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Understanding general flowering and mast fruiting in Southeast Asia: research gaps and consequences for studying faunal communities

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E-mail: zoelieb1@gmail.com**Keywords:** phenology, Southeast Asia, Dipterocarpaceae, resource events, general flowering, mast fruiting, tree reproduction strategySupplementary material for this article is available [online](#)**Abstract**

Southeast Asian trees exhibit synchronous gregarious community-wide reproduction known as general flowering and mast fruiting (GFMF) that underpins ecosystem dynamics and functioning. These events flush forests with flower and fruit resources for several months, often in conjunction with El Niño Southern Oscillation events (ENSO), followed by prolonged periods of scarcity of two to ten years. However, there has been little synthesis of GFMF data and findings, especially at large regional scales and across disciplines, leaving uncertainty about its role affecting the region's imperiled fauna or broader spatial dynamics. Here, we provide a systematic literature review of GFMF in Southeast Asia (SEA) to identify strengths and weaknesses in the understanding of this phenomenon. We find that the extended temporal and spatial scales that GFMF events span complicate research efforts, such that: (1) most GFMF studies are single sites of <1 km², creating a scale mismatch with these events that span thousands of kilometers; and (2) GFMF is rarely included in faunal modeling studies despite the importance of flowers and fruit in animal diets (from pollinators to frugivores to seed predators). Filling these gaps would provide critical insights into the timing and availability of floral and fruit resources, which support animal populations ranging from insects to megafauna. Our review is particularly timely in the context of climate change, which has already altered ENSO frequency. There is an urgent need for broader-scale, integrative approaches to understand GFMF for effective biodiversity conservation and ecological modeling across SEA, especially in the face of climate change.

1. Introduction

General flowering and mast fruiting (GFMF) phenology in Southeast Asian canopy trees, particularly the dominant Dipterocarpaceae giants, is an enigmatic, ecosystem-defining display of synchronous, community-wide, supra-annual reproductivity. It has been called 'one of the most spectacular and mysterious phenomena in tropical biology' (Sakai *et al* 2006). In a region with relatively consistent rainfall, temperature, and photoperiod throughout the year, trees rely on triggers other than seasonality to stimulate reproductivity (Ashton *et al* 1988, Sakai *et al*

2006). These sporadic reproductive events are generally believed to be triggered by weather extremes associated with El Niño Southern Oscillation (ENSO) (Wich and Van Schaik 2000, Williamson and Ickes 2002, Numata *et al* 2003, Cannon *et al* 2007), particularly the synergistic effect of cool temperatures and drought (Satake *et al* 2019), and largely drive resource availability in everwet Southeast Asia (SEA) (Curran and Leighton 2000). Yet, despite its ecological importance, most GFMF research remains site-specific or focused on various theories for the evolution and retention of this reproductive strategy (Janzen 1974, Hosaka *et al* 2011, Kurten *et al* 2018, Satake *et al*

2021), leaving a major gap in regional-scale, integrative understanding of how GFMF shapes ecosystem dynamics and biodiversity across SEA.

1.1. Spatial-temporal complexity

The non-cyclical spatial-temporal dynamics of GFMF events create challenges for monitoring tree reproductive phenology. These patterns play out over years or decades rather than within years in SEA, time scales that are not conducive to western-centric human annularity expectations, typical research agendas, or funding cycles (van Schaik *et al* 1993, Cannon *et al* 2007, Chen *et al* 2018); (figure 1). Further, GFMF phenomena occur over hundreds of kilometers of forest (Appanah 1985, Sakai 2002). Capturing the spatial extent and patterning of GFMF likely requires coordinated monitoring efforts across diverse and often inaccessible landscapes. The reproductive patterns of trees are well understood in systems that function within predictable and short time-scale food resource cycles (figure 1(A)), such as seasonal fruiting in temperate forests (Park *et al* 2021, Bogdziewicz *et al* 2024), yet are poorly understood in the suprannually reproductive SEA (Davis *et al* 2022). Even compared to tropical regions, SEA is frequently unrepresented in global reproductive phenology studies (Hackett-Pain *et al* 2022, Qiu *et al* 2023). Detecting these spatiotemporal patterns of *supra-seasonality*—irregular weather and associated phenology events with periods >12 months—is essential to our ability to understand the ebbs and flows of primary producers, and fauna that rely on them for survival.

1.2. Human influence and conservation concerns

The impact of human-induced pressures on GFMF events remains poorly understood, such as habitat fragmentation, logging, reduced plant or animal species diversity, or climate change (Kettle *et al* 2011, Pearse *et al* 2021). Malaysia and Indonesia each have more Dipterocarpaceae species than any other country in the world (Khoo *et al* 2023), the family of trees that dominate Southeast Asian tropics and generally exhibit strict masting behavior. Over 60% of these species are classified as threatened, primarily due to agroindustrial land use change and logging (Khoo *et al* 2023). Compounding these threats to these tree communities, climate change may alter the weather events that trigger GFMF, with as yet unknown consequences for nutrient resource cycling and trophic dynamics throughout SEA (Sullivan *et al* 2024). Some research predicts a decrease in flowering and fruiting among these trees under future climate change scenarios (Numata *et al* 2022), jeopardizing the survival of these carbon-dense, ecosystem-building species. Alterations to ENSO and tree reproduction triggers could also reduce the predator-satiating effect of

masting strategy, thus reducing fecundity of masting trees globally (McKone *et al* 1998). Further, it is unclear whether conservation strategies, including protected area management or ecological restoration, have an influence on GFMF ecological processes or can adequately address the climate-related risks of reduced reproductive synchrony, decreased pollination, and increased seed predation as has been shown in temperate in Europe (Bogdziewicz *et al* 2023). Understanding the interplay between anthropogenic impacts, climate change, conservation strategy, and GFMF is critical for how we study the broader trophic systems of Southeast Asian rainforests.

1.3. Faunal responses to GFMF resources

Staggered GFMF events dictate the food availability for many Southeast Asian rainforest fauna (Curran and Leighton 2000, Wong *et al* 2005, Fredriksson *et al* 2006). This has significant cascading effects on all trophic levels, creating booming and busting populations of insect and other seed predators, and dramatically altering total edible food availability to nearly all species (Curran and Leighton 2000, Clark *et al* 2019, Sullivan *et al* 2024). This is well studied through direct observational non-modeling based studies that consider fauna populations and diets in conjunction with observations of GFMF, but this consideration is largely missing from modeling studies. Quantifying faunal food resource availability is critical to our ability to accurately model their populations, which in turn informs conservation efforts and management (Morellato *et al* 2016, Clark *et al* 2019). Scientists have an arsenal of increasingly complex statistical modeling approaches for fauna populations that draw on a dizzying wealth of biotic and abiotic data and variables (Yates *et al* 2018, Kelt *et al* 2019, McCrea *et al* 2023). However, the extent to which GFMF data has been used in these modeling approaches is unclear. This potentially undermines the utility of fauna monitoring because pulse resource events have been shown to dictate local population dynamics (Morellato *et al* 2016, Kanamori *et al* 2017), body condition, reproduction, survival (Wong *et al* 2005), and migrations (Curran and Leighton 2000, Granados *et al* 2019). GFMF can complicate plant and animal demographic analysis, where short-term monitoring can significantly misrepresent long-term trends of seed production, seedling recruitment, and resources for animals (Vacchiano *et al* 2018, Pearse *et al* 2021). A regional synthesis of research on this phenomenon may improve faunal conservation and management at a scale appropriate for large-bodied animal movement and ranges.

We conducted a systematic review of the peer-reviewed articles pertaining to GFMF in Southeast Asian rainforests (figure 2). Additionally, we conducted a supplemental literature review to identify

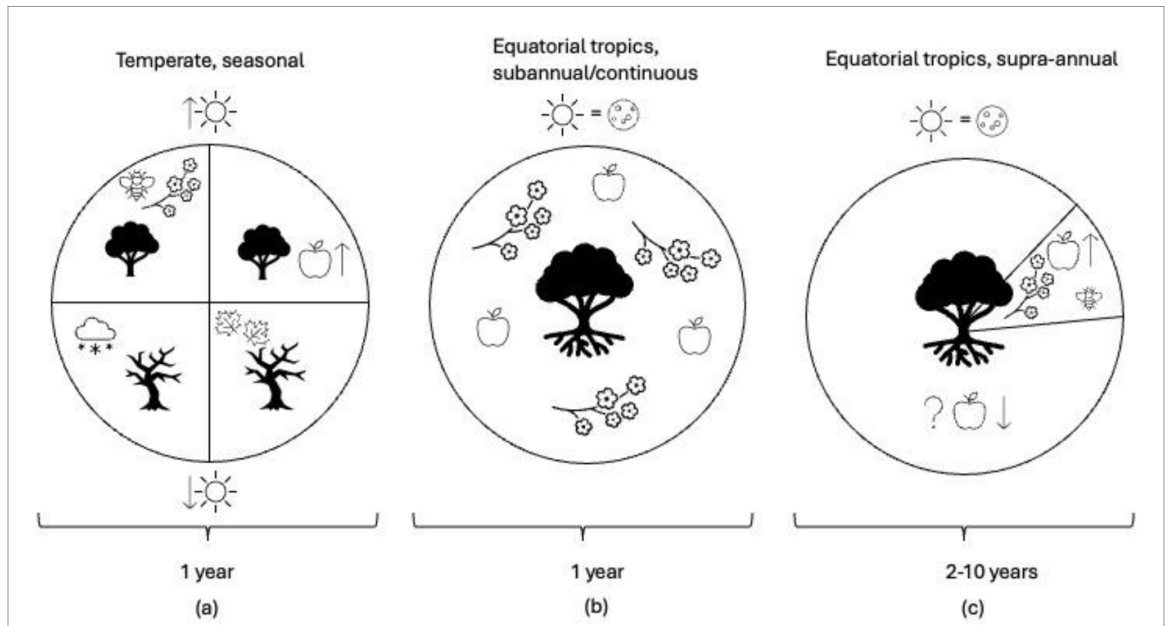


Figure 1. Conceptual figure of tree reproductive phenology patterns. In temperate environments (a) there is relatively reliable seasonality, and therefore annual triggers for synchronous reproduction. In the Neo- and Afro-tropics (b), there is generally year-round high productivity and reduced variance in rainfall, temperature, or photoperiod, or wet and dry seasons, often leading to continuous or sub-annual reproduction. However, in the Southeast Asian tropics, trees will experience long periods of low reproductivity, only reproducing when climate anomalies create short periods of low rainfall and low temperature that trigger flowering and subsequent fruiting (also known as general flowering and mast fruiting) (c). In the seasonal system, photoperiod is substantially longer in warmer months and shorter in winter months. In tropical, equatorial systems, day and night are similar lengths with less variation throughout the year, represented by the sun and moon symbols (top).

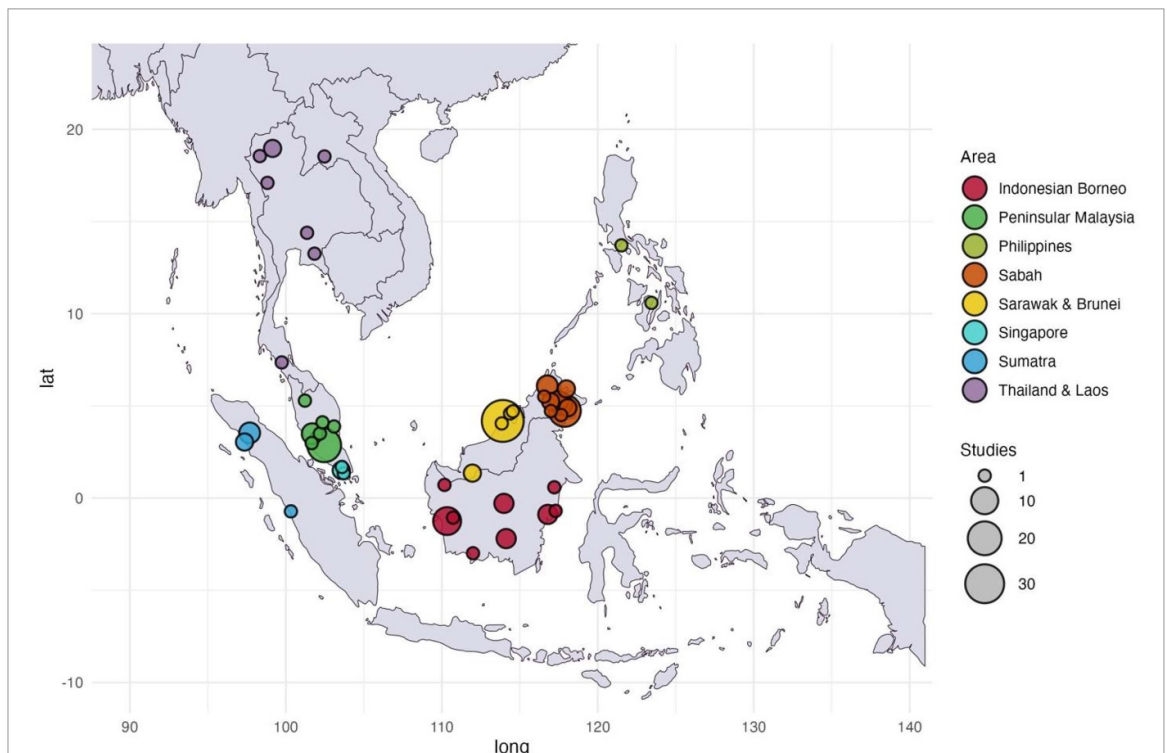


Figure 2. Locations of general flowering and mast fruiting (GFMF) phenology research in Southeast Asia. A total of 150 papers met the criteria for the literature review. Symbols are graduated based on the number of studies per site.

Southeast Asian faunal modeling studies and determined the extent to which they considered GFMF as a variable influencing demographics. Our aims were to:

- (1) Identify the spatial and temporal scales of GFMF studies
- (2) Determine whether GFMF studies consider anthropogenic factors (e.g. climate change) or conservation action (e.g. protected areas)
- (3) Quantify the number of faunal population modeling studies in SEA that consider resource availability
- (4) Highlight key knowledge strengths and research gaps
- (5) Propose priority research areas for conservation related to GFMF

In doing so, we lay the groundwork for aligning future GFMF research with the ecological complexities and conservation challenges of Southeast Asian forests.

2. Methods

2.1. Review of GFMF studies

2.1.1. Searching literature

We conducted a literature search with Web of Science and Scopus databases, including peer-reviewed articles, reports, and conference proceedings. An initial unfiltered search on Web of Science yielded 2,099 papers. Search terms were ‘general flowering,’ OR ‘mast fruiting,’ OR ‘mast*,’ AND (‘Southeast Asia’ OR ‘Malaysia’ OR ‘Borneo’ OR ‘Indonesia’ OR ‘Singapore’ OR ‘Thailand’ OR ‘Kalimantan’ OR ‘Sarawak’ OR ‘Sunda*’). There were 304 articles after excluding papers from irrelevant disciplines, including history, literature, medical science and education (based on Web of Science subject categories). A Scopus search with the same terms resulted in 210 relevant results, 125 of which were duplicates. To seek out additional studies that may have been missed, we added a Web of Science and Scopus search with the following terms: ‘phenology,’ ‘Southeast Asia,’ and ‘flower*’ OR ‘fruit*’. This yielded 56 studies of which 35 were not duplicates.

2.1.2. Criteria

We imported these 424 sources into EndNote and Covidence, an online systematic literature review tool (Covidence systematic review software 2024). For papers to be included, they needed to include at least one site in SEA, relate to tree reproductive phenology, be based on a natural system (rather than an agricultural system), and relate to rainforests or other

tropical forested landscapes. We excluded 171 papers for our topic by screening the titles and abstracts and 103 were excluded during a full-text review based on these characteristics (figure 3(a)). The final sample size was 150 papers. For papers that met these criteria, we extracted data with a series of fixed answer questions. Some questions included a free text box to add detail where needed.

2.1.3. Extraction

We extracted the following information from each study: study site(s), geographical scale [single site, dual sites, multiple sites in one country; regional (sites spanning multiple SEA countries), pantropical; global, and no location specified], primary and secondary topic [primary topic refers to the main overarching topic of the paper that is most emphasized in the title, introduction, and discussion; secondary topic refers to the supporting theme of the paper which is still of major significance in the introduction and discussion but is less central to the paper than the primary topic].

We identified a study as including anthropogenic effects if it mentioned climate change, hunting, logging, fragmentation, or human-driven deforestation, or other human-caused environmental impacts, in any part of the paper. We also noted when studies had direct or indirect reference to conservation action; a paper was considered to have indirect reference to conservation action if it mentioned an action in the conclusion or more generally suggest that conservation action is needed. Whereas a paper was directly related to conservation action if the authors made a specific recommendation for conservation action relevant to their findings, or otherwise significantly related their work to conservation action.

For full list of extraction questions see SM1 table 1.

2.2. Review of fauna studies

To determine the extent to which GFMF is included as a factor in fauna population modeling, we conducted a supplemental literature search using keywords: ‘ecology’ AND ‘model*’ AND ‘Southeast Asia’ AND ‘rainforest’ on both Web of Science and Scopus. We limit our search to rainforests that are likely to exhibit strict masting reproductive behavior, although we note that masting is possible in other habitats. This yielded 82 non-duplicate studies. Studies were included if they were modeling fauna and related to natural extant rainforest systems. Studies were also excluded at the title and abstract stage if they only modeled species phylogeny rather than existing populations. This excluded an additional 66 papers, leaving 17 papers for review (figure 3(b)).

For full list of extraction questions see SM2 table 1.

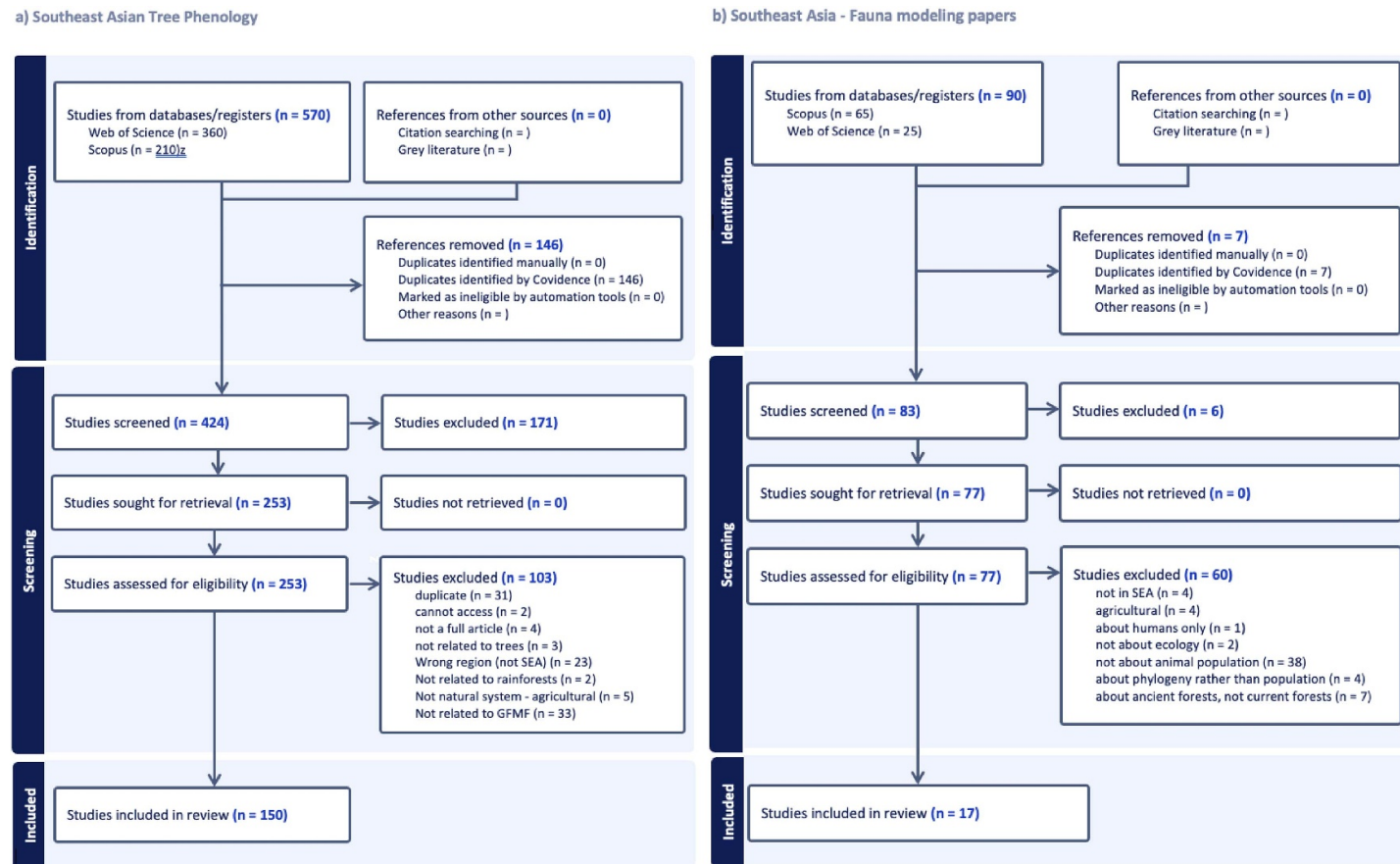


Figure 3. Literature review inclusion outcomes shown using the PRISMA output from Covidence. (a) General flowering and mast fruiting papers GFMF studies. (b) Faunal studies focused on population modeling.

3. Results

3.1. Spatial and temporal scale of Southeast Asian GFMF studies

In the review of GFMF, 72% of studies (108 of 150) were based on a single site (figure 4(b)). Ten studies (7%) included multiple sites within a single country, 10 studies (7%) were regional (multiple sites within SEA) and nine were international (combining ‘pan-tropical’ and ‘global’; figure 4(a)).

There were 47 sites included throughout all 150 studies (figure 2), though some studies were model-based, theoretical, literature-based, or otherwise did not pertain to a specific geographical location. Only 20 sites (42.6%) were included in more than one study (figure 5(a)).

The bulk of studies concentrated on a small handful of sites (figure 5(a)); the three most studies sites were Lambir Hills National Park (Sarawak, Malaysia) included in 37 studies (25% of all studies), Pasoh Forest Reserve (Peninsular Malaysia) included in 20 studies (13%), Danum Valley Conservation Area (Sabah, Malaysia) included in 17 studies (11%), and Gunung Palung included in 11 studies (7%). Only four sites (excluding the ‘No location’ category) were represented more than five times in all the reviewed literature (figure 5(a)). Most studies took place in Sarawak and Brunei, Sabah, and Peninsular Malaysia subregions (figure 5(c)), corresponding to the most established and longest-term monitoring sites in the region. There were no studies in Sulawesi (Indonesia), Papua New Guinea, Cambodia, or Vietnam.

Over a third (56) of studies included a single mast-ing event, whereas 21 studies (14%) covered 4 or more GFMF events. Thirty studies (20%) observed an area for a year or less, 78 studies (52.67%) were less than five years, and 26 studies (17%) that assessed phenology for ten or more years (figure 4(b)).

3.2. GFMF topics

In the GFMF review, the most frequent primary topics (in order) were ‘masting & animal populations’, ‘cues & triggers’, seed survival, dispersal, predation’, ‘masting hypotheses’, ‘pollination & pollen dispersal’, ‘seedling survival & dynamics’, ‘masting & resource availability’, and ‘animal diets’. There were only single studies matching the following topics: ‘climate change’, ‘conservation’, ‘ectomycorrhizal fungus’, ‘limitations or impacts on masting behavior’, and ‘protected areas & land management’. Only one study specifically focused on conservation, and one on climate change as a primary topic; however, more papers (11 and five respectively) had these as secondary focuses. Protected areas & land management was only represented once for both primary and secondary topics.

3.3. Anthropogenic effects and conservation

Beyond the primary and secondary topics, we also noted when studies referenced anthropogenic effects or conservation action as recommendations or conclusions, even if they were not the primary or secondary theme of the paper. There were 46 studies (37% of all studies) that mentioned some anthropogenic effect, such as climate change, hunting, logging, fragmentation, or human-driven deforestation. The most common reference to anthropogenic activities and/or effects was climate change (21 studies, 46% of papers that included mentions of anthropogenic effects), followed by logging (17 studies, 37%). There were 32 studies (21% of all studies) with a direct link to conservation action, where a specific action was referenced or suggested. Area-based management (12 papers directly referenced) was the most referenced conservation action (figure 5(b)).

3.4. Fauna studies relating to GFMF

All 17 Southeast Asian fauna modeling studies that met our criteria were in areas known to experience GFMF. All of the studies made conclusions about the population status, migration, or other population dynamics of fauna based on modeling, but only two studies mentioned GFMF in the introduction or discussion, and only one study integrated food resource availability (based on monthly tree and liana fruit production observations in 50 0.1 and 0.2 ha botanical plots) in their modeling approach (Clink *et al* 2017). Two sites, the Stability of Altered Forest Ecosystems or ‘SAFE project’ in Sabah, Malaysian Borneo, and Gunung Palung National Park in Kalimantan, Indonesian Borneo, were present in papers in both the GFMF review and the fauna review.

4. Discussion

The majority of research on GFMF in SEA comes from small single study sites (with phenology plots often $<1 \text{ km}^2$), with much of the research generated from a limited number long-term phenological datasets collected from well-known sites such as Lambir Hills National Park (Sakai 2025), Danum Valley Conservation Area, Gunung Palung National Park (Knott *et al* 2021), and Pasoh Forest Reserve (Chen *et al* 2018). While these long-term phenology observation sites have become invaluable to understanding the region’s ecology, this reliance on a handful of intensively monitored sites represents a clear mismatch with the GFMF phenomenon itself, whose ecological drivers and consequences operate across vast and varied areas that extend far beyond individual forests (Ashton *et al* 1988, Sakai 2002, Numata *et al* 2003, Azmy *et al* 2016).

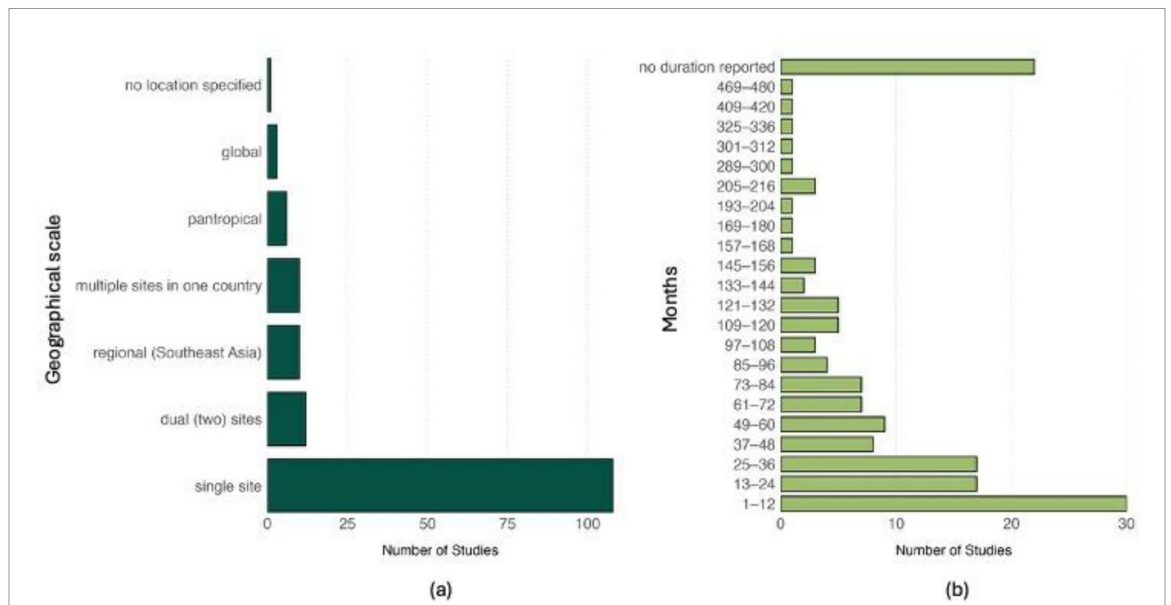


Figure 4. Spatial (a) and temporal (b) scope of 150 peer-reviewed articles on general flowering and mast fruiting in or including Southeast Asia. Each study was assessed for the number and geographical spread of study sites, data utilized, and spatial scope. This was used to categorize them into these geographical categories. Duration of studies was determined by interpreting start and end dates of the study, or if the study stated its timeline explicitly.

4.1. Spatial and temporal scales of GFMF research

Despite the existence of multi-decade records and many single-mast event observations, there are few attempts to synthesize data across multiple locations. Only 10 studies spanned more than one Southeast Asian country, and just two (Wich *et al* 2011, Chechina and Hamann 2019) explicitly examined patterns at a full regional scale, or compared across countries. Without a region-scale compilation of phenology records and broader spatial analysis, we are likely to overlook larger patterns concerning GFMF, such as climate change and the effects of climate anomalies like ENSO and the Indian Ocean Dipole. This lack of regional integration leaves a major blind spot in our understanding of one of the systems that underpins one of the most biodiverse and carbon-storing ecologies on the planet.

Our review also found a dearth of long-term monitoring suitable for capturing the decadal cycles of GFMF. A handful of sites were observed over three or more masting events, but well over half were only observed for a single event. Long-term site monitoring remains critical and continuation of those efforts is a priority. However, without synthesis across compatible datasets, our understanding of GFMF remains constrained to isolated forests rather than landscapes.

4.2. GFMF and conservation

Only a small fraction of reviewed studies addressed anthropogenic impacts on GFMF, and even fewer linked their findings to conservation actions.

Research themes remain weighted towards fundamental science—e.g. masting hypothesis testing and reproductive physiology—with little integration into applied ecology or management contexts. Only one study primarily focused on conservation, and one on climate change; this is a major missing element in our understanding of GFMF; projections suggest climate change will alter ENSO cycles and increase drought frequency (Faranda *et al* 2025), potentially disrupting the climatic cues that trigger GFMF. Even small shifts in temperature or rainfall can reduce dipterocarp reproductive success, with cascading effects on seed predators and forest trophic dynamics (Numata *et al* 2022). Because GFMF strongly affects diet, reproduction, and movement for many taxa, shifts in its timing or magnitude could have significant stochastic effects on wildlife populations and carbon storage. Indeed, well over half of Dipterocarps themselves are endangered and face extinction risk should their reproductive processes be further disrupted by climate change.

GFMF dynamics were rarely mentioned in animal population modeling for SEA, despite their major influence on species presence, abundance, and detectability. In temperate environments, optimal sampling periods can be predicted from seasonal peaks in temperature, rainfall, and photoperiod which related to higher resource availability seasons; in aseasonal Southeast Asian systems, such patterns are driven by infrequent and anomalous climatic events rather than annual cues (Satake *et al* 2019, Staggemeier *et al* 2020). Ignoring these supra-annual cycles

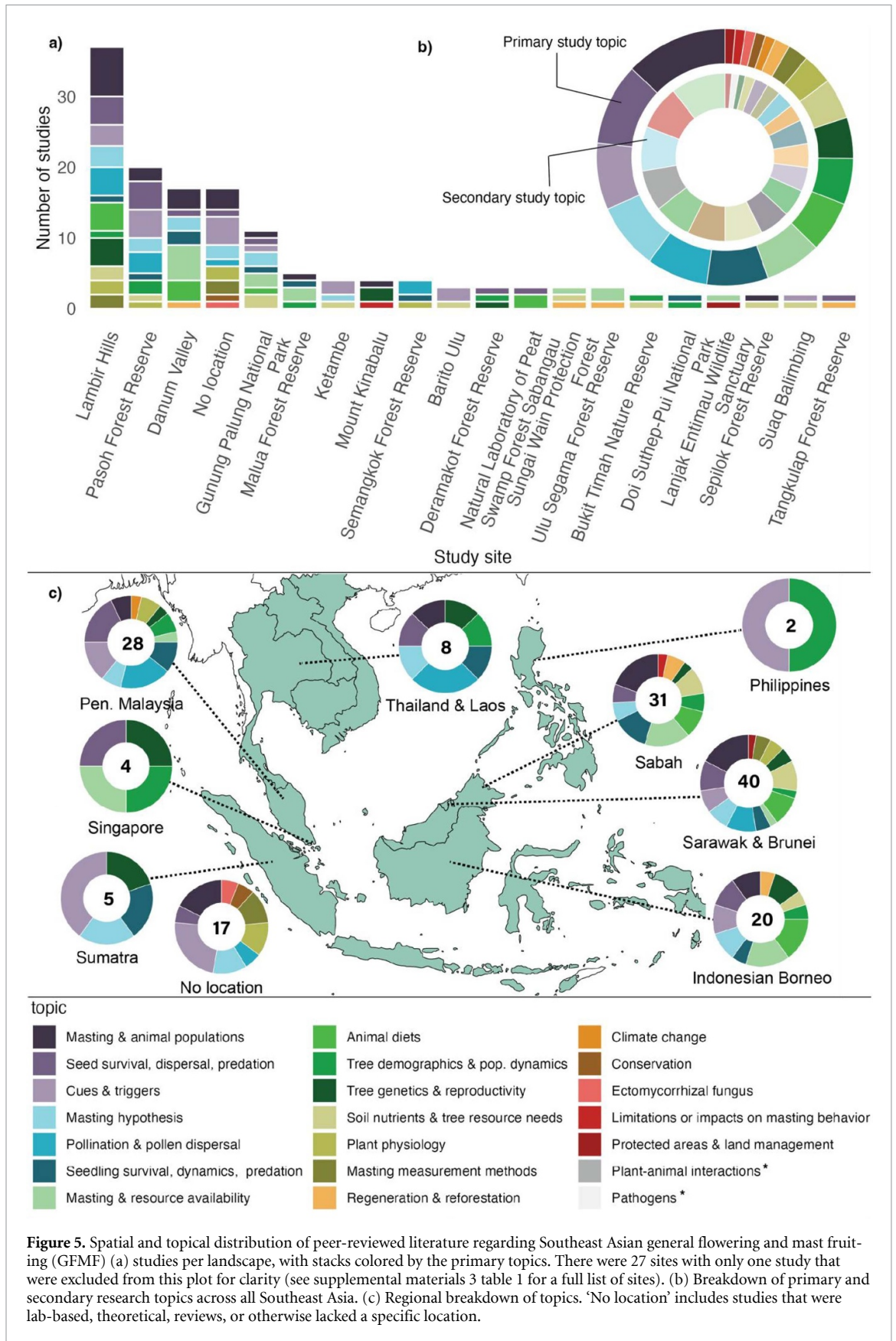


Figure 5. Spatial and topical distribution of peer-reviewed literature regarding Southeast Asian general flowering and mast fruiting (GFMF) (a) studies per landscape, with stacks colored by the primary topics. There were 27 sites with only one study that were excluded from this plot for clarity (see supplemental materials 3 table 1 for a full list of sites). (b) Breakdown of primary and secondary research topics across all Southeast Asia. (c) Regional breakdown of topics. ‘No location’ includes studies that were lab-based, theoretical, reviews, or otherwise lacked a specific location.

is akin to omitting seasonality from fauna surveys in temperate systems, which could lead to significant over- or under-estimations of populations depending on when sampling takes place within the supra-annual cycle of pulse resource events.

4.3. Seeing the forest for the trees; regional data integration

Valuable data exist for tree reproductive phenology, though at precious few sites, over limited timelines, with little regional integration, and often not readily accessible to researchers working outside fundamental tree reproduction. There is also relatively little overlap between sites that have GFMF data and sites used in fauna modeling, despite clear opportunities to pair these datasets. Several fauna population modeling studies were conducted where long-term phenological observations were available but not integrated into models, possibly due to issues of data access, format, or awareness of the importance of GFMF to fauna sampling.

Our findings confirm longstanding calls for more integrated, landscape-scale, multi-site comparative studies (Corlett and Primack 2006, Kettle *et al* 2011, Butt 2019, Sullivan *et al* 2024).

As a next step, we propose a regional data synthesis of all existing GFMF observations across SEA. A region-scale, spatiotemporal map of GFMF could be created by integrating disparate site-level long-term monitoring datasets, gleaned observations from literature, and unifying expert input from researchers and practitioners with extensive but unreported knowledge of these events. Such an integrated dataset would allow us to identify geographic gaps in monitoring coverage, examine whether reproductive events show directionality across the region (e.g. onset of GFMF starting in the east and spreading west), assess whether other climate anomalies mitigate or amplify ENSO effects in particular areas, and model the biotic and abiotic factors that determine or moderate masting. Incorporating spatially and temporally explicit GFMF observations with such covariates could be used to develop predictive models to provide a continuous layer of GFMF spatial and temporal extent of masting over recent decades, and potentially into the future.

A continuous GFMF layer could then be used to produce a related measure of resource availability to animals. This time-since-resource-event metric could be incorporated into fauna population modeling (e.g. as a covariate in occupancy models used to assess camera trapping data), improving demographic inference and conservation assessment. Hands-on fauna conservation practices like reintroductions or culling could be more advant-

ageously timed if better considered in the context of natural food resource availability (Pearse *et al* 2021; (Hallworth *et al* 2024). Region-scale integration of tree phenology with wildlife would also allow investigation of interactions between GFMF and non-cyclical events such as extreme heat, disease outbreaks, or deforestation. For example, for apex predators, the loss of wild pigs as prey due to African swine fever may be exacerbated if declines in other prey occur in years without mast fruiting (Luskin *et al* 2021, Lieb *et al* 2025). GFMF event data could also be integrated into climate change impact models, shedding light on how GFMF may be affected under future climate scenarios, and inform future conservation action.

The conservation of Dipterocarps themselves can be better addressed with improved understanding of GFMF; Pearse *et al* (2021) discuss several uses of mast seeding information for conservation in land management. Most applicable in fragmented SEA is improved timing for seed collecting for reforestation purposes. Lack of access to seeds is a major obstacle to nurseries and restoration projects (Kettle *et al* 2011): without better awareness, preparedness, and scale perspective of oncoming GFMF events, conservationists may miss out on capturing the spread of species that only make their seeds available during relatively short and infrequent mast events.

There are several low-cost and low-labor methods to monitor phenological events. For example, MastWatch (Webb and Maycock 2022) has developed an online forum and iNaturalist project (an online observation repository and organism ID tool) where observations of masting trees and their reproductive status can be recorded by anyone with a smartphone across the region and later verified. The African Phenology Network has developed recommendations for more effective long-term monitoring that could be replicated in SEA (Bush *et al* 2018). Others have recommended strengthening digitization and mobilization of herbarium records for tropical species to enhance our ability to address how phenology will respond to climate change (Davis *et al* 2022). Remote sensing, including satellite imagery products, holds much promise for studying tree reproductive phenomena at scale: PlanetScope, with high spatial and temporal resolution, has successfully detected general flowering in Lambir Hills National Park, Sarawak (Miura *et al* 2023). Increased knowledge and monitoring of GFMF is important at a fundamental ecological level as addressed in this paper; however, it could also be valuable to agricultural communities in predicting larger crop years, or determining when wildlife may become more dependent on scavenging and fallback foods in the intermast periods.

5. Conclusion

Southeast Asian forests are highly vulnerable to climate change, and subtle shifts in GFMF dynamics could have far-reaching consequences for biodiversity and carbon storage. Yet our current understanding of this foundational ecological process remains constrained by small, isolated study sites and limited regional integration. Because GFMF underpins trophic dynamics, wildlife demography, and forest regeneration, understanding its regional dynamics is not only an ecological question but a conservation imperative.

Incorporating supra-annual resource patterns into fauna population modeling and conservation planning is essential to accurately assess and protect these ecosystems. Moving from fragmented observations to integrated regional analysis is now both feasible and necessary. By consolidating existing datasets and embedding GFMF dynamics into wildlife modeling and conservation planning, we can transform a patchwork of local insights into a predictive framework for managing one of the world's most biodiverse forest systems.


Data availability statement


The data that support the findings of this study are available upon reasonable request from the authors.


Phenology lit. review data available at <https://doi.org/10.1088/1748-9326/ae69fc/data1>.

Supplemental Materials available at <https://doi.org/10.1088/1748-9326/ae69fc/data2>.

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