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Beyond Pest Control: Long-Tailed Macaque Conflict, Post-Fire Habitat Change, Economic Injury, and Conservation-Compatible Management in Indonesian Oil Palm Plantations

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ABSTRACT

Long-tailed macaque (Macaca fascicularis) encounters in Indonesian oil palm plantations raise interrelated production, conservation and governance challenges, particularly where adjacent habitat has been disturbed by fire. This qualitative literature review interprets peer-reviewed evidence published during 2020–2026 concerning macaque behavioral ecology, habitat disturbance, immature fruit-bunch injury, economic damage, nonlethal interventions and social–ecological coexistence. It distinguishes increased sightings from verified population growth and separates post-fertilization fruitlet removal from true fruit-set failure. Claims of 10–15% fruit-set reduction and 0.5–1.0 kg fresh-fruit-bunch loss are treated as unverified field observations requiring controlled bunch-to-harvest assessment. A conceptual framework links habitat change, food access, macaque movements, crop injury, economic decisions and institutional responses. The review proposes a marginal avoided-loss decision rule rather than a universal macaque troop-size threshold and develops a monitored, nonlethal-first intervention ladder with welfare and public-safety safeguards. Although Macaca fascicularis is generally absent from Indonesia's national protected-species schedule under P.106/2018, its IUCN Endangered designation and the need for current BKSDA guidance warrant caution before wildlife handling or irreversible control. The contribution is a field-verifiable, conservation-compatible decision architecture for oil palm estates and neighboring communities, together with a ninety-day initiation protocol and longer-term research priorities.

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Introduction

Background and Emerging Plantation Challenge

Oil palm plantations are productive landscapes, but they are also parts of larger ecological mosaics in which animals move across forest remnants, riparian vegetation, roads, drainage lines, villages and cultivated areas. Long-tailed macaques (Macaca fascicularis) can exploit the resources provided by such heterogeneous environments, creating opportunities for coexistence and for conflict. In parts of Riau, plantation personnel describe increasingly conspicuous troops and damage to young and mature fruit bunches. Their concern is operationally serious because a visually damaged immature bunch may remain on the palm for several months before its eventual contribution to recorded fresh fruit bunch output can be assessed. Yet field reports alone cannot reveal whether more animals are present, whether existing troops have shifted their feeding ranges or whether human observers are detecting them more frequently. A credible response therefore begins by separating the observation of increased encounters from demographic population growth, and the presence of macaques from demonstrated economic injury [1-4].

An especially important local narrative links greater macaque activity to fires in scrubland and secondary vegetation beyond the plantation boundary. Forest fire can alter canopy structure, microclimate, food availability and animal space use, and its consequences may persist beyond the period of visible burning. The literature supports taking that pathway seriously without treating every plantation encounter after a fire as proof of displacement. Macaques may enter cultivation because undamaged palms provide attractive foods, because remaining forest strips concentrate individuals, because troop membership changes or because patrol frequency increases. Studies of primate responses to environmental disturbance make these alternative pathways plausible and testable. A before–after comparison without suitable unaffected estates, habitat mapping or consistent observation effort is unable to disentangle them. The central analytical proposition is therefore conditional: post-fire landscape change may alter encounter risk, but the magnitude and mechanism must be reconstructed locally [5-8].

Bunch injury has a second distinctive dimension. The field description of macaques dislodging outer fruitlets from approximately two-month-old bunches and consuming their internal tissue is an observation of feeding-related injury, not a laboratory determination of fruit-set failure. Fruit set conventionally concerns the proportion of flowers or fruiting structures developing into fertilized fruits; later fruit removal, fruitlet abortion and physical scarring can reduce final bunch mass without reducing

the initial fertilization rate. Conflation can magnify or misdirect management estimates. The indicated 10–15% change in fruit set and 0.5–1.0 kg reduction in bunch weight for bunches originally above 10 kg are therefore explicitly considered provisional estate estimates, not measurements independently corroborated by the reviewed literature. A defensible article must show how such claims could be checked against uninjured matched controls, pollination indicators and actual harvest weights [9-11].

Urgency and Research Contribution

A simple pesticide-like treatment of macaque conflict can create ecological, legal and reputational risks. Indonesia's national protected-species schedule and the global conservation assessment answer different questions: the long-tailed macaque is generally not listed as nationally protected under Ministerial Regulation P.106/2018, while the IUCN's 2022 assessment categorizes it as Endangered. That designation does not itself determine the legality of an individual field action, and no universal right to shoot, poison, capture or relocate animals follows from an economic calculation. Contested interpretations of long-tailed macaque population status within the peer-reviewed literature further reinforce the need for geographically explicit evidence rather than assumptions about either universal scarcity or universal abundance. A management model that begins with reversible prevention, animal welfare, worker safety and formal contact with BKSDA is more defensible than treating an animal count as a permit to intervene [12-15].

This article synthesizes work published from 2020 through November 2026 to propose a practical interpretation of the emerging challenge. Its primary contribution is not an original plantation experiment or a national population estimate; rather, it is a linked framework for ecological attribution, agronomic damage verification, contextual economic decision-making and coordinated wildlife governance. The review uses macaque-specific studies wherever available and draws on broader human–wildlife coexistence scholarship for concepts that are potentially transferable. Species differences, local land tenure and intervention conditions are kept visible throughout. Five figures illustrate causal mechanisms, a bunch-level damage timeline, an economic comparison, a tiered management sequence and a ninety-day pilot. The goal is a decision pathway in which plantation productivity and conservation obligations are evaluated together, with uncertainty made explicit and all harmful actions subject to lawful, independent review [16-19].

Literature Review

Macaque Ecology in Anthropogenic Mosaics

Long-tailed macaques are behaviorally flexible primates that can exploit anthropogenic foods and structurally modified habitats, but adaptability must not be confused with negligible conservation vulnerability. Field research from Malaysia shows how direct human activity and food provisioning affect the daily behavior of macaques. A Philippine study documented time-dependent movements between built-up areas and a forest–agricultural mosaic, offering a methodological example for mapping when and where feeding pressure may occur. Recent work in Sarawak demonstrates that both pig-tailed and long-tailed macaques use forest fragments and oil palm settings, reinforcing the ecological importance of habitat configuration. None of these results estimates the exact number of macaques in any particular Riau plantation. They instead identify testable variables: available natural foods, accessibility of oil palm resources, nearby cover, troop composition, peak visiting times, and the spatial continuity between sleeping and feeding areas.

The behavior of social troops complicates simple control strategies. Individuals differ in boldness, learning and exposure to people; troop-level observations also conceal variation by age, sex and rank. Studies of synanthropic rhesus macaque personality illustrate why a deterrent that appears effective initially may fail when highly exploratory individuals learn an alternative route. Long-tailed macaque interactions with domestic animals in Bali demonstrate that shared agricultural and human spaces involve more than a single binary conflict. Research on macaque social behavior in Malaysian plantations, although conducted with a different macaque species, found altered grooming, play and aggression in plantation interiors relative to forest and edges. Such findings argue against interpreting an animal's use of planted land as evidence that it experiences no ecological cost. Intervention evaluation should therefore document macaque responses and group behavior, not solely short-term disappearance from the nearest palm [21-23].

Anthropogenic food subsidies may be highly consequential. Intentional provisioning at tourist areas, accessible household waste, discarded food at labor accommodations and poorly contained plantation refuse may stabilize repeated visits and reduce avoidance of humans. Research from Indonesia identifies roadside provisioning as a safety issue for both people and macaques, while a separate macaque tourism study describes how intensified feeding can change behavior and community relations. These findings justify field assessment of attractants, but they do not establish that labor camps caused the particular problem described by the estate. The management implication is to audit possible attractants without blaming workers or nearby households in the absence of evidence. Food-waste management becomes one component of a coherent response, alongside buffer vegetation, safe movement routes, monitoring and damage prevention [24-26].

Habitat Disturbance, Fragmented Forests and Conservation

Fire changes habitat in ways relevant to primate foraging even when an estate's palms remain unburned. A long-term investigation in Indonesian peat forest linked burning to reduced canopy cover, hotter and more open environments, and persistent shifts in multiple components of biodiversity. A 2026 review of El Niño-related fire and smoke impacts on Southeast Asian primates identifies possible crowding, displacement, altered diets, changes in activity and reduced physical condition. It is important, however, to distinguish evidence on primates in general from direct evidence on long-tailed macaques and on the specific estate at issue. Species differ substantially in diet, dispersal, sensitivity to disturbance and use of human food. Accordingly, fire should enter the conceptual framework as a potentially important upstream driver rather than as an already proven cause of a measured macaque population increase.

A landscape perspective is important because remaining forest fragments can function as refugia, movement corridors and sources of ecological services. Studies in oil palm landscapes have documented mammals and other wildlife within protected forest patches, while research on orangutans shows the value of even small remnant forests for connectivity in broader agricultural mosaics. These are not demonstrations that a particular forest corridor will prevent macaque crop feeding. Indeed, proximity to cover can simultaneously support wildlife persistence and make feeding excursions into palms easier. This dual possibility challenges indiscriminate clearing of vegetated boundaries as an ostensibly simple deterrent. Vegetation removal may displace risk to new blocks, degrade habitat and aggravate public scrutiny.

A better design explicitly maps existing shelter, natural food, riparian areas and routes before making changes, and distinguishes conservation-oriented restoration from attractant placement near vulnerable crops [27-29].

Local coexistence decisions must also consider landscape heterogeneity across estates. Oil palm production systems differ in planting age, management intensity, land cover, forest-retention arrangements and surrounding community land uses. Research from West Kalimantan and West Sumatra demonstrates that plantation and forest-patch biodiversity cannot be represented by one generic species list. At broader scales, recent pantropical assessment links oil palm expansion to the loss of habitat for forest-dependent vertebrates, while Indonesian studies emphasize complex environmental and production trade-offs. These results provide a basis for asking where macaque feeding sites lie relative to high-conservation-value areas and areas that recently burned. Risk maps should combine animal activity and actual damage, not equate every macaque sighting with an unacceptable incident. Mapping is particularly important when operating blocks have different accessibility and observation effort [30-32].

Independent Indonesian spatial evidence also cautions against treating available incident records as complete measures of human–macaque conflict. An analysis of official records and online reports from Java identified broadly similar spatial clustering but meaningful discrepancies between data sources, and recommended more standardized monitoring. The study did not investigate palm bunch damage in Riau; it strengthens the methodological case for cross-checking estate records, community complaints, and georeferenced field observations before drawing population or intervention conclusions [33].

Crop Damage, Economic Injury and the Limits of a Pest Label

The designation of a vertebrate as an agricultural pest describes an adverse human–animal interaction, not the animal's entire ecological role or its legal status. Human–wildlife research distinguishes experienced material damage, perceived risk and deeper conflicts among stakeholders over acceptable responses. Farmers' tolerance may depend on the severity of losses, personal safety, expectations about compensation and trust in management. Because macaques may also move seeds or participate in ecological interactions, an economic analysis should recognize benefits and costs rather than assume unidirectional harm. The present review does not estimate an ecosystem-service value for Riau macaques. It argues that removing an animal from the landscape has additional social and ecological consequences beyond the narrow accounting line of fruit bunch mass, and these should be discussed explicitly when management options are compared [34,35].

Oil palm damage assessment demands a clear agronomic reference unit. A field worker may report injury to fruitlets in an immature bunch; a harvesting crew will later record the weight of a ripe bunch; an estate's monthly ledger aggregates many bunches and numerous agronomic influences. The difference between these endpoints is not automatically attributable to macaque feeding. Pollination, palm age, water availability, nutrient status, harvesting intervals and other pests influence fruit development and marketable fresh fruit bunch output. Published oil palm research provides tools for investigating bunch-weight components and demonstrates that good management can have substantial yield effects independent of wildlife. Therefore, the damage model should track individual marked bunches over time and include exposure, damage stage, follow-up inspection, ripeness at harvest and a comparable control bunch on a palm with similar characteristics [36].

The biological interpretation of fruit set warrants particular caution. Fertilization and successful initial fruit development occur at an earlier stage than feeding-related removal of developing fruitlets. Consequently, post-set removal and actual poor fruit set may produce similarly sparse surfaces while having different causes. Visual appearance, including a bunch described locally as resembling a porcupine, may be a useful screening sign but is not a validated etiology. Direct behavioral observation, photographs at fixed intervals, matching of wound shape, and exclusion of rats or other potential consumers are needed to strengthen attribution. The reported loss of 0.5–1.0 kg per bunch could be a reasonable hypothesis for an estate trial, but a paper must not present it as a peer-reviewed finding until its denominator, sampling method, palm maturity, comparison group and harvest outcome have been documented [37,38].

Recent pollination research provides an independent biological reason to measure fruit set separately from later feeding injury. In oil palm interspecific hybrids, assisted-pollination trials showed that pollen source altered fruit set, while parthenocarpic fruit production partly compensated for low set-in final bunch weight. These findings arise from a different planting system and cannot be transferred as an Indonesian estate loss coefficient; their relevance here is the demonstrated separation among pollination, fruit composition, and final mass [39].

Integrated Deterrence and Coexistence Theory

Human–wildlife conflict interventions differ in their evidential support, durability, costs and unintended effects. Recent reviews of nonlethal crop protection catalog physical barriers, active guarding, sensory deterrents and habitat-related measures, yet emphasize that performance varies with species and local conditions. A field study of human–primate conflict in India tested several types of deterrents and found potential value in simple fences, while noting limited replication and the gap between stated willingness and sustained adoption. A different study found a particular electric fence design useful against African crop-foraging primates, but transfer to oil palm and long-tailed macaques is untested. These results do not justify automatic installation of electrified fencing or any hazardous exclusion device. Designs must first be assessed for human safety, non-target wildlife injuries, local wildlife movement and applicable electrical and conservation approvals [40,41].

Coexistence theory offers a more comprehensive organizing framework than a one-time pest suppression objective. The conflict-to-coexistence approach distinguishes prevention, response, monitoring, mitigation, governance and shared responsibility. Research on relationships between people in conflict landscapes shows why trusted institutions and transparent decisions matter alongside ecological measurements. A resilience perspective adds the possibility that a policy may appear successful for several months while making the longer-term system more fragile, for example if animals shift damage to adjoining farms or become more habituated to human-provided food. In practical terms, an estate should define measurable success as sustained reduction in verified preventable losses with acceptable safety, ecological and social outcomes. Absence of sightings in one high-profile block is an inadequate sole indicator, particularly if the same animals simply relocate to a nearby community.

Methods: Interpretive Qualitative Literature Review

Review Design and Corpus Construction

This study employs a qualitative literature review, understood as a purposive, interpretive integration of research streams to develop a conceptual explanation and a practical decision model. It is not a systematic literature review and does not claim PRISMA compliance, exhaustive retrieval, a registered protocol or quantitative meta-analysis. The review focuses on research appearing between January 2020 and 11 November 2026, with geographic priority given to Indonesia, Malaysia and Southeast Asia. Comparative work on rhesus, Japanese, toque and other macaques is included when it clarifies behavioral mechanisms or field evaluation methods, and broader wildlife studies inform institutional and economic aspects. Relevant journal articles were located iteratively through thematic title searches, publisher records, indexed abstracts and DOI-bearing landing pages. Regulations and the IUCN assessment are treated as non-journal contextual sources, separately from the journal bibliography [42].

Sources were considered for thematic relevance, research transparency, directness to the long-tailed macaque problem, and plausibility of transferring findings to oil palm. Direct studies of Macaca fascicularis and plantations received the greatest contextual weight. Studies on rhesus and pig-tailed macaques were used as analogical evidence with explicit species qualification. Research about other wildlife was limited to transferable concepts, such as causal monitoring designs, land-use connectivity and governance, rather than assumed behavioral equivalence. An individual paper could inform more than one theme; studies with contradictory interpretations were retained to expose uncertainty rather than forced into a consensus statement. The source list is preliminary because the objective is a coherent, critical literature narrative, not a complete citation census. A later journal submission should also confirm publisher metadata and update rapidly changing legal or conservation-status sources.

Thematic Coding and Quality Appraisal

Reading and synthesis were organized around six analytic families: habitat disturbance and landscape configuration; troop behavior and food subsidies; visible bunch injury and yield attribution; economic decision thresholds; comparative intervention effectiveness; and law, legitimacy and adaptive governance. Within each family, attention was paid to observed outcomes, exposure time, site conditions, sample size, comparison groups and causal limitations. For example, a before–after field account was considered informative for hypothesis formation but not equivalent to an independently controlled effectiveness trial. A quantitative estimate from a different crop was not transferred as an oil palm loss coefficient. Evidence was described as direct, indirect, conceptual or provisional, and interpretations were checked for inconsistencies across biological and economic domains. This procedure is consistent with an interpretive qualitative review rather than a numerical evidence-ranking exercise [42,43].

Reflexivity is particularly important because the initial problem formulation arose from plantation observations and understandably prioritizes protecting production. A conservation researcher might instead foreground the consequences of post-fire habitat decline, and nearby residents might emphasize safety or crop losses beyond the estate. The synthesis therefore resists treating any stakeholder's initial explanation as complete. It also avoids implying that the reported 10–15% and 0.5–1.0 kg values were obtained from independently inspected data. There are no raw estate observation sheets, GPS tracks or trial records available for secondary analysis in this review. The proposed equations and field protocols are analytic recommendations, not results from new experiments. These distinctions protect the validity of the journal article while preserving the practical value of field knowledge as a source of hypotheses, locally relevant variables and candidate interventions.

Results: Thematic Findings

Theme A: Habitat Disturbance, Encounter Patterns and Demographic Uncertainty

The literature suggests that increased plantation visits can reflect several different processes. In a true demographic increase, more individuals survive or reproduce within the broader landscape. In a redistribution process, pre-existing troops spend more time in the plantation after disturbance or shifts in food supply. Under increased detectability, the underlying number and distribution may remain similar, but patrols, road access, fruiting patterns or reporting practices create more records. Recent occupancy-modeling work in a West Kalimantan oil palm estate shows that even informal sightings can provide useful ecological evidence if observation bias is recognized and modeled. A multi-estate citizen science study similarly demonstrates the scale of wildlife records that trained staff can collect. For conflict management, these lessons imply that plantation sightings should be reported as encounter rates with quantified observation effort, not interpreted automatically as estimates of population growth [44,45].

Fire is one possible driver of redistribution. Evidence from tropical peatland shows that burned forest may remain structurally degraded for years, while primate-focused synthesis identifies multiple potential short- and medium-term behavioral consequences. Nonetheless, the strength of an oil palm-associated response depends on whether the actual burned vegetation had been feeding habitat, a corridor, a sleeping area or merely adjacent cover. Estates should reconstruct vegetation type before fire, fire timing and severity, accessible unburned patches, seasonal fruit supply, road development and changes in cultivation. Satellite-derived burn scars and field-confirmed habitat transects would reduce recall bias; GPS-defined incident points would allow comparison across damaged and unaffected estate borders. The resulting analysis could support, weaken or complicate a fire-displacement explanation, including the possibility that some troops continued to occupy the same fragment but altered their foraging schedule [51].

Landscape studies also indicate that edge behavior is unlikely to be uniform. Fragmented forests within plantations may conserve valuable wildlife populations, but edges also permit opportunistic access to foods and may concentrate movement along predictable routes. Studies of macaque habitat occupancy in Sarawak and behavior in the Philippines offer direct reasons to monitor boundary conditions and daily activity. Meanwhile, work on orangutan metapopulations and plantation wildlife refugia cautions against interventions that sever remaining connectivity without ecological assessment. The practical result is an ecological zoning approach: identify conservation refuges that need protection; map repeatedly damaged commercial blocks; record connecting routes; and locate labor camps, waste sites and public roads. Such zoning is more informative than labeling an entire division as infested. It also permits targeted measures to reduce contact at vulnerable palms while leaving the wider habitat system functional [46].

These identification safeguards are especially relevant when locations are inferred from unstructured reports. Published spatial comparisons of macaque complaints in Java and occupancy analyses of wildlife observations in Indonesian plantations show that recording systems can produce useful maps while retaining substantial reporting and detection limitations. A monitoring strategy should therefore distinguish observed encounters, independently verified injury, and inferred abundance, with effort-adjusted uncertainty reported for each.

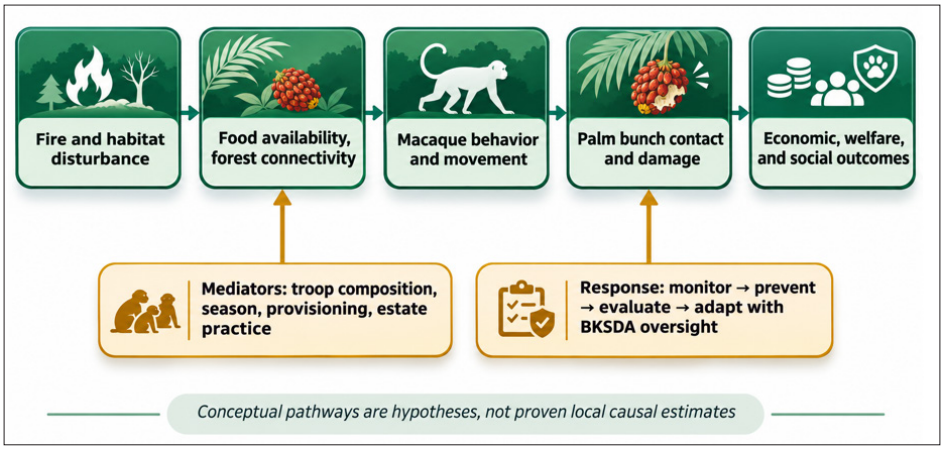


Figure 1: Proposed Social–Ecological Causal Framework Linking Disturbance, Movement, Bunch Exposure and Institutional Response, Arrows Denote Hypotheses

Figure 1 summarizes why causal attribution should move through measurable intermediate processes rather than jumping directly from fire to economic loss. A fire can affect habitat quality, but macaque movement is mediated by natural foods, troop structure, edge accessibility and anthropogenic attractants. Crop damage then depends on contact with susceptible bunches and the duration and intensity of feeding, while its economic significance is mediated by bunch maturation, market prices and the capacity of a feasible intervention to prevent harm. Governance can feed back on ecological and social outcomes by changing waste practices, habitat management, staff behavior and reporting incentives. The diagram should therefore guide a field data form and interview protocol rather than be read as a statistical causal model already validated for Riau.

Theme B: Immature Bunch Feeding and Valid Yield-Loss Attribution

Damage to immature oil palm bunches deserves separate attention from losses caused by feeding on ripe fruitlets. In the reported case, macaques appear to remove fruitlets from the outside of young bunches, producing conspicuous surface gaps. An early wound may influence later bunch development or facilitate secondary deterioration, but the magnitude of such effects depends on timing, number of fruitlets affected and plant physiological response. There is insufficient reviewed evidence to derive a universal conversion factor between the observed surface pattern and harvested bunch weight. Studies on oil palm fresh fruit bunch production show that total bunch mass depends on several yield components and agronomic practices. Therefore, the first result of this qualitative synthesis is a measurement requirement: every damage report should specify bunch stage, number and location of affected fruitlets, photographic severity class, likely animal identity, and whether the bunch reached harvest Three agronomically distinct pathways should be separated. First, poor pollination or failed initial fruit development lowers true fruit set before macaque feeding may occur. Second, direct removal of developing fruitlets changes the number of retained fruits after fertilization. Third, mechanical injury may affect the subsequent survival or quality of neighboring fruitlets or bunch tissues. These pathways may coexist, and their final economic consequences require observation rather than inference from appearance. A protected control bunch matched by palm age, stand characteristics and maturity would permit a more defensible comparison than selecting an uninjured ripe bunch from another block. Where feasible, short-duration wildlife-safe exclusion of selected bunches would help identify exposure effects, but the enclosure itself must be tested for possible changes in temperature, pollination, airflow, harvesting work or bunch physiology [53].

The field sampling unit should be the bunch nested within a palm, block and estate. A baseline cohort can include damage-free bunches and already damaged bunches at comparable development stages, photographed and tagged without disrupting natural development. Repeated visits would record new injuries, fruitlet loss, pruning and other disturbances; the final record would include fresh fruit bunch weight and harvest quality. Specific observations of feeding macaques should be time-stamped, while camera traps can distinguish different animal visitors and measure event frequency. Analysts must anticipate that a macaque may inspect a bunch without damaging it, while a rat or another consumer may injure tissue in the same area. Species confirmation is therefore integral to attributing economic loss and avoiding responses directed at the wrong animal.

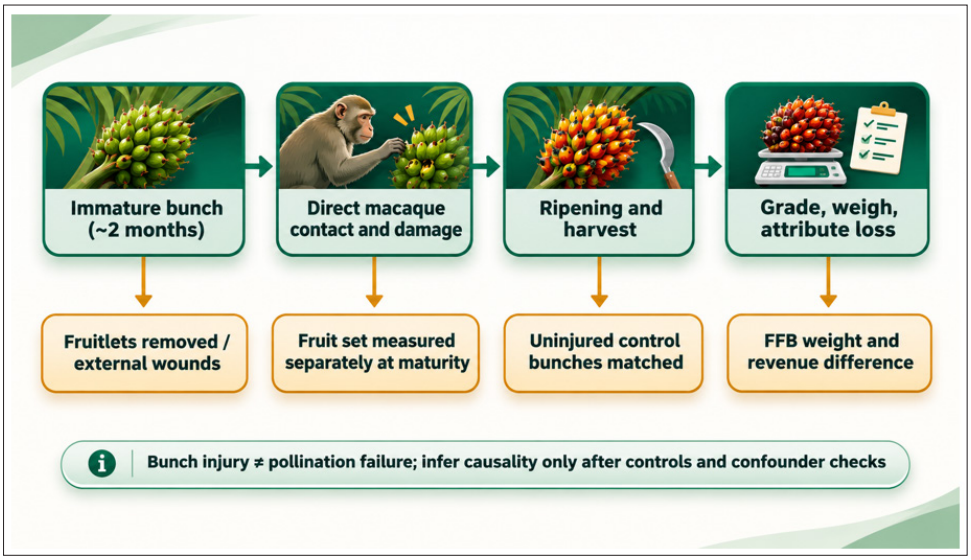


Figure 2: Bunch Development and Proposed Causal Attribution Pathway: Distinguish Fruitlet Removal from True Fruit-Set Failure.

Figure 2 sets out a longitudinal observation design. The sequence begins with a young bunch and an independent measure of its developmental stage, followed by repeated identification of animal contact and injury signatures. A contemporaneous and properly matched comparison group is maintained until the bunches are harvested and weighed. Importantly, the conceptual figure separates the field's colloquial use of fruit set from the biological definition of fertilization success. A scarred bunch may still have experienced normal initial fertilization; conversely, low set could arise without macaque contact. The recommended output is not a single uncontrolled percentage but an uncertainty interval around damage-related change in fresh fruit bunch weight, with confounders and failures to harvest recorded transparently.

Theme C: Economic Losses and Contextual Action Thresholds

Estimating economic injury requires defining both the damage that can be attributed to macaques and the part that an intervention could actually prevent. Let N represent the number of harvestable bunches at risk within a defined area and period; q the estimated probability of macaque-attributable bunch damage; Δw the adjusted mean harvested-weight loss conditional on verified injury; and p the net realized value per kilogram of fresh fruit bunches. An indicative expected baseline damage value is $N \times q \times \Delta w \times p$. This is only a starting estimate because not all observed damage is causal, not all injured bunches would otherwise reach harvest and the harvest value may vary. The analysis should incorporate uncertainty around each quantity, as well as the costs of surveillance, staff time, maintenance, installation and potential displacement of loss to adjacent holdings..

For a specified, permitted intervention j, let e_j denote the proportion of baseline damage that the intervention causally prevents; B_j its documented additional benefits; and C_j its full implementation and monitoring cost, including annualized investment and external effects. The following planning expressions make the comparison explicit. They do not constitute empirical estimates for the reported estate

$$E[AD_j] = N \times q \times \Delta w \times p \times e_j \quad (1)$$

$$E[NB_j] = E[AD_j] + B_j - C_j \quad (2)$$

Here, AD_j denotes avoided agricultural damage and NB_j denotes net benefits for intervention j. A feasible option is economically attractive when expected net benefits are positive, but it remains ineligible if it violates legal requirements, animal-welfare safeguards, worker safety, or protection of non-target species. Confidence intervals and low-, central-, and high-impact assumptions should be reported instead of an ostensibly universal troop-size threshold.

The decision rule is better expressed as a marginal comparison: choose a lawful management package when its expected avoided damage plus demonstrable ancillary benefits exceeds its full cost, subject to binding welfare, safety and conservation safeguards. The threshold is conditional on a specific intervention's effectiveness and opportunity cost; it is not a fixed number of macaques per colony. A large troop may cause little loss if palms are inaccessible or natural food is abundant, while a smaller habituated troop may create repeated damage in a narrow boundary block. Moreover, the cost of a theoretical perfect barrier is irrelevant if it cannot be installed or maintained safely. The appropriate comparison is among feasible alternatives, including a no-new-intervention baseline, and should account for annualized capital costs, harvest cycles and probabilities of successful avoidance rather than only damage observed before action The economic injury logic used for conventional crop pests, such as oil palm leaf-feeding insects, cannot simply be transferred as a biological threshold for a protected or unprotected vertebrate. The useful transferable insight is that preventable value must exceed justified cost. The important differences are that troop counts may be inaccurate, individuals move across estate boundaries, harm may be socially unacceptable, and intervention effects are uncertain over time. A financial scenario table should therefore vary exposed bunch count, verified loss per bunch, net realized fruit price, efficacy, labor requirements and the probability of damage displacement. The report should present central, low and high cases while explaining that no values from another species or crop were inserted as universal conversion coefficients. This approach offers a transparent management trigger without disguising a policy choice as a biological constant [50].

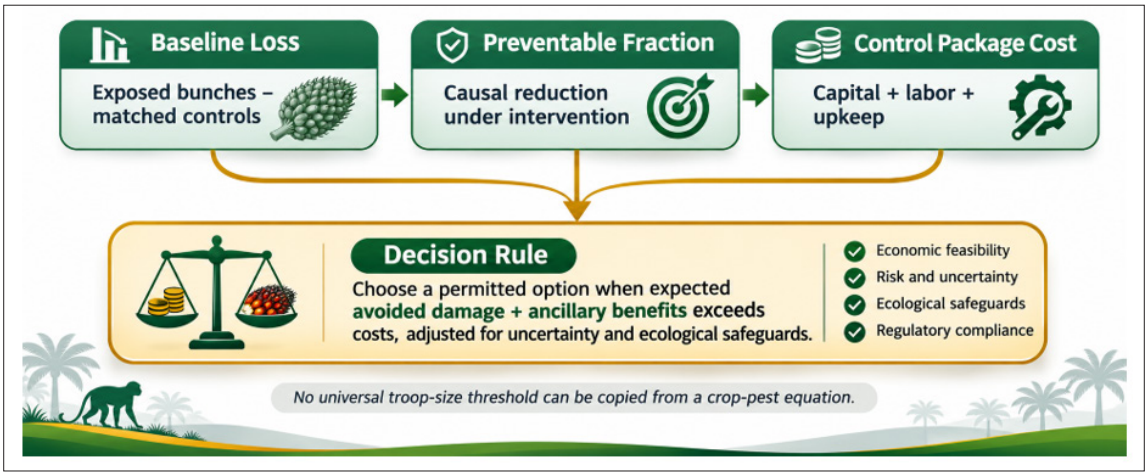


Figure 3: Contextual Economic Decision Architecture Compare Avoided Damage with the full Cost of Authorized Options

Figure 3 visualizes the sequence from baseline loss, to preventable loss, to total intervention cost and safeguards. The key quantity is not the gross value of every visibly damaged fruitlet, but the incremental loss avoided by a particular permitted action in comparison with its defensible counterfactual. A decision may legitimately favor habitat rehabilitation or waste control even when short-term bunch savings are uncertain, if such measures also reduce exposure, danger or recurring public complaints. Conversely, an intervention that marginally reduces local damage but endangers staff, hurts non-target species or creates unapproved capture obligations fails the safeguard test. This diagram is conceptual and explicitly does not supply a numeric monetary threshold or authorization to take animals.

Theme D: Comparative Interventions and Durable Prevention

Evidence for prevention is strongest when physical design, animal behavior and estate operations are evaluated together. Removal of human food subsidies may reduce incentives for repeated visits, but cannot eliminate feeding on oil palm fruitlets where plantation resources themselves are attractive. Active daytime patrols may respond quickly to observed entry points, yet their effect depends on staffing, timing, worker safety and whether macaques learn patrol schedules. Fences, netting or bunch guards must be designed for the ability of climbing primates to bypass obvious barriers. Studies from other crops suggest some forms of exclusion can work, but local trials are essential to avoid costs associated with ineffective designs. Any exclusion device should avoid entrapment and electrocution and should not impede emergency access, harvesting or non-target wildlife movement.

Acoustic, visual or chemical deterrents are attractive because they may be inexpensive initially, but their credibility depends on replicated field outcomes rather than anecdote. Intelligent primates may habituate to cues with no real consequence, and unpredictable noise can affect employees and nearby residents. Some methods also risk moving animals from one block to another rather than reducing total interaction. The estate should use a limited, welfare-screened pilot of permitted options and alternate treatment and comparison blocks where practical, with exposure-adjusted incident rates as an outcome. Deterrence effort should be recorded as rigorously as damage, including operator hours and maintenance requirements. The literature does not establish that a particular commercially promoted device solves long-tailed macaque damage to young oil palm bunches, and claims of universal success should be treated skeptically.

Habitat management requires a finer strategy than clearing all cover at plantation margins. On the one hand, accessible shelter or elevated connecting vegetation may facilitate visits to vulnerable palms. On the other hand, forest fragments, riparian buffers and high-conservation-value patches sustain biodiversity and may reduce broader ecological instability. A practical plan should identify where narrow, locally reversible changes to human food access or vulnerable bunch exposure can prevent contact while protecting designated conservation areas. Forest restoration outside or along estate boundaries may be valuable, but it should be coordinated with landholders and conservation staff and must not be presented as a guaranteed rapid deterrent. Research on integrated biodiversity and economic performance in oil palm underscores the possibility of improving some management outcomes without treating every ecological feature as a sacrifice to output.

Direct removal, translocation, poisoning and shooting should not form the default technical pathway. Population removal can generate welfare concerns, unknown replacement dynamics, danger to people, and significant legal or reputational exposure. Evidence about predator removal is not directly transferable to macaques, but it demonstrates why a short-lived reduction in local animals cannot be equated with robust long-term conflict mitigation. Similarly, relocation may shift risks to receiving habitats and communities and requires professional ecological, veterinary and regulatory assessment. The review does not present operational instructions for harmful control because no plantation-specific authorization or technical justification has been established. Any consideration of capture or other invasive measures must be referred to competent authorities under the current regulatory framework, after transparent documentation of nonlethal alternatives and a formal evaluation of safety and animal welfare.

Theme E: Governance, Law, Social License and Monitoring

The legal distinction between protected-species status and the conservation assessment is critical. The Indonesian schedule amended by Ministerial Regulation P.106/2018 does not generally list Macaca fascicularis as a nationally protected species. In contrast, the IUCN's 2022 global assessment categorized it as Endangered, a conservation-risk category that is not itself a domestic permitting instrument. Ministerial Regulation No. 17 of 2024 addresses wildlife rescue and revokes earlier conflict-management provisions only insofar as those provisions govern wildlife rescue. The precise rules applicable to a particular field

measure, including capture, possession, transport, release and wildlife rescue, require current confirmation from the responsible provincial or national authorities. An economic threshold should therefore be treated as management evidence for requesting advice, not as a legal authorization. The recommended sequence is written consultation, documented assessment and implementation strictly within the scope communicated by BKSDA Reputational exposure emerges not only from the type of control but from the decision process. A plantation with detailed records, clear welfare safeguards, proper institutional consultation, employee training and a transparent community grievance channel is better placed to demonstrate responsible action. Conversely, incidents involving unapproved toxins, informal trapping or unsafe shooting may undermine trust even if managers believe losses are high. Social-ecological research emphasizes that conflict can persist because people disagree about responsibility and fairness, not simply because animals consume crops. Workers, neighboring smallholders and villages may experience different patterns of risk, and the estate should not define an acceptable solution solely by damage within its own cadastral boundaries. Consultation should identify displaced harms, incident-reporting routes, public safety concerns and suitable monitoring arrangements before a contentious policy is implemented [49].

The operational data system should be relatively simple but defensible. Each entry would include date, time, geolocation or block code, trained observer, effort, troop identification confidence, number of individuals visible, behavior, bunch development stage, evidence of direct feeding, photographs, staff response and any injury or community complaint. Duplicated sightings of the same troop should not be added as distinct animals. Camera traps, fixed observation points and photo-identification can improve consistency; independent audits should compare field reports with spatial overlap and harvest records. Recent Indonesian oil palm studies show that staff-collected observations can support occupancy inference when properly handled, while associated citizen-science programs point to the importance of incentives and management backing. Data protection and staff reporting ethics should be built in from the beginning.

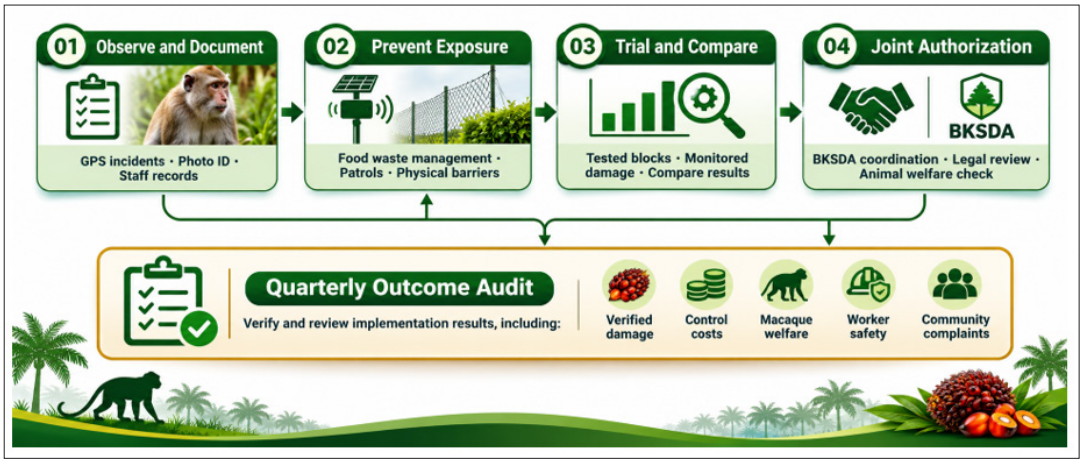


Figure 4: Nonlethal-First Intervention Ladder with Documentation, Evaluation and Institutional Safeguards

Figure 4 translates the evidence into an operational ladder. The first steps establish a factual and legally informed baseline, identify avoidable attractants and protect exposed bunches through targeted, welfare-safe methods. The next step is comparison: test practical permitted interventions under field conditions, explicitly measuring costs, damage avoidance and non-target effects. Coordination with BKSDA is not postponed until an emergency or a population-control decision; it begins early and continues whenever a measure could affect animal movement, welfare or regulatory compliance. Quarterly reassessment prevents an initially effective action from becoming a permanent unexamined practice. The figure intentionally excludes poisoning and shooting from the standard intervention sequence because neither ecological necessity nor legal authorization has been demonstrated.

Discussion and Analysis

Interpreting the Fire-to-Damage Hypothesis

The first research question concerns whether post-fire movement explains reported plantation encounters. The most defensible answer is that disturbance-related redistribution is plausible, but neither necessary nor sufficient as an explanation. Fire-induced structural degradation can reduce habitat resources, yet the direction of macaque response depends on the location and severity of damage, surviving vegetation, seasonality and availability of alternative foods. Repeated entry after fire could be an immediate displacement response, prolonged use of attractive crop resources or enhanced detection near roads and harvesting activity. The strength of this review is to specify those competing hypotheses rather than privilege the most vivid narrative. Establishing a causal effect would require longitudinal observations before and after known burn events and ideally comparisons with unburned but otherwise similar estate edges. Where historical baseline data are missing, triangulation with remotely sensed fire history, habitat field surveys and staff records can generate cautious but useful inference.

The second major issue is whether local conspicuousness justifies describing the species as becoming more abundant. A global Endangered assessment and a reported local nuisance can coexist because conservation status reflects broad-scale risk and population change, not the maximum number visible in one food-rich block. Peer-reviewed interpretations of the species' global risk have been disputed, which further highlights uncertainties in available population data. For transparency, Hilborn and Smith reported financial support from a trade association representing biomedical research organizations that use long-tailed macaques; this disclosed interest is material when weighing the debate, although it does not replace appraisal of the data and arguments. Estates should avoid either extreme: treating every troupe as evidence that the species is nationally safe or assuming all local groups are demographically collapsing. Periodic group counts, age-sex composition estimates, reliable identification of repeated

sightings and records of troop ranging are more informative. A response to verifiable crop damage should not depend on first resolving all global conservation controversies, but it must not claim that the controversy grants operational freedom from wildlife safeguards.

From Disputed Fruit-Set Estimates to Credible Estate Accounting

The third research question asks how losses should be quantified. The proposed injury and economic measures can be integrated through a hierarchical longitudinal field design. A bunch is first categorized by developmental age and condition; it is then monitored for independently verified macaque contact and damage progression; and finally, it is harvested and weighed. Observations are linked to palm, block, palm age, environmental conditions and sampling effort. During analysis, bunches lost to other causes should not simply disappear from the sample, because selective attrition can bias apparent loss rates. Paired or matched comparison bunches help control for background variation. A before–after treatment comparison can be strengthened with untreated comparison blocks, although the independence assumption may fail if the same troops range across both treatments. Geographic separation and monitoring of cross-boundary movement are therefore relevant to experimental design The preliminary range of 0.5–1.0 kg for a bunch that would otherwise exceed 10 kg is large enough to justify measurement, but it cannot be converted reliably into estate-scale loss until its prevalence and confidence are known. If only a small fraction of harvestable bunches are affected, the average loss per hectare may differ dramatically from the loss among damaged bunches. Conversely, repeated attacks on a small set of mature palms may be financially significant within a high-risk boundary without implying a large estate-wide loss. The proposed analysis would estimate the probability of injury, conditional weight reduction, and total vulnerable production, then compare these values with labor, equipment and monitoring costs. Because reduced fruitlet counts, poor fertilization and physical wounds are not identical mechanisms, the reported 10–15% fruit-set figure should remain an unverified local estimate until development-stage measurements support its use The fourth research question concerns action thresholds. For a highly mobile vertebrate, the defensible trigger is a documented case for a particular permitted intervention, not a universal troop-size threshold borrowed from leaf-eating insect management. The economic calculation should value anticipated reduction in attributable loss, adjust for the probability of compliance and equipment performance, and include implementation, maintenance and monitoring costs. Sensitivity analysis is essential because a small change in observed attack prevalence may have a large effect on expected savings. Separate indicators should capture welfare incidents, labor injuries, disruption of neighboring community gardens and damage displacement. This multidimensional interpretation is consistent with research arguing for integrated economic and ecological management of oil palm and for social legitimacy in wildlife decision-making. Under uncertainty, reversible actions with low side-effect risk often provide a rational first option even without a precise numerical damage threshold.

Effectiveness of Nonlethal Options and Adaptive Portfolios

The fifth research question asks which interventions are most credible. The available literature supports a portfolio rather than a miracle treatment. Waste and provisioning controls remove avoidable food subsidies; targeted physical exclusion may protect selected highly vulnerable palms; patrol scheduling can exploit known visiting times; and habitat stewardship can reduce broader pressures without treating every forest strip as an obstacle. However, effectiveness is species-, site- and design-specific. Findings for rhesus macaques or African primates cannot be assumed to predict long-tailed macaque behavior in an oil palm canopy. This review therefore recommends pilot comparisons that report not only incident reduction but also animal avoidance, worker labor, non-target effects, maintenance and adaptation over time. A locally modest but sustained reduction may be more valuable than a dramatic, short-lived response that shifts damage elsewhere Experimental interpretation also depends on the treatment's scale. A single palm guard may succeed while neighboring palms receive more attacks; a noisy deterrent may repel one troop and draw complaints from residents; a fencing project may be circumvented where branches connect across it. Trial outcomes must be reported per exposed bunch and per unit of observation effort, not only as a raw reduction in complaints. Negative findings are useful and should be documented rather than hidden. The program should specify stop rules for animal entanglement, worker injury, crop damage caused by the device itself or a significant increase in off-estate incidents. This approach applies a conservative reading of intervention studies: good causal evidence requires appropriate comparison and transparent documentation of implementation, and no management category remains effective simply because it worked in a different crop or country.

Landscape strategy must balance potential conflicts with the benefits of conservation-compatible land management. Studies of wildlife in oil palm landscapes show ecological value in retained fragments and understory configurations, while research on agricultural productivity demonstrates opportunities to improve management without automatically reducing biodiversity. At the same time, habitat may have multiple ecological effects, including influencing how macaques reach a crop. A collaborative estate plan should identify existing high-conservation-value areas, assess fire-affected fringe land and restore vegetation in ways consistent with wildlife and community objectives. Monitoring should extend beyond the fence line because ecological outcomes depend on adjoining properties and habitat continuity. This is a reason for joint landscape-level planning, not a basis for relocating animals into unmanaged forest or burning new vegetation to force them away [47].

Legal Institutions, Implementation and Governance

The sixth research question asks how conservation and legal legitimacy can be integrated. The operational sequence should start with formally documented communication with the local BKSDA office, accompanied by georeferenced incidents, preliminary counts with clear uncertainty, images of alleged damage, estimated production exposure and a record of measures already attempted. A written legal review should establish which measures are permitted and whether additional approvals or professional specialists are required. The estate should designate accountable representatives from agronomy, sustainability, occupational safety and community relations to avoid contradictory instructions. Nothing in this review should be interpreted as a permit to capture, move or kill macaques. Ministerial Regulation No. 17/2024 and any newer applicable instruments should be confirmed from official sources before any intervention involving wildlife rescue or handling.

Responsibility cannot rest solely on a plantation's conservation officer. Agronomy provides bunch-level measurements; operations provides staff training and practical feasibility information; sustainability identifies high-conservation-value and grievance obligations; and legal staff review authorizations. BKSDA provides governmental coordination on wildlife-related measures,

while nearby communities supply information about changes beyond estate boundaries and may bear displaced costs. An independent ecological reviewer could periodically audit species identification, troop estimates and intervention outcomes. This arrangement reduces the risk that financial calculations are used to rationalize a preselected control technique. Social research shows that stakeholder perceptions and institutional trust are critical to coexistence, especially where perceptions of harm and ecological facts do not align. Documented consultation is therefore a substantive part of the method, not merely a communications response after controversy[52].

A ninety-day program is a practical first milestone, although some questions require longer monitoring. The first two weeks should focus on legal consultation, safety rules, fixed observation methods and baseline bunch sampling. The next two weeks should map troop activity and improve evidence about which animals actually contact bunches. The second month can introduce carefully selected nonlethal prevention pilots with matched untreated observations. The final month should audit costs, harvested bunches that have matured, observer consistency, staff exposure and animal welfare events, recognizing that immature bunches identified at baseline may not yet have reached harvest. A rigorous damage-to-harvest estimate will therefore extend over the relevant maturation period. The ninety-day period is for commissioning, testing and institutional learning, not a guarantee of resolving every production impact.



Figure 5: Ninety-day Initial Implementation and Responsibilities Full Bunch-to-Harvest Outcome Monitoring May Extend Beyond Day 90.

Figure 5 expresses the proposed division of work across operations, ecological assessment and institutions. It avoids a false separation between scientific monitoring and managerial decision-making: the same incident forms can inform a welfare audit, an economic estimate and a formal BKSDA consultation. A pilot should be reviewed when either loss indicators or safety indicators deteriorate, and a favorable short-term outcome should not be assumed durable without repeated measurement. In particular, the figure distinguishes the ninety-day launch from the longer time horizon needed to follow tagged immature bunches through harvest and assess multi-season troop movement. The most credible program is one that learns from the estate's heterogeneity rather than translating a generic recommendation into identical measures across every block.

Synthesis, Limitations and a Future Research Agenda

Taken together, the literature answers the research questions with varying certainty. Evidence is relatively strong that land-use modification and food availability shape macaque encounters, that some nonlethal barriers and protective techniques can reduce crop feeding under specified conditions, and that unmeasured observation effort can distort wildlife counts. The evidence is weaker on a direct Riau fire-to-macaque-population causal chain, on a validated conversion from immature fruitlet removal to oil palm fresh fruit bunch weight, and on the long-term efficacy of individual interventions in local oil palm settings. The central scientific limitation is not merely a small number of papers, but the mismatch between the level of available evidence and the specificity of the managerial question. The review therefore emphasizes falsifiable field predictions and transparent monitoring variables rather than presenting strong practical confidence unsupported by species-specific controlled data [48].

Future work should prioritize paired estate-edge studies with documented fire history, consistent troop recognition, and bunch-to-harvest tracking. Spatial models could combine burn severity, distance to forest remnants, road density, natural-food resources and management practices to predict where encounters occur. Behavioral sampling should document troop composition and encounter type, while injury research should distinguish confirmed feeding from inferred damage. Economic analysis should incorporate bunch weights and prices measured at the same estate and season, avoiding comparisons between incomparable management blocks. A social component should interview workers, neighboring smallholders and BKSDA staff about perceived risks, trust and acceptable options. Where ethically and legally possible, controlled nonlethal pilots should be replicated across seasons and report both efficacy and non-target outcomes. These studies would allow the conceptual framework to become a testable interdisciplinary model.

There are also important limitations to the reference base and the review method. The manuscript draws on peer-reviewed studies across species and regions, including several whose primary focus is not long-tailed macaques or oil palm. Comparative evidence can clarify mechanisms without supporting direct parameter transfer. The qualitative design does not quantify the prevalence of positive study findings or estimate a pooled effect size. Publication and language biases may remain because the source selection was interpretive rather than exhaustive, and rapidly emerging 2026 papers may not yet have undergone extensive replication. Most importantly, the estate reports embedded in the prompt were not accompanied by primary sample sheets or verifiable harvest records, so the claimed loss coefficients remain hypotheses. The

paper should not be presented as original empirical proof of crop losses, population growth or prevention success.

Conclusion and Recommendations

Long-tailed macaque interactions in Indonesian oil palm plantations should be understood as a linked production, landscape ecology and institutional governance issue rather than automatically as a population-control emergency. Disturbed habitat and accessible plantation resources may intensify encounters, but observations following fires cannot on their own determine whether the cause was displacement, population growth or greater detection. The reported extraction of immature fruitlets is a serious candidate source of damage that deserves bunch-level measurement, yet apparent surface loss is not synonymous with failed fertilization, and the cited 10–15% fruit-set and 0.5–1.0 kg bunch-loss values cannot be generalized without controlled validation. A sound response starts with accurate troop and incident monitoring, confirmed species attribution and realistic estimates of preventable economic loss. These elements make it possible to distinguish visually dramatic damage from sufficiently large and avoidable production losses. The recommended operational pathway is nonlethal-first and adaptive: reduce anthropogenic food subsidies, secure vulnerable bunches through welfare-screened approaches, trial targeted physical and behavioral measures, protect high-conservation-value habitat, and evaluate outcomes with matched controls and transparent costs. Avoided economic injury, welfare and safety indicators, and potential displacement to neighboring land should be considered together. A census and an agricultural economic threshold can inform decisions, but cannot automatically authorize shooting, poisoning, capture or translocation. Indonesia's national protected-species classification should not be confused with the IUCN global Endangered assessment, and current regulatory procedures should be checked in writing with BKSDA before any action involving animal handling or irreversible impacts. Coordinated conservation, agronomy and community governance provides a more durable basis for protection than an isolated deterrence tactic For research and management, the priority is a defensible monitoring program rather than a predetermined numerical troop limit. A ninety-day commissioning plan should establish consistent observations, site-specific fire and habitat mapping, tagged bunch cohorts, nonlethal prevention pilots, accountability assignments and early BKSDA consultation. Complete evaluation of immature bunch outcomes must continue to harvest and preferably across multiple seasons. Publication-quality evidence should report exposure, comparison groups, effect uncertainty, implementation costs and animal-welfare outcomes together. The broader contribution is a decision architecture that allows plantations to address genuine fruit losses while recognizing the ecological roles and conservation risks of macaques and the legitimacy of affected communities. This approach converts a potentially polarizing pest narrative into an empirically testable, legally careful and socially accountable coexistence program.

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