoperiod is a significant parameter for modelling phenophase (Craufurd & Wheeler 2009; Zhang & Liu 2022), the effect of anthropogenic climate change regarding photoperiod mainly revolves around mismatches in phenological timing through forced migration or temporal shifts in phenology (Ettinger et al. 2021). Since photoperiod is invariable throughout the year near the equator (Azam-Ali and Squire 2002) and spatial changes in cropping areas were not factored into the model, photoperiod was not considered in this study.

GDD models consider the fact that effective growth in poikilothermic organisms has been observed to occur within a certain temperature range. Growth below a minimum temperature is nonexistent while any additional growth past a maximum temperature is negligible (Trudgill et al., 2005). Ranges vary between crops and are experimentally determined (Paredes et al., 2025b). The approximation for a given day is provided by the equation:

$$GDD = \begin{cases} \dfrac{T_{max} + T_{min}}{2} - T_{base} & T_{base} \leq T_{ave} \leq T_{upper} \\ 0 & T_{ave} < T_{base} \\ T_{upper} - T_{base} & T_{ave} > T_{upper} \end{cases} \quad (1)$$

An average value T_{ave} can be computed from the meteorological observations T_{max} and T_{min} corresponding to the maximum and minimum temperatures recorded for a certain day. T_{base} and T_{upper} provide the temperature range for crop growth. A GDD value is computed daily and is accumulated over time. Reaching defined accumulated totals corresponds to reaching different phases of crop development. These totals are also experimentally determined and differ between crops (Paredes et al. 2025a).

Crop Selection

Three major commodity crops were chosen to ensure economic relevance while also considering unique cultivation practices.

Rice

Asian rice (*Oryza sativa*) is the major crop of the region. It is culturally important as the staple grain while also being the largest agricultural export of SEA (FAO 2024b). It is an annual grass usually harvested twice a year. Notably, some exceptionally productive areas can harvest up to three times annually (Dang et al. 2020). Relevant experimental values for GDD for rice were adopted from a database published by Paredes et al. (2025b).

Defining a uniform rice crop calendar for the entire region is challenging due to significant variations in cultivating seasons across SEA. For instance, Thailand's prolonged main season runs from May to January, with a secondary season spanning January to June (FAO 2026a). South Vietnam's autumn/winter crop spans July to December, followed by a winter/spring season from December to early March (FAO 2026b). The Philippines cultivates its main crop from April to early December and its secondary crop from October to April (FAO 2026c). These crop schedules generally align with the monsoon regimes. The main planting window coincides with the wet summer monsoon and the secondary window encapsulates the dry winter monsoon (Chang et al. 2005). Conversely, Indonesia operates on a reversed schedule, with a main window from October to April and a secondary window from late March to early October (FAO 2026d). This inversion occurs because portions of the Indonesian archipelago lie south of the equator, subjecting the islands to a reversed seasonal rainfall and monsoon cycle compared to its northern neighbors (Chang et al. 2005) To capture an appropriate overlap and simplify analysis, a general calendar based on the dominant northern hemisphere pattern was established. A planting season from January to May was set as the dry season rice_A while June to December was set as the wet season rice_B.

Coffee

Four species of coffee are commercially cultivated around the region. Coffee is harvested throughout the region, however the leading producers of coffee in SEA, Vietnam and Indonesia, cultivate majority Robusta coffee (*Coffea canephora*) (Nguyen 2025; Rahmanulloh 2025). For this reason, Robusta was selected as the coffee species for projection to better reflect regional production preference. GDD values for coffee species were experimentally determined by Salazar et al. (2019). Their values for Robusta were adopted with modifications. Coffee is a perennial tree crop and reaches maturity once in its phenological development. Thereafter, flowering and fruiting occurs repeatedly throughout its life cycle. Since the study projected regular harvesting seasons, GDD computation disregarded the vegetative growth phase and assumed regular flowering seasons. Coffee flower bud development follows thermal time; however, a critical amount of precipitation is necessary for bud break. In cultivation practice, flowering occurs after a significant time of water scarcity followed by sudden precipitation or irrigation. This allows farmers some control over the timing of Coffee flowering. Usual flowering in SEA countries occurs in the dry season between January to April (Marsh 2007; Salazar et al. 2019;). Given this, the GDD model assumed a regular flowering date every February. Consequently, only the GDD values from flowering to berry ripening were considered.

Sugarcane

Sugarcane (*Saccharum officinarum*), is an annual grass planted in tropical regions. Sugarcane can be harvested multiple times in one planting cycle through a unique cultivation mechanism. Ratooning is an agricultural technique wherein the crown of a crop is maintained after an initial harvest to facilitate regrowth from the residual parts. The first harvest is often called the plant crop and subsequent harvests are defined as the first ratoon, second ratoon, and so on (Plucknett et al. 1970). Ratooning is a common practice in sugarcane cultivation, approximately 50% to 75% of cane areas globally practice ratooning (Xu et al. 2021). Multiple ratoon crops can be harvested over several years before replanting. Ultimately, the number of ratoon harvests, if any at all, depends on the decision of the farmer. In areas of Northern Thailand which replant annually, 1-2 ratoon crops are usually grown for a cycle. In Java, 1-3 ratoon harvests was the most common but some farmers can exceed 7 harvests (Prasara-A & Gheewala 2016; Saputro et al. 2021). The model assumed a conservative harvesting of one ratoon and one plant harvest. A conservative assumption ensured the model reflected ratooning practices while maintaining an annual timeseries. All relevant GDD values for sugarcane were adopted from Teruel et al. (1997).

The planting season of sugarcane is highly variable in the region. Philippine sugarcane is usually planted from October up to May of the following year (Mojica-Sevilla 2025). Java begins its growing season in September (Saputro et al. 2021). Thailand practices two planting seasons, one from January to March another from September to November (Prasara-A & Gheewala 2016). Given this, a planting season later into the year would be the most adequate overlap. Therefore, an October planting date was selected for the projection.

Table 1. Relevant GDD Values and Planting Dates

Crop	T_{base} (°C)	T_{upper} (°C)	Target GDD_A	Planting Date
rice_A	12.0	35.0	1700	Jan
rice_B	12.0	35.0	1700	Jun
Coffee (Robusta)	10.0	32.0	3730	Feb (flowering)
Sugarcane	18.0	35.0	2400	Nov

Climate Data Processing

Since the computations were run in Google Earth Engine (GEE), both historical and future period climate datasets native to the platform were utilized. ERA5 is the fifth generation global reanalysis of the European Centre for Medium-Range Weather Forecasts (ECWMF), combining historical observations and numerical models into an estimate of atmospheric conditions (Hersbach et al. 2020). Specifically, the daily maximum and minimum 2-meter surface temperatures of ERA5 Land

Daily Aggregate dataset was used for the historical period of 1986-2025. The dataset is available on GEE with a resolution of 0.1° (Munoz-Sabater 2019). ERA5 has been found to overestimate daily maximum temperatures in SEA and generally performs better over mainland SEA than the maritime continent (Li et al. 2022). Despite this, ERA5 was used given its extensive temporal range and resolution as well as adequate spatial resolution. Additionally, literature demonstrates its reliability for individual areas in the region namely Vietnam (Ngo-Duc and Tam, 2026), Central Java (Harmoko et al. 2026), and Central Luzon (Cabigao et al. 2026).

The latest Coupled Model Intercomparison Project (CMIP6) provides simulated climate data for the future period through multiple global climate models (GCMs). Each model projects future climates corresponding to unique Shared Socio-economic Pathways (SSP) which dictate global greenhouse gas (GHG) emissions and subsequent future climates. GEE hosts the NEX-GDDP-CMIP6 data as its native CMIP6 database, which contains 34 GCMs downscaled by NASA to a resolution of 0.25°. This dataset comes with the SSP 2-4.5 intermediate GHG emissions scenario and SSP 5-8.5 very high GHG emissions scenario (Thrasher et al. 2022; IPCC 2021). The three available and best performing GCMs for SEA temperature as assessed by Desmet and Ngo-Duc (2022) were selected. These are CNRM-CM6, HadGEM, and CNRM-ESM2-1, and will cover a future period of 2026 to 2065.

Preprocessing was applied to the collected climate data. ERA5 was aggregated to align with CMIP6 resolution. Further, each GCM was bias corrected through Linear Scaling (Londhe et al., 2023). Equation for bias correction is given by equation (3).

$$X_{Corrected} = X_{Simulated} + \left(\overline{X}_{Historical} - \overline{X}_{Simulated} \right) \quad (2)$$

$\overline{X}_{Historical}$ refers to the average minimum or maximum temperature provided by ERA5 over the reference period 1986-2015. $\overline{X}_{Simulated}$ is the simulated data of a GCM averaged over the same reference period. Their difference served as the correction factor for projected data represented by $X_{Simulated}$.

GDD Modeling

The relevant accumulated GDD values (GDD_A) are listed in Table 1. A 5 arc-minute gridded spatial distribution of all crops was taken from the Spatial Production Allocation Model (SPAM) (IFPRI 2024) and clipped to SEA boundaries using the Large Scale International Boundary Polygons (LSIB) public dataset. The specific LSIB dataset available in GEE is the 2017 version, which is usable since no significant changes in the land borders of ASEAN occurred since.

For each planting season, GDD (equation 1) was accumulated daily until it reached the target GDD_A. The minimum days necessary to reach an accumulated GDD equal to GDD_A was taken as the days to maturity (DTM) for a given cell. DTM was taken annually over the study period and different models. GDD was computed for a year onward from the first day of the planting or flowering month.

The starting date for Sugarcane was offset to the previous year and the ending date for Coffee was offset to the following year. This adjustment ensures that the majority of GDD was accumulated within the year of its datapoint. Further spatial and temporal analysis were performed on the DTM results through the following sections.

Time Series Analysis

An annual DTM time series was generated in GEE by computing the spatial mean for each year. Linear regression based on ordinary least squares (OLS) was applied using the R stats package (R Core Team, 2026) to model the inter-annual trend represented in equation (3) where m represents the slope, or annual shift in DTM, and b is the intercept.

$$\mathrm{DTM} = m(\mathrm{Year}) + b \tag{3}$$

For projected periods, the ensemble mean was used for regression. Time series analysis was conducted for the entire region, as well as for individual countries using boundaries from the LSIB database.

Geospatial Analysis

Twenty-year DTM means were computed in GEE and exported to QGIS (v.3.44) for further analysis. Change maps were generated by subtracting the 2006–2025 baseline layer from the SSP projections for the 2026–2045 and 2046–2065 periods (equation 4):

$$\Delta\mathrm{DTM} = \mathrm{DTM}_{\mathrm{projected}} - \mathrm{DTM}_{\mathrm{baseline}} \tag{4}$$

For better policy translation and visual representation, these change maps were aggregated to the provincial level via zonal statistics using the Global Administrative Areas (GADM) database.

Results

The projections revealed accelerated phenology for all considered crops (Fig 1) in the majority of cultivated areas in the region (Fig 3). A negative slope in DTM change can be observed throughout all periods, although statistical significance ($p < 0.01$; $p = 0.014$; $p = 0.03$) is only reached by 2006-2025 with wet season rice, coffee, and sugarcane respectively. Although all SEA nations were projected with accelerated phenology, the per-country linear regression (see Supplementary Table S4) suggests some countries with no significant phenological acceleration for specific crops and scenarios. The projection results are discussed in depth by crop in the following section.

Shifts in Dry Season Rice

Overall, dry season rice exhibited the gentlest decreasing DTM slope throughout all future scenarios, suggesting it would have the most gradual phenological acceleration (Fig 1). However, magnitude of acceleration diverged between future emissions scenarios, with the high emission scenarios corresponding to faster acceleration (Fig 1). Rate of DTM change for SSP5-8.5 is projected to remain constant between the near and midterm (m=-0.25). Meanwhile, SSP2-4.5 projected a minor increase in DTM acceleration from the near-term (m=-0.21) to mid-term (m=-0.22). Negative DTM slopes are observed for both historical periods but do not exhibit statistical significance (p=0.340; p=0.112).

Indonesia ($p< 0.01$), Philippines (p=0.048) and Timor-Leste (p=0.039) already showed significant decreases in DTM by 2006-2025. Notably, all countries were projected significant acceleration in phenology, except Vietnam for the SSP 2-4.5 midterm scenario ($m<0.01$, p=0.943) and both SSP 5-8.5 time periods (m=0.02, p=0.721; m=-0.04, p=0.407). Timor-Leste showed the steepest drop in rice_A DTM for both near-term scenarios (m=-0.25; m=-0.32) and SSP 5-8.5 midterm scenarios (m = -0.37).

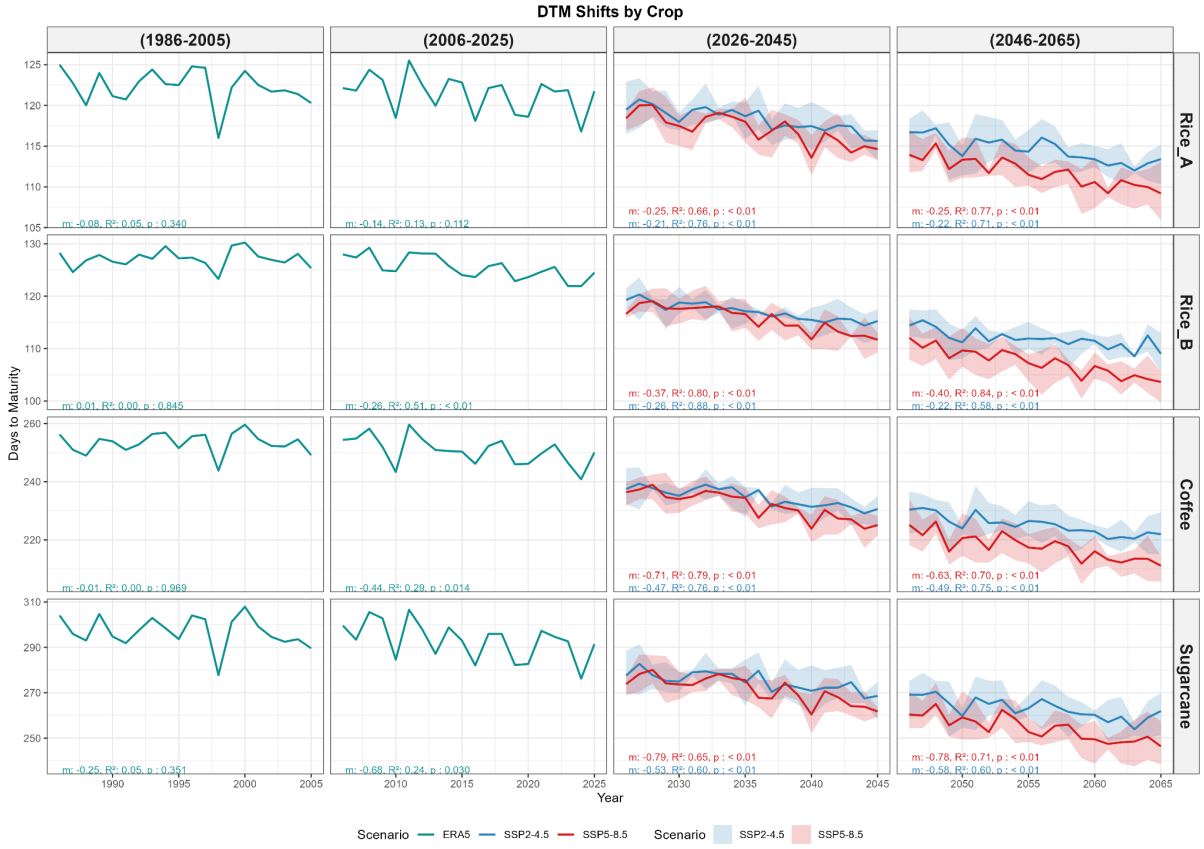


Fig 1 Days to Maturity (DTM) shifts per crop by period for the entire region.. The plots for all four crops (rice_A, rice_B, Coffee, Sugarcane) are presented. Each plot is divided into four 20-year periods (1986 - 2005, 2006 - 2025, 2026 - 2045, 2046 - 2065). The historical period (1986 - 2025) is denoted by a teal line; projected period (2026 - 2065) is split into SSP 2-4.5 (blue) and SSP 5-8.5 (red). The solid line for the projected period represents the ensemble mean; shaded ribbons present variance between climate models

There are a substantial number of subnational divisions which did not show significant reductions in dry season rice DTM. As with all the crops, greater negative shifts were projected for midterm scenarios. The agriculturally significant Tonle Sap lake of Cambodia and Mekong delta in southern Vietnam were all projected to decrease in rice DTM for all scenarios. Meanwhile, the northeastern part of Luzon island in the Philippines was projected to maintain and even elongate growing times for all scenarios (Fig 3a).

For the near-term (Fig 3a-1; Fig 3a-3), the provinces around the Vietnam-Cambodia-Laos junction maintained their phenological timing for rice_A. This consists of provinces in eastern Cambodia, southern Laos and most of the Vietnamese Central highlands and Southcentral coast. A small enclave of stable DTM in Northern Thailand in the near-term. Indonesia had some pockets of stability for the near-term scenarios.

By midcentury (Fig 3a-2; Fig 3a-4), mainland SEA is projected to experience significant shortening of growing seasons with only the northernmost state of Myanmar at baseline DTM for both scenarios, a handful of provinces for the moderate SSP2-4.5 scenario (Fig 3a-2), and just three

Vietnamese provinces for SSP5-8.5 (Fig 3a-4). Indonesia contracts its stable provinces to just southwest Sulawesi for SSP5-8.5 (Fig 3a-4).

Shifts in Wet Season Rice

Wet season rice phenology is projected to accelerate faster than its dry season counterpart based on Fig 1 (m=-0.26, m=-0.37, m=-0.22, m=-0.40). With the exception of the SSP2-4.5 mid-future scenario, which returned an equal negative DTM slope with its corresponding Rice-A counterpart. Interestingly, rice_B phenological acceleration is already statistically significant from the 2006-2025 period (m=-0.26, $p<0.01$). Projected rates of acceleration diverged based on emissions scenarios, with SSP5-8.5 demonstrating a steeper DTM decline. Unlike dry season rice, a statistically significant negative trend starting from the 2006-2025 period was observed in all countries. However, the 1986-2005 historical period showed a statistically insignificant negative slope similar to rice_A (m=0.01, p=0.845). At present, Timor Leste (m=-0.49) has the steepest DTM slope of all SEA nations. Meanwhile, Lao PDR (m=-0.50, m=-0.36, m=-0.58) is projected to experience the fastest decrease in DTM for all rice_B future scenarios except near-term SSP 2-4.5 which projected Malaysia (m=-0.30) with the steepest decline.

Compared to dry season rice, a larger swath of peninsular SEA is projected to experience negative DTM shifts in wet season rice. Almost all of mainland SEA returned shorter growing seasons, with the exception of the Vietnamese northcentral coast. Notably, the entirety of Malaysia, East Timor, and Brunei showed rice_B phenological acceleration (Fig 3-b).

For the nearterm (Fig 3b-1; Fig 3b-3), alongside the Vietnamese northcentral coast, only a singular province in Thailand was the sole subdivisions in the mainland with stable DTM. Portions of Sumatra and Sulawesi are also projected to remain at or increase from baseline DTM in the near-term, alongside three clusters of stable DTM in the Philippine archipelago.

For midcentury scenarios (Fig 3b-2; Fig 3b-4), mainland SEA provinces are limited to just two Vietnamese provinces that maintain DTM. Indonesian areas collapsed to the Sulawesi provinces by SSP 2-4.5 midterm (Fig 3-b2) and just South Sulawesi for SSP 5-8.5 (Fig 3-b4). By the high emissions mid century (Fig 3-b4), only the northeastern provinces of Luzon had at least baseline values while SSP 2-4.5 (Fig 3-b2) also included some central-eastern provinces of Mindanao.

Shifts in Coffee

For coffee, statistically significant negative DTM shifts manifested by the 2006-2025 historical period (m=-0.44, p=0.014). This suggests that phenological acceleration of coffee cherry ripening may be observed within the recent 20 years. Future scenarios all projected DTM decline, with high emission scenarios having a steeper decline. Not all nations showed phenological acceleration for coffee by the 2006-2025 period, only nations in the maritime continent and Thailand had computed decreasing DTM slopes. For future scenarios, all nations computed a significant negative trend for all projections.

Vietnamese coffee is projected to experience the most drastic drop in DTM for near-term scenarios (m=-0.43, m=-0.69) while the same is expected for Myanmar (m=-0.55, m=-0.70) but for midterm scenarios. As with the other crops, the projected magnitude of acceleration varied based on SSP scenarios, with moderate emission scenarios leading to slower acceleration.

The majority of all sub-national divisions were projected to accelerate in coffee cherry maturity, intensifying greater by the midterm scenarios. Although select provinces in the Vietnamese northcentral coast, northeastern Luzon, and Sulawesi were all projected to maintain or even increase in DTM over all scenarios. Critically, coffee cultivation along the Mekong delta region accelerated in ripening for all scenarios. (Fig 3c).

In addition to those mentioned, other provinces were projected to maintain coffee DTM but only for the near-term scenarios (Fig 3c-1; Fig 3c-3), such as some provinces in southern Vietnam and southern Mindanao. For just the SSP 2-4.5 near-term scenario (Fig 3c-1), a single Thai province along with North Sumatra also returned stable phenology. All provinces then demonstrate decreased DTM by the midterm scenarios (Fig 3c-2; Fig 3c-4), with the exception of the three areas that maintained DTM for all scenarios.

Shifts in Sugarcane

Sugarcane is projected to experience the fastest phenological acceleration among the crops considered. It returned the steepest negative DTM slope for all future scenarios (m= -0.53, m=-0.79; m=-0.58, m=-0.78) with greater acceleration for SSP5-8.5 scenarios compared to SSP2-4.5 scenarios (Fig 1). Similar to dry season rice, projected phenological acceleration of sugarcane in Vietnam is insignificant for both near-term scenarios and the SSP 2-4.5 midterm scenario (Fig 2). Mainly nations of maritime SEA along with Myanmar returned significant accelerating trends for 2006-2025. For future projections, Malaysia saw the fastest change in Sugarcane DTM for both near-term scenarios and the SSP 2-4.5 midterm scenario. Meanwhile, sugarcane cultivation in Lao PDR was projected to experience the gentlest phenological shift.

As with all the crops, sugarcane phenology is projected to accelerate in almost all areas with some exceptions. The most intense shifts are projected to occur in the central area of the mainland. Clusters in North and Central Luzon are projected to increase in DTM consistently over all scenarios.

The near-term scenarios (Fig 3d-1; Fig 3d-3) only agreed on six subdivisions to maintain baseline DTM in mainland SEA. Five of these are spread around Vietnam the other is in northern Myanmar. All other provinces in the maritime continent accelerated in the near-term except for the southern tip of Sumatra and several clusters in the Philippines, with a greater positive DTM shift for the moderate scenario.

In the midcentury SSP 5-8.5 scenario (Fig 3d-4) no stable areas are projected for mainland SEA. Meanwhile, only the prior mentioned five Vietnamese provinces remained stable for the SSP 2-4.5 scenario (Fig 3d-2). The previously mentioned provinces of Luzon were the only remaining

provinces above or equal to baseline in the entirety of SEA for the midterm high emissions scenario (Fig 3d-4). The moderate scenario adds central Mindanao provinces to the stable provinces of the Philippines.

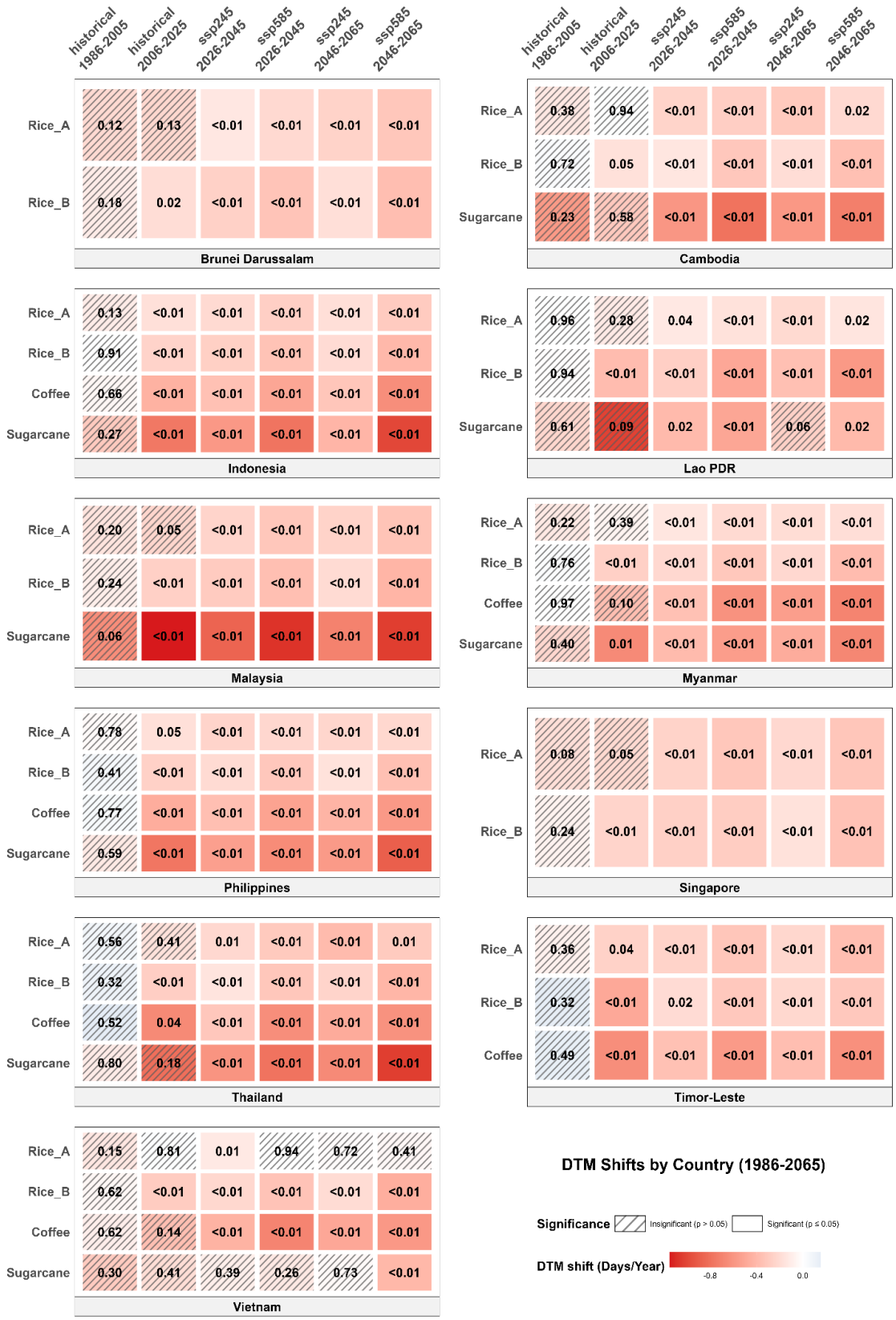


Fig 2 Annotated heatmap of Days to Maturity (DTM) shifts by country. Each division by country contains six columns corresponding to different periods (1986 - 2005, 2006 - 2025, ssp245 2026 - 2045, ssp585 2026 - 2045, ssp245 2046 - 2065, ssp585 2046-2065). The color of each cell reflects the slope of DTM change for that specific period. Darker red indicates a steeper slope, lighter means a gentler slope. Hashed cells indicate an insignificant pvalue (> 0.05) for that specific period

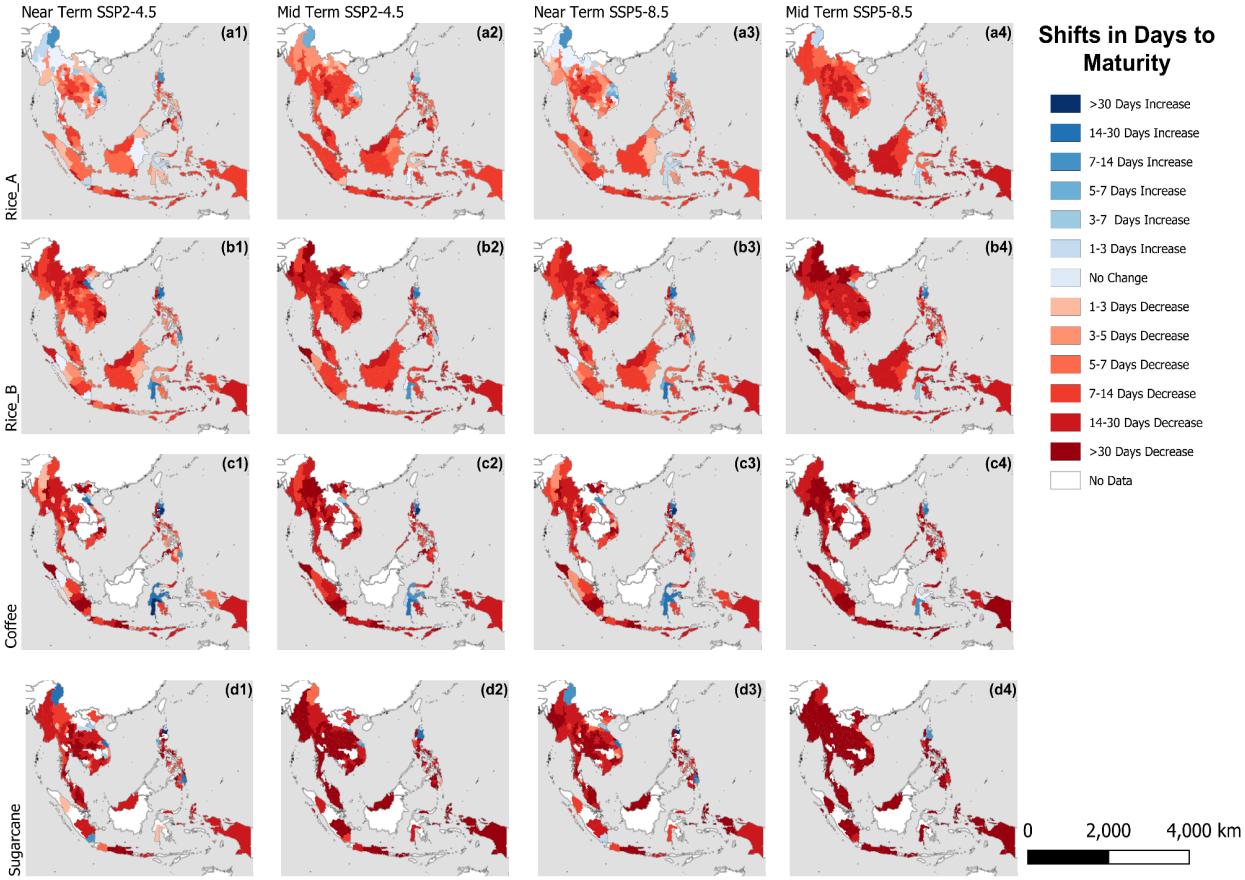


Fig 3 Projected Days to Maturity (DTM) shifts per crop by period for the entire region. Red shades indicate decrease in DTM while blue shades indicate an increase. All crops are represented per row (a) rice_A; (b) rice_B; (c) Coffee; (d) Sugarcane. Each emissions scenario period is represented per column (1) 2026 - 2045 SSP2-4.5; (2) 2046 - 2065 SSP2-4.5; (3) 2026 - 2045 SSP5-8.5; (4) 2046 - 2065 SSP5-8.5.

Discussion

Phenological Acceleration as Climate Change Impact

The analysis of GDD using projected and historical temperature scenarios highlights the substantial repercussions climate change will have on SEA crops. All considered crops have shown negative linear trends of projected DTM, meaning a unanimous shortening of growing seasons in the region. This is undesirable as it is detrimental to crop productivity. The current calculated DTM trends corroborate studies that have observed phenological acceleration in agricultural crops from outside the region (Abbas et al. 2017; Liu et al. 2019; Ahmed et al. 2026). Further, as regional temperatures are projected to increase (Hamed et al. 2022; Try & Qin 2024), the results posit further acceleration well into the midcentury. It is critical to recognize this acceleration as a slow-onset event that may be

attributed to anthropogenic climate change. This is reiterated by the difference in results between SSP scenarios; wherein higher-emission pathways force greater temperature increases, resulting in significantly more pronounced negative shifts in DTM than moderate scenarios. Optimistically, these findings suggest that emissions reductions and temperature-moderating climate solutions could effectively minimize or prevent further phenological advancement.

Variability of Impacts in the Region

All considered crops are projected to experience accelerated phenology in the near and mid-future. However, the magnitude of acceleration varied between crops. This was expected, as different crops have different phenological requirements (Paredes et al. 2025a; 2025b) and therefore respond with some variability to increasing temperatures. Meanwhile, the difference in wet and dry season rice shifts can be explained by the difference in their sowing dates. Although the driest month in SEA is projected to see a sharper temperature increase than the wettest month, Hamed et al. (2022) demonstrated that the wettest quarter as a whole will experience greater warming than the driest quarter within the century. This suggests that crops sown during the wet season would experience a more pronounced decrease in year-to-year DTM in contrast with dry season planting.

The projections also indicate that phenological acceleration is not spatially uniform over the region. This spatial heterogeneity proceeds from local temperature variations projected over SEA (Hamed et al. 2022; Try & Qin 2024). Countries in the maritime continent have likely already begun to experience significant phenological acceleration while some peninsular nations may only begin to experience significant advancement in the following years. Vietnamese agriculture warrants special attention in this context. Aggregated nationally, Vietnam is not projected to see a statistically significant reduction in DTM for dry-season rice and sugarcane across most scenarios. Analyzing at the sub-national scale revealed that not all subdivisions of Vietnam will maintain phenology. In fact, some polities are expected to accelerate comparable to other nations. This highlights that different provinces have varying magnitudes of DTM shifts. Notably, some provinces maintain current DTM or even increase in growing period. The magnitude of positive DTM shifts must be interpreted cautiously, as the linear-scaling bias correction may transform minimal warming into false cooling signals. Nevertheless, areas demonstrating these increases are still likely to maintain or exceed their current baseline DTM, even if not to the projected magnitude. Negative shifts in DTM are less affected by this linear scaling bias because any changes in temperatures above T_{upper} do not reflect in DTM. For these reasons, areas consistently projected to maintain or exceed baseline DTM, such as provinces of the Vietnamese north central coast, southwestern Sulawesi, and northeastern Luzon (Fig 4), remain valid resilient zones relative to the wider region. Conversely, the broader SEA region remains at risk, with Thailand, Cambodia, Laos, Malaysia, and Timor-Leste emerging as highly vulnerable to phenological shifts. Projected DTMs in nearly all sub-national divisions within these nations showed acceleration regardless of crop or scenario. Acceleration is also a concern for agricultural importers such as

Singapore, Brunei, and the Philippines which may see disruptions cascade into their agricultural supply chains.

Finally, the assumption of homogenous region-wide cropping seasons may obscure sub-regional intricacies of cropping calendars. Notably, the model fails to represent three-cropping and single-cropping rice areas as well as non-ratooning and multiple ratooning sugarcane areas. Furthermore, subregions which practice early or late cropping were constrained to an assumed calendar. Therefore, these areas may return projected DTMs that do not reflect local agricultural practices. This is apparent in Fig 3, which returned no data for Northern Vietnamese provinces. This indicates that rice in the area failed to reach maturity within January to May. Rice cultivation in subtropical North Vietnam follows a later cropping schedule than southern rice and is typically harvested until the end of June, falling outside the model's parameters (FAO 2026f).

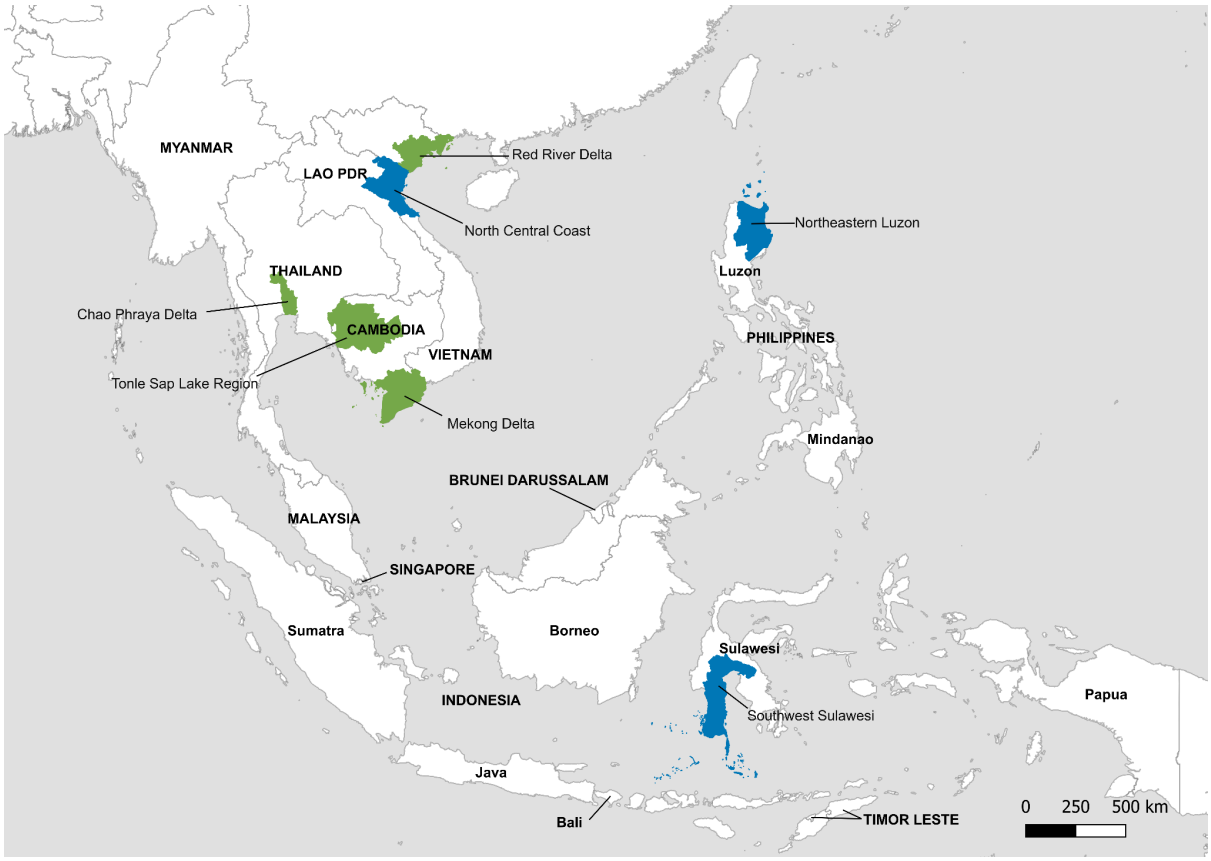


Fig 4. Map of Southeast Asia with relevant sub-regions labeled. Green areas highlight agriculturally significant areas in peninsular SEA while blue areas highlight projected phenologically stable regions.

Prioritization of Adaptation

The present results show the necessity of agricultural adaptation systems regarding increasing temperatures. Analysis of projected linear trends reveals a shift of less than a day per year, meaning a decadal timescale before substantial changes are realized. This provides a temporal buffer for adaptation measures to be deployed before irreversible damage to livelihood occurs. There is adequate time for

local governments to explore various options for adaptation. The construction and procurement of climate-control systems is afforded by the temporal scale of projected acceleration. Building up agroforestry capacities that can mitigate the adverse effects of climate change such as lower ground temperatures through shading (Gomes et al. 2020) is also viable. The breeding of regionalized and locally responsive climate resilient varieties also requires substantial development time before deployment. Variety development of this nature can be directed to produce varieties with larger GDD requirements to counteract phenological acceleration (Abbas et al. 2017; Challinor et al. 2016). Based on the magnitude of acceleration, Sugarcane must be the priority for adaptation efforts. On the other hand, by production area, rice is clearly the priority.

Since acceleration is not spatially uniform, certain areas are uniquely positioned to redirect adaptation resources for other climate-related agricultural risks. It may also be an option for countries to intensify dry season rice production, since significant areas are projected to maintain phenology when rice is planted around January. This may be especially effective for the northern subdivisions of mainland SEA. On the other hand, earlier ripening due to phenological acceleration may help enable farmers to practice early harvesting in response to typhoons (Yao et al. 2024). For the vast majority of polities in SEA, ignoring phenological acceleration is not an option. Specifically concerning is the anticipated impact on major agricultural areas. Regions such as the Mekong river delta, Tonle Sap lake area, Chao Phraya river delta, Central Luzon, and most of Java island are among the most productive agricultural zones in SEA (Fig 4) and are projected to experience phenological acceleration. 'Agricultural baskets' such as those mentioned must have primacy in adaptation efforts given their importance to national production. Small holder dominated food systems such as those in SEA will face significant losses if they fail to properly adapt for projected phenological shifts. Ultimately, SEA governments must urgently integrate the issue of long-term phenological acceleration into adaptation plans.

Limitations as a Temperature-focused Study

The critical limitation of the present study is its isolation of temperature for phenological acceleration. As mentioned, some studies have considered other variables as predictors for phenology. Given this, ground reality of phenological acceleration may be minimally compounded or counteracted by other environmental variables. This includes changes in precipitation, which is projected to see an increase in positive and negative anomalous events within the region (Try & Qin, 2024). As discussed, crops such as coffee partially rely on precipitation events for phenological timing (Marsh 2007) but rainfall was not considered in the study. Further research can cover rainfall variations and phenological acceleration in the region. Photoperiod was also not considered since it is essentially invariable in the equatorial region (Azam-Ali and Squire 2002). Despite the exclusions, limiting the scope of the study to temperature remains useful, given that literature shows it is the major driver of phenological timing (Craufurd & Wheeler 2009; Zhang & Liu 2022).

Conclusion

The present study projected the general DTM trend of commodity crops over SEA using a simple GDD model. Through this framework, the study demonstrated that crop maturity in the region has already begun advancing due to increasing temperatures and is expected to accelerate further into the near and mid future. Because this acceleration can be attributed to climate change, the continued mitigation of emissions remains an effective approach for managing it.

The magnitude of these phenological shifts varied significantly across the region. As expected, species responded differently based on unique GDD requirements. Seasonal timing also influenced these shifts, with wet season rice accelerating greater than dry season rice. Furthermore, spatial heterogeneity was evident with the intensity of acceleration. In fact, some subregions are projected to be unaffected by phenological acceleration. However, most of the region will experience varying degrees of phenological acceleration. The results highlight the necessity of adapting to what seems to be an inevitable climate reality. Fortunately, the slow onset nature of phenological acceleration due to rising temperatures provides an essential temporal buffer for adaptation policies to be rolled out. Adaptation solutions such as climate control technologies, agroforestry, and resilient varieties are all critical options to consider. Ultimately, the need to act is urgent, especially to protect smallholder dominated systems that form the backbone of the region.

Declarations

Data Availability

The datasets used in this study, including the ERA5 atmospheric reanalysis and CMIP6 climate projections, are publicly available and accessible through the Google Earth Engine (GEE) platform (https://developers.google.com/earth-engine/datasets)

Author Contributions

Conceptualization: Gabriel Mesina and R. Sedricke Lapuz; Methodology and data collection: Gabriel Mesina and R. Sedricke Lapuz; Formal analysis and investigation: Gabriel Mesina, R. Sedricke Lapuz, and Bernard Racoma; Writing - review and editing: Gabriel Mesina, R. Sedricke Lapuz, and Bernard Racoma; All authors read and approved the final manuscript.

Competing Interests

The authors have no competing interests to declare that are relevant to the content of this article

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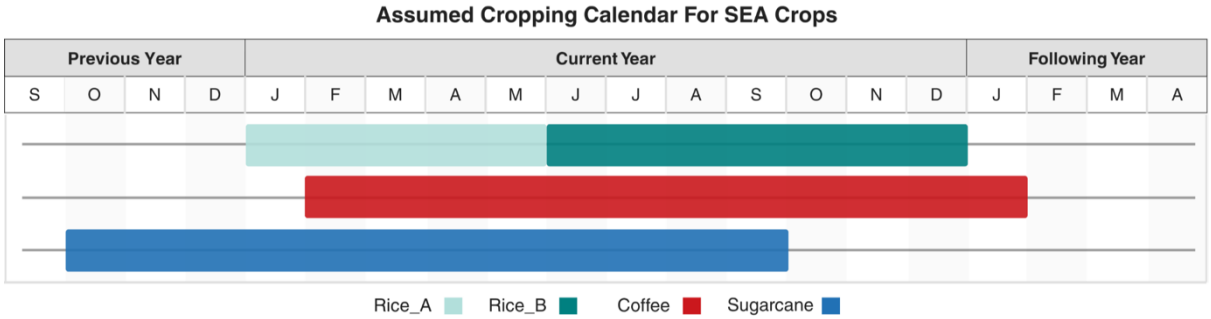
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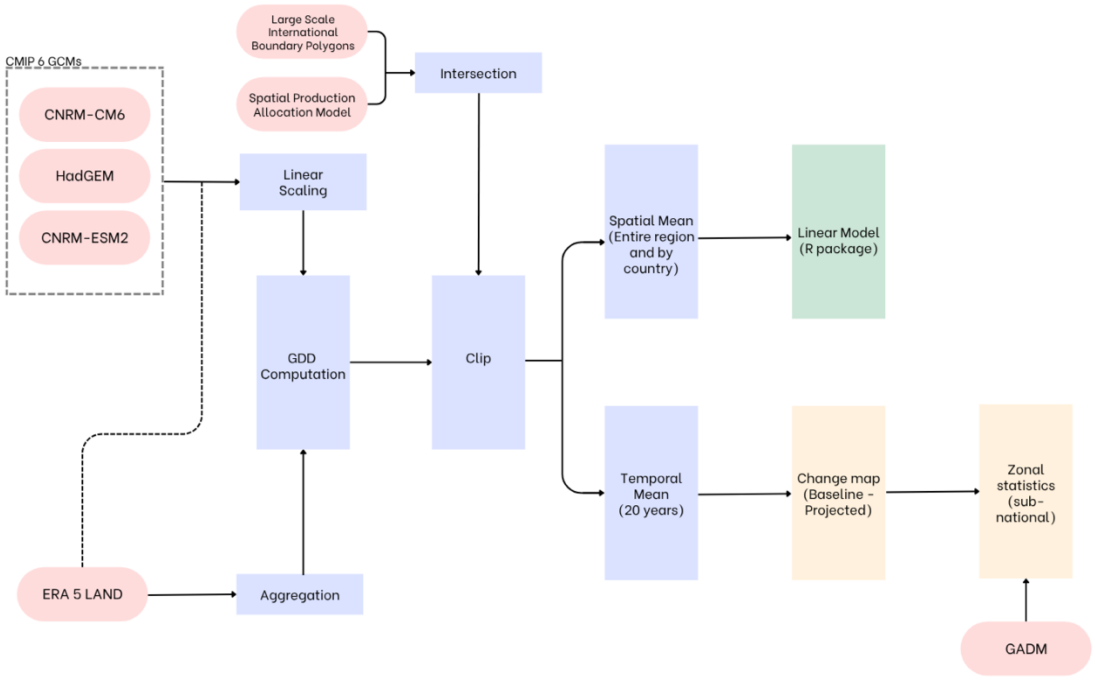
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S1. GDD_A for Relevant Phenological Phases of Crops

Robusta Coffee		**Sugarcane**	
Stage	GDD_A	Stage	GDD_A
Berry development	3350	Ripening (plant)	1300
Berry Ripening	297	Ripening (ratoon)	1100
Red ripe berry stage	83		



S2 Assumed Cropping Calendar For SEA Crops. Rice cropping calendar is represented by the teal bar, the lighter shade indicates Rice_A and the darker shade represents Rice_B. The red bar depicts the assumed cropping calendar for Coffee, it begins in February (flowering) and its 12th month is offset to the following year. Sugarcane is represented by the blue bar that begins in October of the previous year and ends in September of the current year.



S3 Geospatial Analysis Flowchart. Presents the primary datasets utilized in red. Blue boxes represent processes performed on the various datasets, while outputs are in green and yellow.

S4. Per-country linear regression statistical values of DTM

	Country	1986-2005		2006-2025		2026-2045 ssp245		2046-2065 ssp245		2026-2045 ssp585		2046-2065 ssp585	
		m	p	m	p	m	p	m	p	m	p	m	p
Rice_A	Brunei	-0.209	0.124	-0.222	0.132	-0.135	<0.01	-0.252	<0.01	-0.215	<0.01	-0.320	<0.01
	Cambodia	-0.128	0.375	0.013	0.935	-0.246	<0.01	-0.304	<0.01	-0.276	<0.01	-0.213	0.015
	Indonesia	-0.107	0.127	-0.178	0.009	-0.211	<0.01	-0.181	<0.01	-0.272	<0.01	-0.296	<0.01
	Lao PDR	0.004	0.965	-0.117	0.284	-0.129	0.038	-0.212	<0.01	-0.167	<0.01	-0.146	0.017
	Malaysia	-0.153	0.196	-0.234	0.051	-0.243	<0.01	-0.252	<0.01	-0.319	<0.01	-0.337	<0.01
	Myanmar	-0.126	0.225	-0.064	0.394	-0.143	<0.01	-0.195	<0.01	-0.210	<0.01	-0.186	0.001
	Philippines	-0.026	0.784	-0.176	0.048	-0.244	<0.01	-0.231	<0.01	-0.225	<0.01	-0.223	<0.01
	Singapore	-0.180	0.079	-0.212	0.053	-0.252	<0.01	-0.221	<0.01	-0.318	<0.01	-0.323	<0.01
	Thailand	0.083	0.559	-0.167	0.411	-0.219	0.015	-0.385	<0.01	-0.302	<0.01	-0.298	0.013
	Timor-Leste	-0.080	0.365	-0.258	0.039	-0.253	<0.01	-0.227	<0.01	-0.323	<0.01	-0.369	<0.01
	Vietnam	-0.134	0.154	0.017	0.805	-0.125	0.014	-0.020	0.721	0.003	0.943	-0.043	0.407
Rice_B	Brunei	-0.105	0.177	-0.191	0.023	-0.261	<0.01	-0.183	<0.01	-0.333	<0.01	-0.368	<0.01
	Cambodia	0.033	0.721	-0.172	0.048	-0.143	<0.01	-0.193	<0.01	-0.316	<0.01	-0.360	<0.01
	Indonesia	0.008	0.905	-0.250	<0.01	-0.269	<0.01	-0.202	<0.01	-0.341	<0.01	-0.401	<0.01
	Lao PDR	-0.009	0.942	-0.378	<0.01	-0.270	<0.01	-0.358	<0.01	-0.497	<0.01	-0.580	<0.01
	Malaysia	-0.099	0.237	-0.268	<0.01	-0.297	<0.01	-0.205	<0.01	-0.364	<0.01	-0.420	<0.01
	Myanmar	0.025	0.757	-0.267	<0.01	-0.219	<0.01	-0.220	<0.01	-0.313	<0.01	-0.380	<0.01
	Philippines	0.064	0.414	-0.261	<0.01	-0.207	<0.01	-0.166	<0.01	-0.315	<0.01	-0.356	<0.01

S4. cont

	Country	1986-2005		2006-2025		2026-2045 ssp245		2046-2065 ssp245		2026-2045 ssp585		2046-2065 ssp585	
		m	p	m	p	m	p	m	p	m	p	m	p
Rice_B cont.	Singapore	-0.069	0.243	-0.243	<0.01	-0.265	<0.01	-0.167	<0.01	-0.286	<0.01	-0.345	<0.01
	Thailand	0.106	0.324	-0.277	<0.01	-0.154	<0.01	-0.244	<0.01	-0.320	<0.01	-0.417	<0.01
	Timor-Leste	0.150	0.320	-0.493	<0.01	-0.202	0.023	-0.222	<0.01	-0.310	<0.01	-0.311	<0.01
	Vietnam	-0.046	0.615	-0.289	<0.01	-0.223	<0.01	-0.201	<0.01	-0.338	<0.01	-0.459	<0.01
Coffee	Indonesia	-0.048	0.660	-0.440	<0.01	-0.351	<0.01	-0.325	<0.01	-0.504	<0.01	-0.637	<0.01
	Myanmar	0.009	0.967	-0.368	0.101	-0.354	<0.01	-0.549	<0.01	-0.618	<0.01	-0.696	<0.01
	Philippines	0.047	0.771	-0.464	<0.01	-0.362	<0.01	-0.429	<0.01	-0.524	<0.01	-0.577	<0.01
	Thailand	0.154	0.525	-0.660	0.041	-0.316	<0.01	-0.474	<0.01	-0.638	<0.01	-0.616	<0.01
	Timor-Leste	0.133	0.489	-0.638	<0.01	-0.353	<0.01	-0.368	<0.01	-0.571	<0.01	-0.627	<0.01
	Vietnam	-0.094	0.623	-0.364	0.139	-0.434	<0.01	-0.498	<0.01	-0.691	<0.01	-0.584	<0.01
Sugarcane	Cambodia	-0.574	0.232	-0.306	0.580	-0.594	<0.01	-0.584	<0.01	-0.786	<0.01	-0.719	<0.01
	Indonesia	-0.299	0.266	-0.759	<0.01	-0.582	<0.01	-0.418	<0.01	-0.780	<0.01	-0.996	<0.01
	Lao PDR	-0.229	0.606	-1.017	0.086	-0.391	0.022	-0.261	0.060	-0.505	<0.01	-0.394	0.020
	Malaysia	-0.645	0.062	-1.147	<0.01	-0.860	<0.01	-0.703	<0.01	-1.076	<0.01	-1.036	<0.01
	Myanmar	-0.225	0.404	-0.660	0.010	-0.386	<0.01	-0.470	<0.01	-0.553	<0.01	-0.677	<0.01
	Philippines	-0.118	0.590	-0.770	<0.01	-0.543	<0.01	-0.572	<0.01	-0.651	<0.01	-0.886	<0.01
	Thailand	-0.113	0.802	-0.805	0.184	-0.607	<0.01	-0.659	<0.01	-0.783	<0.01	-1.036	<0.01
	Vietnam	-0.293	0.295	-0.189	0.412	-0.091	0.395	-0.031	0.726	-0.126	0.256	-0.405	<0.01