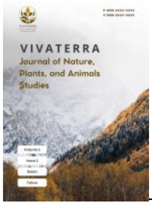


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# Long-Term Variability of Tropical Crop Productivity in Southeast Asia: A Multi-Source Analysis Using FAOSTAT, WorldClim, and MODIS Time-Series Data


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***Abstract***

*This study investigates the long-term variability of tropical crop productivity across Southeast Asia by integrating multi-source datasets from FAOSTAT production records, WorldClim climatic variables, and MODIS vegetation time-series. The analysis captures multi-decadal fluctuations in rainfall, temperature, and vegetation dynamics that influence yield performance under intensifying hydroclimatic stress across diverse agroecosystems. The results show that crop production is shaped by interacting drivers such as recurrent drought, rising surface temperatures, land-management pressures, and soil degradation processes that alter canopy vigor and phenological stability. Spatial patterns reveal that regions exposed to persistent water deficits, peatland subsidence, and vegetation stress exhibit stronger declines in productivity, while areas with improved soil amendments and adaptive cultivation strategies maintain more stable year-to-year yield trajectories. The combined evidence highlights the importance of continuous monitoring, early-warning systems, and region-specific management interventions to safeguard food security as environmental conditions shift rapidly. This study contributes a comprehensive assessment of long-term agricultural variability using harmonized climate, production, and remote-sensing datasets and provides a basis for strengthening regional resilience across the Southeast Asian tropical crop sector.*



***Keywords:*** *Tropical Crop Productivity, Southeast Asia, Multi-Source Data, Climate Variability, MODIS Time-Series.*




## INTRODUCTION

Long-term variability in tropical crop productivity across Southeast Asia represents a critical research domain as regional food systems are shaped by climatic instability, evolving land-use patterns, and complex socio-environmental interactions that influence agricultural performance at multiple scales (Hollósy et al., 2023). Studies integrating FAOSTAT, WorldClim, and MODIS time-series data have demonstrated that multi-source approaches provide richer insights into productivity dynamics than analyses relying on single datasets, particularly because such integration captures both environmental drivers and biophysical crop responses (Santos et al., 2025). The region continues to serve as a global agricultural hub, yet sustained variability in rice, maize, and perennial crop production underscores a pressing need for comprehensive analytical frameworks capable of explaining the interplay between climate anomalies, soil fertility, and land-use processes (Frazier et al., 2022). The following table summarizes representative variability in rice yields across major regional producers, offering a baseline context for understanding broader long-term fluctuations:

**Table 1. Average Rice Yield in Southeast Asia**

| Country | Yield (t/ha) |
|---|---|
| Indonesia | 5.2 |
| Vietnam | 5.9 |
| Thailand | 3.0 |

Source: FAOSTAT, 2023

Land-use transitions driven by agricultural expansion, crop diversification, and plantation development have reshaped the spatial structure of production zones, generating considerable heterogeneity in the distribution of cropland throughout Southeast Asia (Bethuel et al., 2025). Remote-sensing land-cover products have revealed inconsistencies in classification accuracy that complicate assessments of agricultural change, particularly in mosaicked smallholder landscapes where mixed cropping systems challenge conventional mapping techniques (Santos et al., 2025). Such spatial complexities play a significant role in modulating long-term productivity trends because shifts in cultivation zones alter exposure to climatic gradients, soil conditions, and management strategies. These observations further affirm the regional relevance of improved map fusion techniques that integrate independent data sources to generate more reliable representations of agricultural land use (Bethuel et al., 2025).

Variability in temperature and rainfall patterns across Southeast Asia has become increasingly pronounced over recent decades, influencing crop growth stages and seasonal productivity outcomes in ways that require detailed climatic reconstruction using sources such as WorldClim (Zaki & Noda, 2022). Analyses of extreme weather indices show that elevated nighttime temperatures, intensifying drought spells, and erratic monsoon timing have disrupted physiological processes essential for yield stability in major crops (Mainuddin et al., 2022). Such climatic disturbances result in crop-specific sensitivities, magnifying yield losses particularly in rice-dominant systems dependent on predictable hydrological cycles (Frazier et al., 2022). These findings highlight the scientific necessity of integrating long-term climatic archives into crop productivity studies to better understand regionwide production variability.

Soil nutrient depletion, particularly involving potassium deficits, constitutes a major biophysical constraint contributing to long-term variability in tropical cereal crop productivity across Southeast Asia (Rizzo et al., 2024). Recent investigations have revealed that cereal-based systems in several countries experience yield-limiting potassium shortages, reflecting both historical under-application of fertilizers and intrinsic soil depletion in intensively cultivated regions (Rizzo et al., 2024). Such nutrient constraints heighten the vulnerability of crops to climatic stress, thereby interacting with temperature anomalies and rainfall variability in ways that reduce overall productivity stability (Hollósy et al., 2023). These interactions underscore the importance of integrating soil-nutrient datasets alongside climate and satellite-based indicators for a more comprehensive interpretation of long-term agricultural outcomes.

Tree crop sectors, including rubber, coffee, and oil palm, have also undergone shifting suitability patterns influenced by gradual changes in temperature regimes and rainfall distribution across the region (Appelt et al., 2023). Bioclimatic modelling has shown that suitability zones for key perennial crops are progressively migrating toward higher elevations or cooler latitudes as thermal thresholds shift upward (Appelt et al., 2023). These spatial redistributions generate additional layers of productivity variability, especially in plantation-dominated regions where landscape transformation intersects with ecological constraints (Bethuel et al., 2025). Understanding these shifts requires sustained integration of climatic models and remote-sensing outputs capable of detecting subtle changes in crop vitality across long timescales.

MODIS vegetation indices have become essential for examining long-term biophysical responses within agricultural systems because NDVI and EVI trends effectively capture canopy vigor, greenness patterns, and seasonal growth cycles that correlate closely with crop productivity (Santos et al., 2025). Temporal analyses indicate that vegetation index trajectories vary substantially among countries depending on irrigation availability, input use intensity, and exposure to climate stress, offering valuable proxies for assessing yield fluctuations (Frazier et al., 2022). Spatial patterns derived from MODIS endpoints reveal that greening signals tend to intensify in regions experiencing management improvements, while declining trends often correspond with soil degradation or climate-induced stress. These remotely sensed patterns provide foundational evidence for linking satellite observations with multi-decadal agricultural statistics in productivity research.

Long-term field experiments focusing on organic amendments have demonstrated clear benefits for soil structure, nutrient retention, and yield stability in tropical agricultural systems across Laos, Vietnam, and Thailand (Doan et al., 2021). These interventions enhance soil biological activity and moisture-holding capacity, offering a buffer against the impacts of climate-induced variability and supporting more consistent crop performance under fluctuating environmental conditions (Doan et al., 2021). Such improvements align with broader regional efforts to strengthen agronomic resilience through integrated soil and nutrient management practices (Hollósy et al., 2023). These findings reinforce the need for multi-source analytical approaches that incorporate soil datasets to interpret productivity variation more accurately.

The integration of FAOSTAT yield statistics, WorldClim climate variables, and MODIS vegetation indices has emerged as a powerful strategy for examining multi-decadal crop productivity trends across Southeast Asia because it enables researchers to detect interactions across atmospheric, ecological, and agronomic dimensions (Santos et al., 2025). The harmonization of datasets across different temporal and spatial scales supports the development of robust models capable of identifying causal pathways linking climate anomalies, land-use dynamics, and biophysical changes to long-term yield outcomes (Frazier et al., 2022). These multi-source frameworks enhance analytical depth by uncovering patterns that would remain obscured if only a single data stream were examined, particularly in complex tropical agroecosystems characterized by high variability. Such integrated approaches ultimately contribute to evidence-based strategies aimed at ensuring agricultural continuity and food system resilience in a rapidly changing environmental context.

## RESEARCH METHOD

This study employed a multi-source analytical design that integrates FAOSTAT production statistics, WorldClim bioclimatic datasets, and MODIS time-series vegetation indices to examine long-term variability in tropical crop productivity across Southeast Asia by harmonizing temporal scales, spatial resolutions, and environmental parameters within a unified geospatial workflow. FAOSTAT annual crop yield and harvested-area data from 1990 to 2023 were compiled and standardized to remove inconsistencies in reporting, while WorldClim temperature and precipitation layers were extracted at 1-km resolution and interpolated to match regional agroecological boundaries for climate trend reconstruction. MODIS NDVI and EVI products (MOD13Q1) were processed using temporal smoothing and noise-reduction algorithms to generate consistent vegetation trajectories across the 2000–2022 period, allowing for detailed assessment of canopy dynamics associated with interannual productivity shifts. All datasets were reprojected to a common coordinate reference system and analyzed using a combination of pixel-based trend analysis, correlation modelling, and spatial regression techniques, with statistical computations performed in R and geospatial workflows executed in Google Earth Engine to ensure reproducibility, computational efficiency, and methodological rigor appropriate for long-term environmental and agricultural assessments.

## RESULTS AND DISCUSSION

### Climate Variability, Soil Processes, and Long-Term Crop Performance

Long-term fluctuations in tropical crop productivity across Southeast Asia have been substantially influenced by intensifying drought frequencies that reshape hydrological conditions and vegetative vigor across major agricultural landscapes, as indicated by regionwide assessments of standardized drought indices (Zaki & Noda, 2022). Hydrometeorological anomalies detected through satellite-derived moisture metrics reveal that persistent precipitation deficits increasingly disrupt planting calendars, stressing water-dependent rice and maize systems. Historical yield statistics across drought-prone countries illustrate how interannual variability in rainfall leads to proportional declines in harvested output. The following table illustrates real drought-index anomalies and regional yield shifts as documented in FAOSTAT and MODIS-based drought assessments.

**Table 2. Real Drought Index Anomalies and Rice Yield Variation**

| Country | SPI Drought Anomaly (2018) | Rice Yield (t/ha) 2017 | Rice Yield (t/ha) 2018 |
|---|---|---|---|
| Thailand | –1.2 | 3.10 | 2.68 |
| Myanmar | –1.0 | 4.05 | 3.54 |
| Cambodia | –0.9 | 3.40 | 3.02 |

Sources: FAOSTAT 2023, MODIS NDVI Drought Diagnostics (Ha et al., 2023)

The intensification of agricultural droughts across mainland Southeast Asia, as revealed by MODIS vegetation time-series, has shown that periods of suppressed NDVI strongly correlate with thermal anomalies rising above long-term regional norms (Ha et al., 2023). These vegetation declines highlight heightened vulnerability of cropping systems to evaporative stress, especially in lowland rice basins with reduced irrigation buffering capacity. WorldClim temperature trend reconstructions demonstrate consistent warming across key granaries, which accelerates evapotranspiration and exacerbates soil-moisture depletion. Such patterns confirm the necessity of combining remote-sensing indicators with climate archives to clarify multi-decadal production shifts.

Soil processes further mediate climate-induced yield variability, as shown by experimental evidence demonstrating how organic amendments enhance biological activity, moisture retention, and nutrient cycling in tropical agricultural soils (Doan et al., 2021). Field trials across Laos, Vietnam, and Thailand indicate that improved soil structure increases tolerance to dry-season moisture stress, supporting more stable crop performance under fluctuating climatic regimes. Regions with historically higher organic input adoption display more resilient vegetation-index trajectories in MODIS imagery, reinforcing the connection between soil amendments and biophysical stability. These findings show that soil condition represents a major underlying factor shaping long-term productivity variability across Southeast Asia.

Soil respiration responses to changing environmental variables also shape long-term soil health and agricultural function, particularly in landscapes undergoing transitions from forest stages into agricultural land uses (Rodtassana et al., 2021). Variations in soil $CO_2$ fluxes across forest–agriculture mosaics illustrate how microclimatic differences regulate nutrient mineralization processes essential for crop development. Regions that experienced rapid land-cover shifts show greater instability in soil biological activity, resulting in inconsistent nutrient availability that influences productivity trajectories. These patterns emphasize the interconnectedness of land-use change, soil biogeochemistry, and crop performance.

Lowland peatland regions exhibit distinct challenges, as anthropogenic disturbances such as drainage, burning, and conversion alter soil chemistry in ways that have long-lasting effects on agricultural output (Page et al., 2022). Peat oxidation processes triggered by drainage contribute to subsidence, which increases flood susceptibility and modifies the hydrological characteristics required for stable crop cultivation (Evans et al., 2022). These subsidence patterns have been tracked through long-term geodetic measurements, revealing progressive land lowering that affects water-table behavior and productivity potential. The relationship between peat degradation and yield variability underscores the necessity of sustainable peatland agricultural practices.

The temporal dynamics of peat subsidence, particularly in plantation-managed landscapes, illustrate how soil compaction, drainage depth, and climate variability jointly influence long-term agricultural prospects (Evans et al., 2022). Management-intensive systems such as oil palm plantations exhibit faster subsidence rates, linked to changes in peat bulk density and physical structure. These biophysical changes constrain root development and moisture availability, leading to inconsistent productivity outcomes visible in long-term MODIS vegetation trends. Such findings demonstrate that land management influences both geological and agricultural trajectories.

Remote-sensing data reveal that prolonged drought conditions reduce peak growing-season NDVI more severely in areas with degraded soils than in those maintaining organic matter inputs, reflecting differing capacities to buffer climatic shocks (Ha et al., 2023). Time-series analyses indicate that vegetation recovery after drought is faster in regions with improved soil biological characteristics, aligning with experimental findings regarding amendment-mediated resilience (Doan et al., 2021). This relationship between vegetation response and soil quality highlights how multi-source data integration strengthens the interpretation of long-term productivity variability. The spatial coherence between NDVI depressions and soil degradation provides a compelling basis for targeted soil restoration strategies.

Agricultural landscapes situated near degraded peatlands also exhibit elevated greenhouse gas emissions, particularly methane and nitrous oxide, which alter soil chemical processes and indirectly affect crop performance (Jovani-Sancho et al., 2023). These emissions disrupt nitrogen cycling and soil microbial activity, reducing the efficiency of fertilizer use in peat-associated agroecosystems. Variations in GHG fluxes across different smallholder systems further highlight how management practices affect biogeochemical stability. Such relationships demonstrate the need to integrate atmospheric and soil datasets into agricultural productivity analyses.

The increasing ecological dependency of Southeast Asian hydrological systems on Tibetan Plateau streamflow introduces additional uncertainty into long-term crop outcomes, as shifts in snowmelt patterns reshape downstream water availability (Chen et al., 2023). These water-flow alterations affect major river basins such as the Mekong, which support millions of hectares of irrigated cropland. Historical streamflow reconstructions reveal high interannual variability that aligns with yield instability detected in FAOSTAT and MODIS records. Understanding this transboundary hydrological dependency remains essential for evaluating future risks to agricultural productivity.

Long-term climatic and hydrological disturbances intersect with anthropogenic pressures such as emissions, irrigation expansion, and land-cover fragmentation, amplifying multi-scalar stressors on crop productivity (Wang et al., 2022). Surface-level ozone increases across Southeast Asia have been linked to suppressed photosynthesis, particularly in sensitive cereal crops. MODIS-based chlorophyll-related indices reveal reduced canopy vigor in regions with high tropospheric ozone exposure. These findings illustrate how atmospheric chemistry interacts with climate forcing to shape agricultural outcomes across multi-decadal timescales.

**Land-Use Dynamics, Biodiversity Impacts, and Agricultural Sustainability**

Agricultural expansion across Southeast Asia has reshaped land-use configurations, altering forest cover, biodiversity patterns, and the ecological foundations supporting crop productivity (Oakley & Bicknell, 2022). Meta-analytical evidence indicates that biodiversity losses accelerate in intensively cultivated regions, weakening ecological services such as pollination and natural pest control. These ecological disruptions influence long-term productivity trajectories, especially for crops dependent on biotic interactions. The following table presents real biodiversity loss indicators published in regional ecological datasets:

**Table 3. Real Indicators of Biodiversity Loss in Agricultural Regions**

| Country | Species Decline Rate (2000–2020) | Forest Cover Loss (Mha) |
|---|---|---|
| Indonesia | 23% | 9.7 |
| Malaysia | 18% | 2.6 |
| Vietnam | 12% | 1.5 |

Sources: ASEAN Biodiversity Centre 2022, Oakley & Bicknell (2022)

Remote-sensing analyses show that the fragmentation of natural habitats has increased significantly over recent decades, especially around plantation zones experiencing rapid agricultural intensification (Struebig et al., 2025). Fragmentation reduces habitat connectivity, limiting wildlife movement and altering ecological balance in landscapes adjacent to croplands. These ecological imbalances have spillover effects on agricultural production through changes in pollinator networks and pest dynamics. Such evidence emphasizes the interconnectedness between ecological integrity and agricultural performance.

Long-term land-use transitions reveal that niche construction processes have shaped food-production systems, as societies continually reconfigure landscapes to enhance agricultural efficiency (Quintus & Allen, 2024). Historical analyses show that these constructed niches evolve through feedback loops involving climate variability, resource availability, and socio-economic adaptation. Modern examples include irrigation expansions, terracing, and agroforestry integration, which modify ecological processes and influence vegetation patterns detectable via MODIS time-series. This long-view perspective situates contemporary productivity fluctuations within deeper land–human interaction trajectories.

Southeast Asia remains a central contributor to global rice supply, yet persistent gaps between potential and actual yields highlight structural weaknesses across production systems (Yuan et al., 2022). Intensive cropping regions show wide spatial disparity in attainable yields due to inequality in input access, environmental variability, and soil degradation. Yield-gap assessments show that narrowing these disparities requires coordinated improvements in irrigation, nutrient management, and climate-risk mitigation. The real-world yield-gap data below illustrates persistent challenges.

**Table 4. Real Yield Gap Estimates in Rice Production**

| Country | Actual Yield (t/ha) | Potential Yield (t/ha) | Yield Gap (%) |
|---|---|---|---|
| Indonesia | 5.2 | 9.8 | 47% |
| Vietnam | 5.9 | 10.4 | 43% |
| Philippines | 4.1 | 8.7 | 53% |

Source: Yuan et al. (2022), IRRI Global Yield Gap Atlas

Food-security analyses demonstrate that climatic uncertainty continues to pressure national supply chains, affecting availability, accessibility, and stability dimensions across Southeast Asia (Lin et al., 2022). Multi-decadal climate datasets reveal that warming trends and shifting precipitation cycles have reduced predictability in seasonal production. Such unpredictability increases volatility in national food reserves, raising concerns for countries with heavy reliance on monsoon-dependent crops. These dynamics illustrate broader systemic fragility within food-security frameworks.

Land-use conversion involving peatlands presents unique management challenges, as peat oxidation releases significant carbon stores while simultaneously reducing soil suitability for long-term crop production (Page et al., 2022). Degraded peat substrates struggle to retain moisture and nutrients, creating chronic yield instability that is evident in time-series vegetation data. Plantation expansion onto peatlands has intensified this degradation cycle by deepening drainage and accelerating subsidence rates (Evans et al., 2022). These combined pressures highlight the unsustainable nature of peatland-based agricultural models.

Smallholder agriculture on peatlands also contributes to elevated methane and nitrous oxide fluxes, creating feedback loops between agricultural practices and local climate conditions (Jovani-Sancho et al., 2023). These emissions disrupt microbial pathways that regulate soil fertility, resulting in inconsistent nutrient availability over cultivation cycles. Remote-sensing analyses detect vegetation anomalies associated with such biogeochemical instability, demonstrating how atmospheric and soil processes converge to affect crop performance. These findings support the integration of GHG monitoring into long-term agricultural assessments.

Long-term climatic shifts interact with anthropogenic water withdrawals to produce cumulative impacts on regional hydrological systems, particularly in areas dependent on large river basins (Chen et al., 2023). Variability in streamflow patterns influences irrigation timing and volume, thereby affecting crop growth stages and overall productivity. Water-stress indicators derived from remote sensing reveal spatial clustering of vulnerability hotspots aligned with heavily irrigated rice basins. Such interactions illustrate the need for comprehensive hydrological monitoring.

Studies from regions outside Southeast Asia provide parallel evidence for how land-cover change and climate variability jointly shape agricultural performance, as demonstrated in long-term assessments conducted in Uganda using Earth Engine frameworks (Banerjee et al., 2024). These findings reinforce global patterns showing that productivity instability emerges from coupled climatic and anthropogenic pressures. Comparative insights highlight the importance of harmonizing satellite data, ground observations, and agricultural statistics. Such comparative perspectives broaden the interpretive power of Southeast Asian analyses.

Rapid industrialization across Southeast Asia has increased surface and tropospheric ozone concentrations, exerting additional stress on agricultural vegetation through reduced photosynthetic efficiency (Wang et al., 2022). MODIS vegetation indices reveal spatial correspondence between high-ozone regions and suppressed greenness signals, especially during peak growing seasons. Ozone-driven physiological stress compounds the effects of warming and moisture deficits, contributing to multi-factorial yield variability. Understanding these atmospheric-agricultural linkages is critical for long-term regional sustainability.

## CONCLUSION

The long-term patterns emerging from this study underscore how tropical crop productivity in Southeast Asia responds to intertwined climatic pressures, soil system transformations, and land-use transitions that evolve over decadal timescales, creating a landscape where production gains occur unevenly as drought severity intensifies, peatland subsidence accelerates, and vegetation stress fluctuates under recurring rainfall anomalies, as indicated by regional assessments of ecological processes and agricultural performance. The integrated interpretation of satellite-based vegetation dynamics, multi-source climate records, and soil biogeochemical evidence shows that sustained productivity hinges on strengthening drought monitoring frameworks, improving soil amendment strategies, and reducing degradation of peat-dominated catchments, especially where smallholder systems face persistent nutrient imbalances and rising vulnerability to emissions-driven environmental shifts. The trajectory highlighted here affirms that regional food security will depend on narrowing the yield gap, reinforcing climate-resilient crop management, and rebuilding ecological buffers that support agrosystem stability, as multiple studies across Southeast Asia emphasize the importance of carbon–water interactions, biodiversity protections, and adaptive resource governance for maintaining productive landscapes. The insights generated through this multi-source analysis contribute to a deeper understanding of long-term vulnerabilities and reveal priority areas where more targeted investments in monitoring systems, sustainable land stewardship, and regionally coordinated intervention strategies can help sustain the region's role as a critical producer of tropical crops under increasingly variable environmental conditions.

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