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From Forecast to Field: An Integrated Climate-Risk Mitigation Framework for Indonesia's Oil Palm Plantations under the 2026 El Niño and Emerging Positive Indian Ocean Dipole

Loso Judijanto

IPOSS Jakarta, Indonesia

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Abstract

Indonesia's oil palm sector entered the second half of 2026 under an active and strengthening El Niño, the anticipated emergence of a positive Indian Ocean Dipole, below-normal rainfall probabilities, above-normal temperatures, and increasing drought and fire danger. This article develops a qualitative integrative literature review to identify the principal risk pathways and the measures required to protect plantation productivity, workers, surrounding communities, and peatland landscapes. Evidence published predominantly between 2020 and 2026 was purposively drawn from climatology, crop physiology, agronomy, hydrology, fire science, occupational health, smallholder studies, and climate-governance research. The synthesis finds that the 2026 threat is best understood as a compound and cascading risk system rather than a single rainfall shock. Water deficit and elevated atmospheric demand can reduce photosynthesis, disrupt reproductive development, weaken nutrient uptake, and create yield losses that emerge months or years after the initial stress. Dry fuels, declining peat groundwater levels, human ignition, worker heat exposure, mill-water shortages, and smallholder resource constraints can magnify the consequences. The article proposes a multi-scale mitigation portfolio centred on climate intelligence, trigger-based operating procedures, soil- and water-conservation measures, adaptive nutrient management, peat hydrological control, fire prevention, occupational heat protection, supply-chain continuity, and targeted smallholder support. Its practical contribution is a phased action framework linking forecast lead time and locally observed indicators to no-regret, threshold-triggered, recovery, and longer-term resilience measures. Effective implementation requires coordination from the palm and block levels to mills, catchments, peat hydrological units, financial institutions, and public policy.

*__Corresponding author__: Loso Judijanto, IPOSS Jakarta, Indonesia.

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Introduction

Background and the 2026 Climate Context

Oil palm is embedded in Indonesia's rural economy, export structure, food system, oleochemical industries, and renewable-fuel strategy. Its high biological productivity per unit of land gives it an important role in global vegetable-oil supply, but the crop's long economic life also creates exposure to climatic shocks that cannot be corrected within a single planting season. A plantation established today will experience several phases of climate variability before replanting, while the income of workers, independent growers, transporters, and mills depends on the continuity of fresh fruit bunch production. Recent research therefore frames the sector's central challenge as improving yields and resilience on existing land while reducing pressure for further expansion, protecting biodiversity, and addressing persistent smallholder yield gaps [1-3].The climatic conditions observed and forecast in mid-2026 make this challenge immediate. Indonesia's meteorological authorities reported an active and strengthening El Niño and projected a drier and, in many locations, longer dry season, with the national peak concentrated broadly between July and September. The oil-palm-specific climate bulletin and the Executive Climate Outlook highlighted below-normal rainfall, above-normal air temperature, a higher probability of extended rainless periods, increasing water deficit, and elevated fire danger during August–October. International monitoring likewise indicated a rapidly strengthening El Niño. At the start of the assessment period, however, the Indian Ocean Dipole had not yet become firmly positive; it was better described as an emerging or anticipated positive IOD for the following months. This distinction matters because seasonal outlooks are probabilistic, time-sensitive, and spatially heterogeneous rather than deterministic predictions for every estate [4-8].

For plantation management, the principal danger is not an isolated lack of rain. El Niño, an emerging positive IOD, reduced rainy-day frequency, above-normal temperature, elevated vapour pressure deficit, soil-water depletion, dry vegetation, peat desiccation, and human ignition can reinforce one another. These interactions can produce a sequence of impacts: physiological stress in palms, declining nutrient-use efficiency, reproductive disruption, higher fire probability, hazardous heat exposure for workers, insufficient raw water for mills, smoke-related transport interruptions, and financial stress among growers. The system is therefore exposed to compound hazards, cascading consequences, and delayed biological effects. Studies of oil palm have repeatedly shown that the yield response to weather is shaped by interactions among water balance, endogenous production cycles, stand age, genotype, and the timing of reproductive development [9-11].

Figure 1 illustrates why the 2026 climate threat should be interpreted as an interacting chain of drivers, local hazards, hydrological stresses, crop responses, and operational consequences rather than as a single rainfall anomaly.

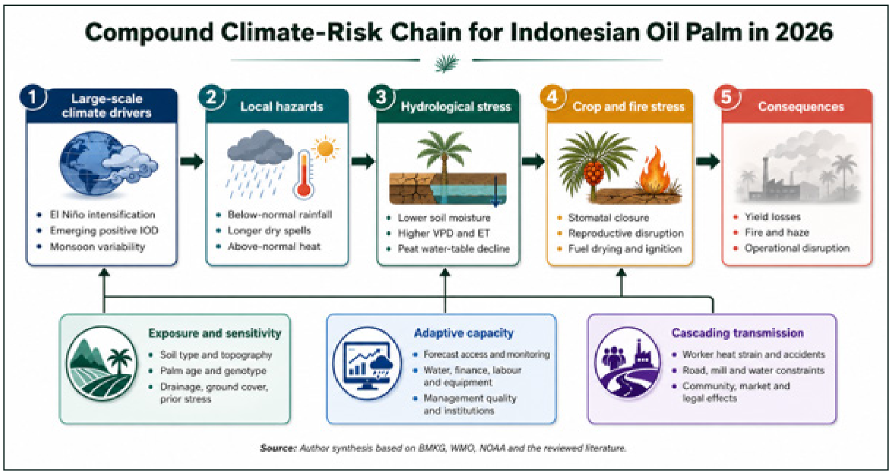

Figure 1: Compound climate-risk chain for Indonesian oil palm plantations in 2026.

Source: Author's synthesis based on [4-10, 12].

The upper part of Figure 1 separates large-scale climate drivers from locally measurable hazards. This separation prevents managers from using an ENSO label as a substitute for field observation. The middle of the figure shows the hydrological and biological transmission mechanisms through which reduced rainfall and higher atmospheric demand become soil-water deficit, peat groundwater decline, crop stress, and fuel drying. The lower part demonstrates that the final severity of loss depends on exposure and adaptive capacity. Two estates receiving similar rainfall may experience very different outcomes because their soil cover, reservoirs, drainage systems, peat hydrology, fire preparedness, labour protection, and decision authority differ substantially. Climate risk is thus produced jointly by weather and the organization's ability to anticipate, absorb, and adapt to it [12-14].

Urgency, Research Questions, and Objectives

The urgency of preventive action is reinforced by the time structure of oil palm production. Water stress can affect stomatal conductance and photosynthesis immediately, yet visible changes in bunch production may emerge only after reproductive processes have been disturbed. A stable harvest during the early months of drought does not prove that the crop has escaped damage. Climate stress can alter inflorescence sex determination, abortion, anthesis, fruit set, bunch number, and bunch weight at different stages, transmitting the effects of the 2026 dry season into 2027 or 2028. Multi-season yield records and physiological experiments therefore support a longer monitoring horizon than the conventional emergency period used for fire response [11,15,16].

This article addresses four questions. First, which climate signals and compound hazard patterns are most relevant to Indonesian oil palm during the second half of 2026? Second, through which biophysical, agronomic, environmental, occupational, operational, and financial pathways can those conditions affect plantation performance? Third, which critical measures should be implemented at palm, block, estate, smallholder, mill, landscape, and policy levels? Fourth, how can probabilistic climate information be converted into trigger-based decisions without encouraging overreaction, false precision, or maladaptation? The objective is not to produce another seasonal forecast, but to translate a changing forecast into a coherent risk-management architecture grounded in recent interdisciplinary literature.

The article makes three contributions. Conceptually, it connects climate hazard, crop physiology, fire and peat hydrology, worker exposure, smallholder vulnerability, and institutional capacity within one compound-risk model. Analytically, it distinguishes immediate, delayed, and cascading consequences, thereby preventing management from focusing only on visible stress. Practically, it proposes a phased portfolio of no-regret and threshold-triggered actions that can be differentiated by soil type, stand age, plantation scale, location, and available resources. Although the user's term 'mitigation' is retained, most measures discussed here are technically climate adaptation and risk reduction; a subset—especially fire prevention, peat conservation, and avoided land expansion—also contributes directly to greenhouse-gas mitigation [1,17,18].

Literature Review

Climate Risk as a Dynamic and Multi-Dimensional Construct

Climate risk is commonly understood as the interaction of hazard, exposure, vulnerability, and adaptive capacity. In an oil palm system, hazards include rainfall deficits, long dry spells, heat, high atmospheric water demand, fire weather, and intense rainfall after drought. Exposure includes palms, nurseries, workers, roads, mills, reservoirs, peat soils, riparian systems, and nearby settlements. Vulnerability refers to the sensitivity of these elements and the limitations that prevent them from coping effectively. Adaptive capacity includes knowledge, finance, infrastructure, institutional coordination, access to inputs, and operational flexibility. This formulation is useful because it makes clear that a seasonal anomaly does not translate automatically into a fixed level of loss. Risk can be reduced even when the hazard cannot be controlled, provided that exposure and vulnerability are managed before critical thresholds are crossed [2,19,20].

Three extensions are especially important. Compound risk arises when hazards occur together or in close sequence, such as heat combined with soil-water deficit. Cascading risk arises when an initial disruption propagates through connected systems—for example, drought lowers peat groundwater levels, enabling fire; smoke then impairs worker health, road safety, harvesting, and mill utilization. Accumulated risk develops when repeated dry periods reduce recovery capacity or interact with prior nutrient deficiency and disease. These dynamics are often nonlinear: a small additional decline in fuel moisture or groundwater level may cause a disproportionate rise in fire probability, while a modest temperature increase can sharply reduce safe work capacity once physiological thresholds are exceeded [12,21-23].

Climatic Drivers and the Importance of Local Translation

ENSO influences rainfall and convection across the Maritime Continent, but the local outcome depends on event timing, strength, monsoon circulation, sea-surface temperatures, topography, and intraseasonal variability. A strong El Niño increases the probability of rainfall deficits in many Indonesian regions, yet it does not impose identical rainfall totals on all plantation districts. The Indian Ocean Dipole can amplify or offset these patterns; a positive IOD is commonly associated with relatively cool waters near Indonesia and reduced moisture transport toward parts of the archipelago. When El Niño and a positive IOD coincide, drying can be more severe, but the relationship remains probabilistic and must be checked against updated observations. The 2026 management response should therefore use national and global outlooks to establish preparedness while relying on local rainfall, soil-moisture, and hydrological data to determine action [4,6-8].

Plantation analysis should also distinguish rainfall amount from rainfall distribution. Monthly totals can conceal a damaging sequence in which most rain falls during a few intense events separated by long dry intervals. Relevant indicators include consecutive dry days, rainy-day frequency, effective rainfall, infiltration, root-zone water content, groundwater level, and the timing of rainfall relative to palm development and fertilizer application. Temperature adds a separate pressure by increasing evaporative demand and vapour pressure deficit. Consequently, a block can experience functional drought even when the seasonal rainfall anomaly appears only moderate. Empirical and modelling studies increasingly combine weather, soil moisture, and management variables because rainfall alone is an incomplete predictor of yield [9,24,25].

Oil Palm Ecophysiology, Drought, and Delayed Yield Effects

Oil palm responds to declining soil moisture through stomatal regulation that reduces water loss but also restricts carbon assimilation. Sustained deficits can reduce leaf expansion, biomass accumulation, root activity, and recovery after stress. Experimental studies have identified changes in osmotic regulation, carbohydrate metabolism, amino-acid pathways, oxidative balance, gene expression, and root and leaf morphology. Multi-omics research confirms that drought is not a single physiological event but a coordinated reprogramming of pathways related to energy, carbon, protective compounds, and stress signalling [26-28].

Drought response also varies by genotype, plant age, soil condition, and previous exposure. Nursery and young field palms have shallower and less extensive root systems, while mature palms possess greater root exploration but a larger transpiring canopy and a substantial reproductive load. Studies comparing cultivars and genotypes report meaningful variation in growth, photosynthetic response, osmotic adjustment, and recovery, supporting the use of drought-tolerance traits in breeding and replanting decisions. This variation does not eliminate the need for management: planting material and agronomy are complementary rather than substitutable sources of resilience [16,29-35].

The long development of oil palm inflorescences creates a lag between stress and harvest loss. Weather may influence sex differentiation, inflorescence abortion, anthesis, pollination, fruit set, and bunch growth at different moments before harvest. Yield variation is also affected by endogenous cycles, so a decline following drought should not be attributed to one mechanism without examining block history and developmental timing. Multi-season records are therefore more informative than a simple comparison of annual rainfall and annual yield. Research using long time series shows that water deficit and ageing can interact, and that the climatic signal may appear in bunch number and average bunch weight at different lags [9,11,15].

Figure 2 maps the principal routes through which climatic stress beginning in August 2026 can generate immediate physiological changes, reproductive disruption, and delayed production outcomes extending into 2027–2028.

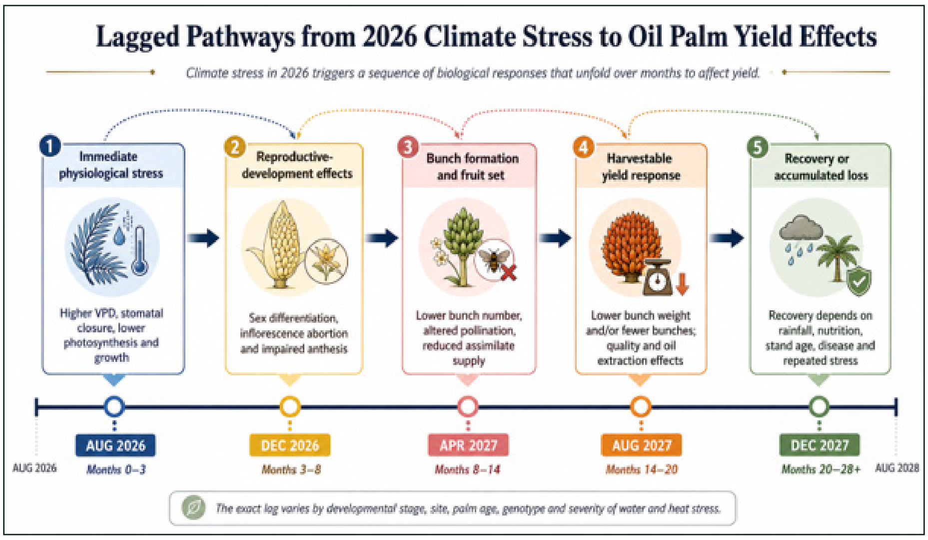

Figure 2: Lagged pathways from 2026 climate stress to oil palm yield and recovery outcomes.
Source: Author's synthesis based on, [9-11,15,16].

Figure 2 separates the emergency-management horizon from the biological-impact horizon. During the first weeks, the most visible effects may be soil-moisture loss, stomatal closure, heat stress, and increased fire danger. Reproductive processes affected during the same period may not be reflected in fresh fruit bunch output until much later. After rainfall returns, management must therefore evaluate recovery rather than simply declare the event closed. Monitoring should include vegetative symptoms, flower and bunch development, sex ratio where feasible, abortion, bunch number, average bunch weight, harvest interval, and block-level yield anomalies. The lag structure also has financial implications: estates and smallholders may face lower revenue after emergency expenditure has already depleted cash reserves [36-39].

Agronomic, Operational, and Systemic Risk Pathways

Dry soil reduces nutrient mobility and can constrain root uptake, so fertilizer effectiveness depends on soil moisture, fertilizer characteristics, placement, and the probability of follow-up rain. The appropriate response is not a blanket cancellation of fertilization. Instead, managers should prioritize blocks, split applications, avoid high-risk timing immediately before an extended dry period, and resume or adjust doses when rainfall and soil conditions support uptake. Smallholder studies show that nutrient supply is often insufficient, imbalanced, or poorly timed even under normal conditions; severe drought can magnify these inefficiencies and make indiscriminate cost-cutting counterproductive [40-43].

Soil cover and organic residues are important because they influence evaporation, infiltration, erosion, and soil biological activity. Frond stacking, leguminous cover crops, empty fruit bunch mulch, and protection of riparian vegetation can reduce bare-soil exposure and improve water retention, although application rates and environmental safeguards must be site-specific. Organic amendments cannot substitute for adequate water management, but they can increase the time available before a critical deficit develops. Conversely, excessive clearing for fire prevention can expose soil, reduce infiltration, and create maladaptation. The objective is strategic fuel management combined with retained living cover, not indiscriminate removal of vegetation [1,44-46].

Climate stress also intersects with plant health. Drought does not directly 'cause' basal stem rot, but physiological stress, soil conditions, stand age, and pathogen pressure may interact to influence disease expression and recovery. Climate-suitability studies for Ganoderma indicate that temperature and moisture regimes should be considered in surveillance and long-term risk mapping. During 2026, estates with known disease incidence should increase observation of symptomatic palms, crown condition, mortality, and sanitation compliance rather than treating drought and disease as unrelated problems [44,47-49].

Operational pathways are equally important. Field heat can reduce work capacity, increase fatigue, impair judgement, and raise injury risk among harvesters, sprayers, transport workers, and fire crews. Moving strenuous tasks to cooler hours can reduce exposure, but research indicates that this strategy becomes less effective as even the coolest hours warm. Hydration, shaded rest, acclimatization, work–rest cycles, heat-index monitoring, and authority to suspend unsafe work are therefore essential components of climate adaptation, not optional welfare measures. Worker protection also supports harvest continuity and emergency response capacity [14,21,22].

Mills and logistics create additional points of failure. Processing requires adequate raw water, energy, access roads, labour, and timely delivery of fruit. Drought may reduce water quantity or deteriorate water quality, while smoke can disrupt transport and expose workers. A later transition to intense rainfall can damage roads, mobilize ash and sediment, and create a second operational shock. Climate-risk management must therefore cover the estate–mill system and surrounding catchment rather than focusing only on palm physiology. Predictive tools combining weather, soil moisture, remote sensing, and yield records can support planning, but their value depends on data quality and managerial response, not merely model accuracy [25,50].

Fire, Peat Hydrology, and Landscape Interdependence

Fire risk in oil palm landscapes is generated by the interaction of weather, fuel, hydrology, ignition, and institutions. Dry vegetation and accumulated residues increase flammability, but many large events still require human ignition and weak control. On peat, drainage lowers the groundwater table, accelerates oxidation and subsidence, and can allow fire to penetrate below the surface, where suppression becomes difficult, and re-ignition is common. Weather-only fire indices are consequently insufficient in peat landscapes. Forecast skill improves when soil moisture and groundwater dynamics are incorporated, and local patrols should be guided by both meteorological and hydrological indicators [12,51-53].

The consequences extend well beyond the plantation boundary. Peat and vegetation fires generate greenhouse gas emissions, fine-particle pollution, ecological damage, transport disruption, and public health costs. Economic analyses show that prevention and restoration can produce large avoided losses when health, emissions, and repeated fire damage are considered. Conservation and rewetting can slow the escalation of emissions, but their effectiveness depends on hydrological design, maintenance, landholder cooperation, and climatic conditions. Peat management must therefore operate at the hydrological-unit and community levels, not simply within a company boundary [17,18,54].

Independent smallholders face a distinctive risk profile. They often have limited access to local climate data, soil-moisture instruments, reservoirs, pumps, certified planting material, extension services, credit, insurance, and firefighting equipment. A recommendation that is technically sound for a large estate may be financially or organizationally impossible for an individual grower. Research on resilience and replanting shows that access to finance, institutions, markets, and knowledge strongly shapes the capacity to adopt better practices. Equity is therefore a functional condition of landscape resilience: unassisted smallholders can become involuntary weak points in fire prevention and supply continuity even when nearby companies are well prepared [33-35,40,55,56].

Theoretical Foundations for an Integrated Response

Four theoretical perspectives guide the synthesis. Socio-ecological resilience emphasizes the capacities to anticipate, absorb, adapt, recover, and learn. Anticipatory action treats forecast lead time as a resource that can reduce loss before a hazard peaks. Trigger-based management connects action to observable thresholds rather than to vague concern or fixed calendar dates. Climate-smart intensification seeks to raise productivity and resilience on existing land while reducing expansion pressure and environmental damage. Together, these perspectives support a portfolio approach in which soil cover, water systems, fire readiness, labour protection, and institutional coordination reinforce one another

[1,44,57,58].

The portfolio must also avoid maladaptation. Irrigation can protect palms but may intensify competition for water needed by workers, communities, rivers, and mills. Canal deepening can provide short-term drainage access while increasing peat fire risk. Delaying fertilizer can prevent inefficient application, but prolonged cancellation can deepen nutrient deficiency and future yield loss. Removing vegetation can reduce some fuels while exposing soil and increasing water loss. A robust decision framework therefore evaluates trade-offs, distributional effects, and reversibility. No-regret measures are implemented early because they remain beneficial under multiple forecast outcomes; more expensive or disruptive measures are activated when local thresholds confirm that risk is increasing [18,24,59].

Method

Qualitative Integrative Review Design

This study used a qualitative integrative literature review rather than a systematic literature review. The purpose was to connect evidence from multiple disciplines, interpret mechanisms, identify complementary interventions, and construct a context-sensitive mitigation framework for an unfolding climatic situation. A systematic review is most appropriate when the research question, intervention, outcome, and eligible study designs can be specified sufficiently narrowly for exhaustive retrieval and reproducible screening. The present problem is broader: it combines seasonal climate interpretation, perennial-crop physiology, peat hydrology, fire governance, labour health, operations, and smallholder institutions. Integrative review methods permit the inclusion and critical comparison of empirical, modelling, review, and conceptual studies without claiming that every relevant publication has been captured [60-63].

Literature Identification and Selection

The review was organized around purposive searches of Scopus-indexed and major publisher databases, including Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, PubMed or PMC, and journal platforms. Search concepts combined 'oil palm' with El Niño, Indian Ocean Dipole, drought, water deficit, temperature, vapour pressure deficit, yield lag, irrigation, soil moisture, nutrient management, peat fire, groundwater, smallholders, Ganoderma, heat stress, climate services, early warning, and anticipatory action. Peer-reviewed literature published from January 2020 to August 2026 was prioritized. Earlier sources were not required for the final evidence base because substantial recent literature was available. Official 2026 climate publications from BMKG, NOAA, and WMO were used to establish the time-sensitive hazard context but were not counted toward the minimum of fifty journal articles [61].

Selection was theoretically informed rather than exhaustive. A study was retained when it clarified a causal pathway, quantified or modelled a material risk, evaluated an intervention, revealed an implementation constraint, or supplied a concept needed for synthesis. Preference was given to studies from Indonesia and Malaysia, supplemented by transferable research from other tropical oil palm regions. Quality appraisal considered clarity of design, appropriateness of data and methods, treatment of uncertainty, relevance to soil and stand conditions, and consistency with the wider evidence. Contradictory findings were retained and interpreted in relation to geography, crop age, genotype, soil, management, temporal scale, and model assumptions rather than averaged mechanically [64,65].

Coding and Synthesis

An evidence matrix was used conceptually to organize author, year, location, plantation context, hazard, exposure, vulnerability, outcome, temporal lag, intervention, enabling conditions, and limitations. Initial descriptive codes included rainfall deficit, atmospheric drought, soil-water depletion, reproductive stress, lagged yield loss, nutrient inefficiency, peat groundwater decline, fire ignition, worker heat strain, mill-water shortage, smallholder vulnerability, and forecast-to-action failure. These codes were consolidated into analytical themes: the 2026 climate narrative; biophysical and delayed risks; agronomic and operational pathways; fire and landscape risks; the integrated mitigation portfolio; and phased implementation. Thematic synthesis was iterative, moving between source findings, the climate outlook, and the emerging framework. Saturation was treated pragmatically as the point at which additional sources elaborated existing themes without changing the central architecture, not as proof of exhaustive coverage [65,66].

Scope and Limitations

The review has four limitations. First, a seasonal outlook changes as ocean and atmosphere conditions evolve; recommendations must be updated with new forecasts and observations. Second, evidence from Malaysia, Colombia, Brazil, Ghana, and other regions cannot be transferred without attention to Indonesian soils, planting material, labour systems, and institutions. Third, the review does not estimate pooled effect sizes and should not be read as a meta-analysis. Fourth, detailed estate-level thresholds require calibration using local historical data. These limitations are addressed by presenting the framework as adaptive, differentiated, and trigger-based. The article does not prescribe a single national irrigation volume, fertilizer calendar, groundwater threshold, or work–rest schedule; it specifies the variables and decision logic that local managers should use.

Results: Thematic Findings

Theme 1 — The 2026 Risk Narrative Is Severe but Must Remain Probabilistic

The first theme is that the climatic signal was sufficiently strong to justify anticipatory action by August 2026. BMKG identified an active El Niño, an earlier, drier, and longer dry season in many areas, below-normal rainfall risks, above-normal temperatures, and increasing drought and fire danger. NOAA and WMO described a rapidly strengthening event with a high probability of persistence. These signals support a high preparedness posture for many oil palm regions in Sumatra, Kalimantan, Sulawesi, and Papua. Nevertheless, the specific magnitude and timing of rainfall deficits remain spatially variable, and the IOD signal was still emerging. The correct management interpretation is therefore 'prepare early and update frequently,' not 'assume uniform drought everywhere' [4-8].

Table 1: Principal 2026 Climate Signals and Their Plantation Interpretation

Signal	Evidence Status in Early August 2026	Potential Plantation Consequence	Management Interpretation
El Niño	Active and strengthening; expected to persist	Reduced convection and higher probability of rainfall deficits in many regions	Activate preparedness while verifying local rainfall and soil conditions
Indian Ocean Dipole	Neutral in preceding observations but positive phase anticipated later in 2026	Possible reinforcement of drying in parts of western and southern Indonesia	Treat as an emerging multiplier; update monthly
Rainfall Distribution	Below-normal probabilities and longer dry spells in many areas	Declining root-zone moisture, lower effective rainfall, fertilizer timing risk	Track consecutive dry days and effective rainfall, not monthly total alone
Temperature	Above-normal anomaly expected	Higher evapotranspiration, vapour pressure deficit, worker heat strain	Add heat and atmospheric-demand indicators to drought monitoring
Drought and Fire Danger	Rising during August–October	Dry fuels, peat groundwater decline, ignition and smoke risk	Escalate patrols, hydrological monitoring, equipment readiness, and community coordination

The climate outlook is valuable because it communicates the convergence of hazards and provides plantation-oriented messages on water conservation, fire prevention, immature blocks, monitoring, and fertilizer timing. Its limitations are also instructive. National maps cannot reveal block-level soil-water status, groundwater depth, reservoir storage, or fuel condition, and a snapshot dated 1 August cannot substitute for a rolling forecast. The outlook should therefore be used as a strategic alert that triggers local diagnosis. An estate climate dashboard should preserve the distinction between forecast indicators, observed weather, hydrological response, biological condition, and operational consequence [23,67].

Theme 2 — Water Deficit, Heat, and Biological Lags Create Hidden Production Risk

The second theme is that crop risk can accumulate before a large yield decline becomes visible. Higher temperature and atmospheric demand increase transpiration pressure, while declining soil moisture induces stomatal closure and changes in metabolism. Soil texture, rooting depth, ground cover, compaction, and drainage influence how rapidly this stress develops. Young palms and newly replanted blocks deserve priority because their root systems and canopy establishment are incomplete, but mature blocks with high reproductive load or a history of drought and nutrient stress may also be vulnerable. A block-based risk classification is therefore superior to a single estate average [16,24,32,59,68,69].

The evidence supports three monitoring horizons. The immediate horizon covers leaf symptoms, soil moisture, water availability, heat exposure, and fire danger. The developmental horizon covers inflorescence and bunch formation, where disturbance may not yet affect harvested output. The financial horizon covers the later period in which lower bunch number or weight reduces revenue while recovery, replanting, or debt obligations continue. Management accounts should therefore create a climate-event cohort for affected blocks, enabling 2027–2028 production to be compared with pre-event baselines and matched controls. This converts the drought from an anecdotal event into a learnable dataset [9-11,15,33-35,69].

Theme 3 — Agronomic Responses Must Be Adaptive, Not Calendar Bound

The third theme concerns agronomic timing. Fertilizer application should be linked to soil moisture, short-range rainfall probability, nutrient status, fertilizer form, block accessibility, and expected agronomic return. During a prolonged dry spell, some applications may be postponed or split; in blocks with adequate moisture or localized rainfall, continued application may remain justified. After rain resumes, a large catch-up dose can also be inefficient or environmentally risky. The decision rule should therefore be adaptive: protect the plant's medium-term nutrient status while avoiding placement when dissolution and uptake are improbable. This is particularly important for smallholders, where nutrient deficits and imbalance are already common [40-42].Soil-moisture conservation offers a set of comparatively low-regret measures. Maintaining living ground cover, arranging pruned fronds to protect soil and slow runoff, applying suitable organic residues, controlling erosion, maintaining infiltration structures, and preventing unnecessary soil disturbance can reduce evaporation and improve rainfall capture. These practices should be combined with inspection of drains, culverts, ponds, and water-retention structures. They must also respect disease, access, and fire-safety requirements. For example, residues should not be concentrated in a manner that creates dangerous fuel continuity near roads, buildings, or peat edges. Climate-smart agronomy is therefore a design problem involving water, nutrients, fuel, and operations simultaneously, not a list of independent good practices [1,3].

Irrigation is a contingent rather than universal solution. Research in Brazil and simulation studies show that supplemental water can maintain transpiration and reduce stress, but water demand can be substantial, and infrastructure, pumping cost, energy, and catchment availability constrain feasibility. Priority should be given to nurseries, newly planted areas, high-value breeding material, and blocks where a limited quantity of water can prevent irreversible loss. Before allocating water, estates should inventory storage, streamflow, groundwater permissions, mill requirements, worker and community needs, and ecological flows. Emergency irrigation that depletes shared water or destabilizes peat hydrology is maladaptation [24,59,68,70].

Theme 4 — Fire and Peat Risks Require Landscape-Scale Hydrological Governance

The fourth theme is that fire prevention must begin before ignition. A high-risk programme combines mapping of previous burns and ignition sources, verification of pumps and mobile tanks, water-point inspection, fuel-load management, firebreak maintenance, patrol escalation, hotspot surveillance, trained crews, contractor compliance, community communication, and a clear incident-command system. Daily or near-daily risk classification should integrate weather, soil moisture, peat groundwater level, fuel condition, and observed ignition. Waiting for a hotspot before mobilizing equipment sacrifices the principal advantage provided by seasonal forecast lead time [12,23,52,53,67,71,72]. On peat, hydrology is the central control. Estates should intensify groundwater-table measurement, inspect canal blocks and control structures, prevent unauthorized drainage, identify areas with cracking or unusual subsidence, and coordinate water management across the peat hydrological unit. Rewetting and water retention can reduce extreme fire hazard, but structures require maintenance and should be designed with local elevation, rainfall, access, and community use in mind. A company cannot fully protect a peat block if adjacent land is severely drained or burned; landscape agreements, village fire groups, and shared response resources are therefore operational necessities rather than corporate-social-responsibility additions [51,54,72,73].

The economic case for prevention strengthens when externalities are counted. Direct losses include damaged palms, infrastructure, suppression costs, and production disruption. Wider costs include smoke exposure, medical burden, school and transport interruption, carbon emissions, ecosystem degradation, and reputational or legal consequences. Peatland restoration and conservation studies show that avoided fire and emission damages can justify early expenditure that appears costly when viewed only through a single estate budget. Lenders, insurers, mills, and buyers therefore have a legitimate role in financing and verifying prevention measures [17,18,74,75].

Theme 5 — An Integrated Mitigation Portfolio Must Operate at Multiple Scales

The fifth theme is that no single intervention can manage the 2026 risk. A useful portfolio begins with climate intelligence: seasonal and monthly forecasts, weekly updates, local rain gauges, consecutive dry days, soil-moisture readings, peat groundwater levels, temperature and heat indices, reservoir storage, stream condition, fire-danger ratings, and satellite hotspots. These data should feed an escalation matrix that defines who decides, which action is triggered, how long it remains active, and what evidence permits de-escalation. The value of monitoring lies in decision rights and response speed; a dashboard without authority merely documents deterioration [23,25,57].

At the palm and row level, priority actions are soil cover, residue placement, erosion control, drought-stress scoring, protection of young palms, and plant-health surveillance. At the block level, actions include water-balance assessment, fertilizer adjustment, access planning, fuel management, and prioritized watering. At the estate or smallholder-group level, managers coordinate reservoirs, pumps, fire teams, heat-health procedures, procurement, finance, and reporting. At the mill and supply-chain level, raw-water storage, processing schedules, fruit-delivery contingency, road readiness, energy backup, and communication with suppliers become critical. At landscape and policy levels, the focus shifts to catchment water allocation, peat hydrology, community fire prevention, public climate services, emergency health capacity, and financial support [67].

Figure 3 presents the proposed mitigation architecture as a nested system in which field practices, estate operations, mills, landscape governance, and cross-cutting institutional pillars must function together.

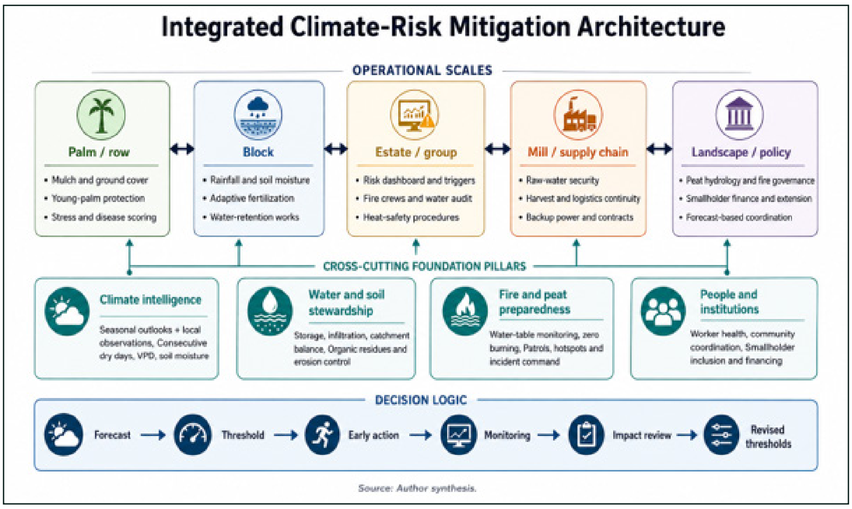

Figure 3: Integrated multi-scale climate-risk mitigation architecture for oil palm.

Source: Author's synthesis of the reviewed literature.

Figure 3 shows that adaptation fails when responsibility is concentrated at only one level. Field teams cannot maintain peat hydrology across property boundaries; government forecasts cannot conserve soil moisture without local action; mills cannot secure fruit supply if smallholders lack fire equipment and finance; and corporate sustainability units cannot protect workers unless supervisors have authority to change schedules. The cross-cutting pillars—data, finance, accountability, learning, and inclusion—link the operational levels. They also determine whether a response becomes routine institutional capacity or disappears after the first rainfall event [2,55].

Worker protection is a core portfolio component. Each estate should define heat-alert levels using a locally appropriate index, specify hydration and electrolyte access, establish shaded recovery areas, adjust strenuous work to cooler periods, apply work–rest cycles, train supervisors to recognize heat illness, and permit suspension of work when risk cannot be controlled. Fire crews require additional protection because they combine heat, smoke, physical exertion, and personal protective equipment. Records of heat symptoms, near misses, productivity, and absenteeism should be analysed alongside weather to refine thresholds. These measures protect human health while reducing the probability that fatigue and cognitive impairment cause accidents or weaken emergency response [14,21,22].

Smallholder support must be designed as shared infrastructure and services rather than as advice alone. Relevant measures include localized climate advisories in accessible language, group rain gauges and soil-moisture monitoring, shared pumps and mobile tanks, village-level fire teams, access to mulch and cover-crop material, agronomic coaching, input and working-capital credit, temporary income support, and participation in mill and company contingency plans. Where index insurance is considered, the index should reflect local exposure and be tested for basis risk. The objective is to prevent a climate event from forcing households to under-fertilize, delay harvest, sell assets, use fire for low-cost land preparation, or abandon replanting [33-35,40,55,56].

Figure 4 emphasizes that the same regional forecast can generate different levels of risk because exposure, sensitivity, and adaptive capacity vary across soils, stand ages, ownership models, and landscapes.

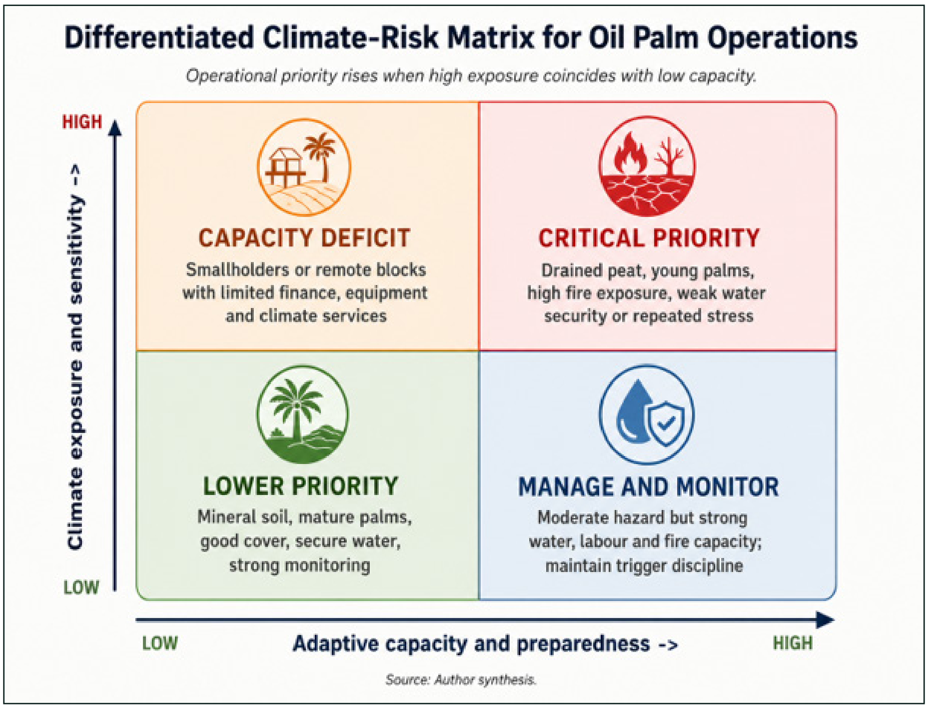

Figure 4: Differentiated risk matrix for prioritizing oil palm climate interventions.

Source: Author's synthesis based on the reviewed literature.

The matrix in Figure 4 supports prioritization. High-exposure, low-capacity units—such as young palms on drought-prone soils, drained peat adjoining fire-prone land, or isolated independent growers—require immediate support and frequent monitoring. High-exposure units with stronger capacity can rely on advanced triggers and contingency resources, but they remain systemically important because a large estate or mill failure affects many suppliers. Lower-exposure units should not be ignored; they are suitable locations for water storage, backup logistics, and recovery support. The matrix should be updated as rainfall, hydrology, fuel, and institutional readiness change.

Theme 6 — Implementation Should Be Phased and Trigger-Based

The sixth theme is temporal sequencing. During the first thirty days, organizations should activate a climate-risk command structure, conduct water and fire audits, identify vulnerable blocks, inspect peat controls, test pumps and communications, protect nurseries and immature palms, revise fertilizer timing, train workers, and engage neighbouring communities. These are largely no-regret actions because they improve readiness even if local rainfall is better than expected. Budget authorization must occur at this stage; a plan without pre-approved expenditure will be too slow when conditions deteriorate [76].

During the following one to three months, actions should be linked to observed thresholds. Examples include escalating patrol frequency after a specified number of dry days, prioritizing water when soil moisture or reservoir storage crosses a locally calibrated level, modifying work–rest cycles as heat indices rise, restricting risky activities under extreme fire danger, and activating transport or mill contingencies when smoke or water supply threatens operations. Thresholds should not be copied mechanically from another region. They should be calibrated from estate history, peat characteristics, soil type, crop age, water infrastructure, and occupational-health guidance.When rainfall resumes, the response enters a recovery phase rather than ending. Managers should inspect roads, drains, erosion, water quality, disease symptoms, palms with severe crown stress, and delayed reproductive indicators. Fertilizer schedules should be restored gradually based on soil moisture and plant status, not through a single large catch-up application. Fire equipment must remain available because intermittent dry periods and underground peat combustion can persist. A structured after-action review should compare forecasts, triggers, decisions, costs, near misses, and losses, creating a revised operating procedure for the next event.

The medium-term phase extends through 2027–2028. It includes monitoring lagged yield effects, redesigning water infrastructure, strengthening digital climate services, improving peat hydrology, selecting more resilient planting material during replanting, institutionalizing heat-health programmes, and financing smallholder adaptation. Data from the 2026 event should be used to estimate avoided losses and the return on adaptation expenditure. This learning horizon is essential because a plantation can appear to recover visually while reproductive and financial effects are still unfolding

Table 2: Illustrative Climate-Risk Register and Trigger Variables

Risk Pathway	Leading Indicator	Potential Consequence	Priority Control
Root-zone water deficit	Consecutive dry days; soil moisture; water balance	Stomatal closure, reduced growth, delayed yield loss	Soil cover, water retention, prioritized supplemental water, stress monitoring
Nutrient inefficiency	Dry soil; low rain probability; nutrient status	Low uptake, poor return on fertilizer, later deficiency	Split and retime applications; prioritize blocks; avoid blanket cancellation
Peat desiccation	Groundwater-table decline; canal condition; cracking	Subsurface fire, oxidation, subsidence	Hydrological control, canal-block maintenance, rewetting, cross-boundary coordination
Vegetation and peat fire	Fire-weather index; fuel moisture; hotspots; ignition reports	Asset loss, haze, emissions, operational disruption	Patrols, zero burning, equipment readiness, community teams, incident command
Worker heat strain	Heat index or WBGT; symptoms; work intensity	Illness, lower productivity, injury, weak response capacity	Hydration, shade, work–rest cycles, cooler hours, stop-work authority
Mill-water shortage	Reservoir storage; raw-water quality; inflow	Reduced throughput, hygiene and steam constraints	Water inventory, conservation, alternative supply, processing contingency
Delayed production loss	Inflorescence and bunch indicators; block yield trend	Lower bunch number or weight in 2027–2028	Longitudinal monitoring, financial provisioning, adaptive agronomy

Figure 5 converts the evidence into a practical action calendar that begins with forecast-based preparedness and continues through recovery and monitoring of delayed yield effects.

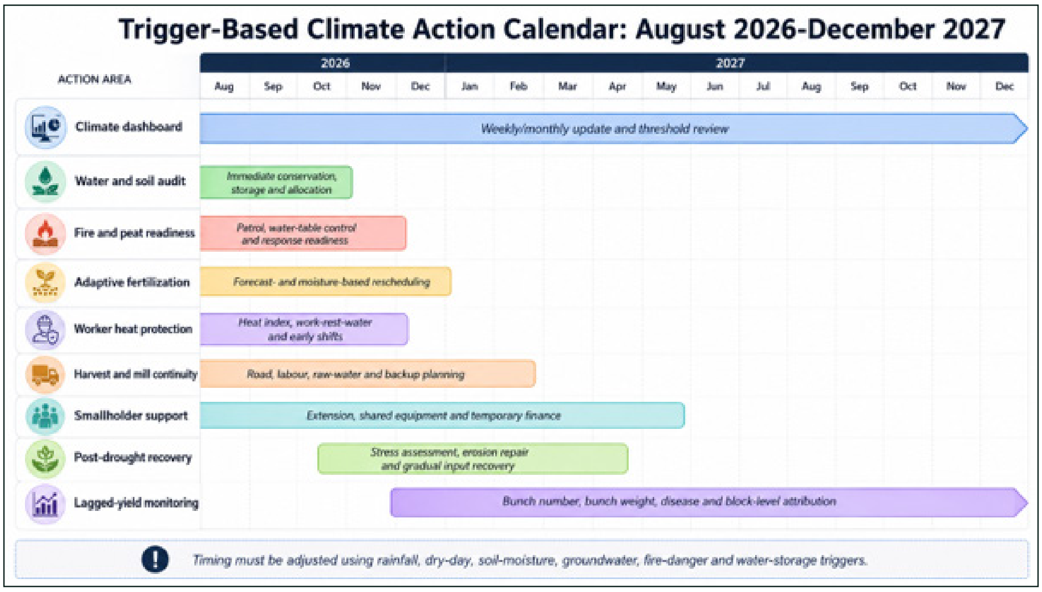

Figure 5: Trigger-based action calendar from August 2026 through December 2027.
Source: Author's synthesis based on the review findings.

The calendar is intentionally longer than the expected dry-season peak. It recognizes four management states: preparedness, active dry-season control, recovery and diagnosis, and structural adaptation. Movement between states should be governed by both time and evidence. For example, an early rainfall event may reduce immediate fire danger without restoring deeper soil moisture, while a later dry spell may require re-escalation. Similarly, the end of fire season does not end the need to monitor bunch development and revenue risk. The calendar therefore promotes adaptive management rather than a one-directional emergency plan [76,77].

Table 3: Phased Implementation Roadmap and Illustrative Performance Indicators

Phase	Priority Actions	Lead Actors	Illustrative Indicators
0–30 days	Command activation; water/fire audits; vulnerable-block map; equipment tests; worker briefing; fertilizer review	Estate manager, agronomy, sustainability, HSE, mill, smallholder liaison	Audit completion; functioning pumps; verified water points; high-risk blocks assigned; budget released
1–3 months	Trigger-based patrols and water allocation; heat protocols; peat monitoring; logistics and mill contingencies	Operations teams, fire crews, HSE, mill, village partners	Dry-day and hydrology dashboard; patrol coverage; response time; heat incidents; mill-water days available
Late 2026 recovery	Damage assessment; gradual nutrient restoration; road and drainage repair; disease survey; after-action review	Agronomy, engineering, finance, HSE, research	Stress recovery score; repaired access; revised SOP; documented losses and near misses
2027–2028 resilience	Lagged-yield monitoring; infrastructure redesign; resilient replanting; smallholder finance; peat and catchment agreements	Corporate leadership, government, lenders, researchers, producer organizations	Yield-lag estimates; adaptation investment; smallholder participation; groundwater compliance; avoided-loss estimate

Discussion and Analysis

From Forecast Information to Accountable Decisions

The synthesis indicates that the central management failure is often not the absence of climate information but the absence of an institutional bridge between information and action. Seasonal forecasts are commonly circulated without an agreed decision owner, a threshold, a budget, or a de-escalation rule. As a result, managers either wait for visible damage or implement broad measures that are poorly matched to local conditions. A forecast-to-action protocol should specify the evidence chain: large-scale outlook establishes preparedness; local observations confirm exposure; block and system indicators identify thresholds; authorized actors implement pre-defined measures; monitoring determines continuation or revision. This architecture makes uncertainty manageable because decisions are staged rather than based on a single prediction [50,78].

Forecast lead time has economic value. Repairing a pump, cleaning an intake, negotiating a village fire agreement, building water inventory, or adjusting fertilizer delivery before the peak is cheaper than emergency procurement after widespread stress or ignition. The value is greatest for actions with long preparation times and low regret. More disruptive actions can remain contingent. This logic resembles a real option: early information does not require an irreversible commitment to the most expensive response, but it justifies preserving the ability to act quickly. Climate services should therefore be evaluated by avoided loss and decision quality, not only forecast accuracy [1,57].

Differentiation Is More Important Than Uniform Prescription

A national risk level is useful for mobilization but insufficient for resource allocation. Mineral and peat soils require different controls; young and mature stands have different sensitivities; large estates and independent growers possess different capacities; and rainfall anomalies vary across regions. The practical unit of diagnosis should be the management block embedded within a hydrological and supply-chain context. A block-level dashboard can combine soil, stand age, historical yield, local rainfall, water storage, peat status, disease incidence, access, and firefighting coverage. This supports prioritization without pretending that all variables can be reduced to one universal score [20].

Differentiation also improves fairness. Uniform compliance requirements may impose costs that smallholders cannot meet, while uniform subsidies may waste resources in low-risk locations. Public agencies, mills, and companies should target shared services toward high-exposure, low-capacity groups. Contracts and certification systems can reinforce preparedness by providing technical support, finance, and transparent obligations rather than simply threatening exclusion after a failure. Evidence on certification and smallholder resilience suggests that institutional design and access to resources determine whether sustainability requirements improve livelihoods or deepen inequality [55,56].

Managing Trade-Offs and Preventing Maladaptation

The most difficult decisions involve scarce water. Plantations, mills, worker settlements, villages, ecosystems, and firefighting systems may rely on the same catchment. An estate that maximizes irrigation without a catchment allocation plan can shift risk to communities or reduce the water available for fire response. Conversely, prohibiting all supplemental watering may sacrifice nurseries or immature palms even when targeted use is feasible. A transparent hierarchy should protect drinking water and essential health needs, maintain critical fire and mill functions, safeguard high-vulnerability plant material, and preserve environmental limits. The hierarchy should be agreed before scarcity becomes acute [77,79].

Peatland management involves a related trade-off between water retention, access, and plantation operations. Excessive drainage reduces short-term waterlogging but amplifies the risks of fire, oxidation, and subsidence; poorly planned rewetting can create local flooding or access problems. The appropriate solution is hydrological design and monitoring rather than a binary choice. Canal controls, water-level targets, emergency access, and neighbouring land use must be planned across the hydrological unit. Because peat fire externalities are large, public regulation and landscape finance are justified even when the direct private return to an individual landholder appears limited [17,18,54,79].

Agronomic trade-offs also require judgement. Short-term cost reduction through fertilizer cancellation can protect cash but deepen later yield loss, especially among already undernourished smallholder palms. Intensive clearing may create the appearance of fire readiness while increasing soil exposure. Early harvesting to manage labour risk may protect continuity but lower fruit maturity and oil extraction if poorly controlled. Each action should therefore be evaluated through an intervention–mechanism–outcome chain: what risk is being reduced, through which mechanism, at what cost, with which side effects, and how will success be measured? This discipline prevents the emergency label from legitimizing ineffective practices.

Governance, Finance, and Organizational Learning

Effective governance requires a clear command structure that integrates agronomy, engineering, sustainability, occupational health and safety, mill operations, procurement, finance, security, and community relations. Fragmented departmental plans create gaps: agronomy may seek water without considering community supply; fire teams may not know mill storage; finance may delay preventive expenditure; and sustainability staff may lack operational authority. Senior leadership should approve a climate-risk charter defining trigger ownership, reporting frequency, escalation authority, emergency procurement, and communication with regulators and communities [36,72].

Finance should shift from reimbursement after loss toward forecast-based prevention. Companies can pre-allocate contingent budgets linked to risk levels. Banks and buyers can offer working capital for water conservation, firefighting equipment, resilient replanting, or smallholder inputs, with safeguards against over-indebtedness. Insurance products can support recovery, but weather indices must be locally calibrated to reduce basis risk. Public finance is especially important for shared goods—community fire teams, peat hydrology, catchment monitoring, health services, and climate information—that no single plantation can provide efficiently.

The 2026 event should also be treated as a natural experiment. Estates can compare similar blocks with different soil-cover practices, water systems, genotypes, or intervention timing. Records should preserve forecast versions, rainfall, soil moisture, water-table depth, heat indices, actions, costs, fire incidents, health events, bunch components, and later yield. Such data allow the company and research partners to identify which measures produced avoided losses. Machine learning may assist once data quality and causal interpretation are adequate, but a complex model cannot compensate for missing observations or inconsistent management records [9,25].

Toward a Holistic Climate-Resilient Oil Palm System

The broader analytical implication is that resilience is an emergent property of the whole production landscape. A drought-tolerant genotype can still fail if planted in degraded soil without water retention. A well-managed estate can lose supply if independent growers burn or cannot harvest. A peat-rewetting structure can fail without maintenance and neighbouring cooperation. A fire team can be ineffective when heat stress, smoke, or water shortage reduces capacity. A mill can remain operational yet damage community relations if it monopolizes scarce water. Holistic mitigation therefore means coordinating biological, hydrological, human, financial, and institutional systems around shared risk indicators [37,38].

This systems perspective also links adaptation with sustainability. Closing yield gaps through better agronomy and climate resilience can reduce pressure for expansion, while peat conservation and fire prevention reduce emissions and health damages. However, intensification is sustainable only when it does not increase water extraction, fertilizer pollution, or inequality. The preferred pathway is climate-smart intensification embedded in landscape safeguards and inclusive support for smallholders. This is more demanding than a narrow productivity programme, but it aligns plantation continuity with environmental legitimacy and social stability [1,2,56,76].

Conclusion and Policy Recommendations

The 2026 climate outlook presents a material risk to Indonesian oil palm, especially where a strengthening El Niño, anticipated positive IOD, below-normal rainfall, above-normal temperatures, and longer dry spells coincide with vulnerable soils, drained peat, weak water systems, dry fuels, and limited institutional capacity. The risk is compound and cascading: climate drivers become hydrological stress, crop and worker impacts, fire, operational disruption, and financial loss. It is also temporally extended because reproductive effects can reduce bunch number and bunch weight after the visible drought has ended. For this reason, success cannot be measured only by the absence of fire or the survival of palms in late 2026.

The critical managerial recommendation is to establish a trigger-based climate-risk command system. Every estate or producer organization should integrate updated forecasts with local rainfall, consecutive dry days, soil moisture, peat groundwater level, heat indices, reservoir storage, fuel condition, hotspots, and biological observations. Pre-approved actions should cover water conservation, prioritized supplemental water, adaptive fertilization, soil cover, fire patrols, peat controls, worker protection, mill-water continuity, transport, plant health, and smallholder support. Decision rights, budgets, indicators, and de-escalation rules should be explicit. No-regret measures should begin immediately; costly or disruptive measures should be activated when local evidence confirms escalation.

Policy should focus on capabilities that individual growers and companies cannot supply alone. BMKG and agricultural agencies should provide commodity-specific and district-level climate advisories that translate probabilities into management implications while communicating uncertainty. Provincial and district governments should finance shared water monitoring, community fire teams, peat hydrological management, emergency health preparedness, and extension. Mills and large companies should include independent suppliers in forecasts, training, equipment sharing, and contingency planning. Banks and buyers should create forecast-based credit windows for preventive investments and protect viable growers from climate-induced liquidity shocks. Certification and disclosure systems should evaluate preparedness, peat hydrology, worker heat protection, and support to smallholders, rather than relying only on post-event compliance.

Finally, monitoring must continue through 2027–2028. Block-level data on inflorescence development, bunch number, bunch weight, yield, disease, recovery, worker health, and finances should be linked to 2026 exposure and intervention records. This will reveal delayed losses, identify effective practices, and improve thresholds for future events. The durable lesson is that climate forecasts create value only when they change decisions before damage becomes irreversible. Indonesia's oil palm sector can reduce the losses associated with the 2026 event, but only through an integrated portfolio that treats water, soil, peat, fire, workers, smallholders, mills, and governance as parts of a single climate-risk system.

References

1. Juan P Monzon, Maja A Slingerland, Suroso Rahutomo, Fahmuddin Agus, Thomas Oberthür, et al. (2021) Fostering a climate-smart intensification for oil palm. Nat Sustain 4: 595-601.
2. DJ Murphy, K Goggin, RRM Paterson (2021) Oil palm in the 2020s and beyond: challenges and solutions. CABI Agric Biosci 2: 39.
3. T Rhebergen (2020) Closing yield gaps in oil palm production systems in Ghana through Best Management Practices. Eur J Agron 115: 126011.
4. BMKG (2025) Climate Outlook 2026 (Pandangan Iklim 2026): Rekomendasi terhadap Sektor Pertanian/Perkebunan/Kualitas Udara/ Kesehatan/ Sumber Daya Air/Kebencanaan. Jakarta, 2025. doi: https://www.bmkg.go.id/iklim/buletin-iklim/climate-outlook-2026.
5. AA Zahro (2026) BMKG: Puncak Musim Kemarau Agustus 2026, Perkuat Kesiapan Hadapi Dampak El Nino. BMKG Siaran Pers https://www.bmkg.go.id/siaran-pers/bmkg-puncak-musim-kemarau-agustus-2026-perkuat-kesiapan-hadapi-dampak-el-nino.
6. K Prasetyaningtyas (2026) Buletin Informasi Iklim Perkebunan Komoditas Sawit Bulan Juli 2026. Buletin informasi Iklim Perkebunan Komoditas Sawit https://www.bmkg.go.id/iklim/buletin-informasi-iklim-perkebunan-komoditas-sawit-bulan-juli-2026.
7. Climate Prediction Center (2026) El Nino Southern Oscillation (ENSO) Diagnostic Discussion. ENSO Alert System https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/ensodisc.shtml.
8. WMO (2026) Global Seasonal Climate Update for August-September-October 2026. Global Seasonal Climate https://wmo.int/resources/publication-series/global-seasonal-climate-update/gscu-aso2026.
9. Juan P. Monzon, Mohamed Jabloun, James Cock, Jean Pierre Caliman, et al. (2022) Influence of weather and endogenous cycles on spatiotemporal yield variation in oil palm. Agric For Meteorol 314: 108789.
10. JF Khor, L Ling, Z Yusop, WL Tan, JL Ling, et al. (2021) Impact of El Niño on oil palm yield in Malaysia. Agronomy 11: 2189.
11. Alex Hermanto, Siew Hua Gan, Ivan Rendi Mustopa, Wei Chee Wong, Patrick Hong huan Ng, et al. (2023) Use of multiseasonal oil palm yield data to assess drought tolerance. Sci Hortic 308: 111603.
12. Symon Mezbahuddin, Tadas Nikonovas, Allan Spessa, Robert F. Grant, Muhammad Ali Imron, et al. (2023) Accuracy of tropical peat and non-peat fire forecasts enhanced by simulating hydrology. Sci Rep 13: 619.
13. A Abubakar, MY Ishak, AA Makmom (2021) Impacts of and adaptation to climate change on the oil palm in Malaysia: a systematic review. Environ Sci Pollut Res 28: 54339–54361.
14. S Dasgupta, EJZ Robinson, S Shayegh, F Bosello, RJ Park, et al. (2024) Heat stress and the labour force. Nat Rev Earth Environ 5: 859-872.
15. Jen Feng Khor, Lloyd Ling, Zulkifli Yusop, Ren Jie Chin, Sai Hin Lai, et al. (2023) Impact Comparison of El Niño and Ageing Crops on Malaysian Oil Palm Yield. Plants 12: 424.
16. C Bayona-Rodríguez, HM Romero (2024) Drought Resilience in Oil Palm Cultivars: A Multidimensional Analysis of Diagnostic Variables. Plants 13: 1598.
17. Chandra S Deshmukh, Dony Julius, Ankur R Desai, Adibtya Asyhari, Susan E Page, et al. (2021) Conservation slows down emission increase from a tropical peatland in Indonesia. Nat Geosci 14: 484-490.
18. L Kiely, DV Spracklen, SR Arnold, E

Papargyropoulou, L Conibear, et al. (2021) Assessing costs of Indonesian fires and the benefits of restoring peatland. Nat Commun 12: 7044.
19. AA Abubakar A, Ishak MY, Makmom (2022) Nexus between climate change and oil palm production in Malaysia: A review. Environ Monit Assess 194: 262.
20. MA Fulazzaky, I Ismail, H Harlen, S Sukendi, M Roestamy, YI Siregar (2022) Evaluation of change in the peat soil properties affected by different fire severities. Environ Monit Assess 194: 783.
21. Kristie L Ebi, Anthony Capon, Peter Berry, Carolyn Broderick, Richard de Dear, et al. (2021) Hot weather and heat extremes: health risks. Lancet 398: 698-708.
22. LA Parsons, D Shindell, M Tigchelaar, Y Zhang, JT Spector (2021) Increased labor losses and decreased adaptation potential in a warmer world. Nat Commun 12: 7286.
23. Albertus Sulaiman, Mitsuru Osaki, Hidenori Takahashi, Manabu D. Yamanaka, Raden Dwi Susanto, et al. (2023) Peatland groundwater level in the Indonesian maritime continent as an alert for El Niño and moderate positive Indian Ocean dipole events. Sci Rep 13: 939.
24. H Akram, DF Levia, JE Herrick, H Lydiasari, N Schütze (2022) Water requirements for oil palm grown on marginal lands: A simulation approach. Agric Water Manag 260: 10729.
25. Nuzhat Khan, Mohamad Anuar Kamaruddin, Usman Ullah Sheikh, Mohd Hafiz Zawawi, Yusri Yusup, et al. (2022) Prediction of Oil Palm Yield Using Machine Learning in the Perspective of Fluctuating Weather and Soil Moisture Conditions: Evaluation of a Generic Workflow. Plants 11: 1697.
26. André Pereira Leão, Cleiton Barroso Bittencourt, Thalliton Luiz Carvalho da Silva, Jorge Cândido Rodrigues Neto, Ítalo de Oliveira Braga, et al. (2022) Insights from a Multi-Omics Integration (MOI) Study in Oil Palm (Elaeis guineensis Jacq.) Response to Abiotic Stresses: Part Two—Drought. Plants 11: 2786.
27. WRL Lopes Filho, FHS Rodrigues, IVL Ferreira, LO Correa, RL Cunha, HA Pinheiro (2021) Physiological responses of young oil palm (Elaeis guineensis Jacq.) plants to repetitive water deficit events. Ind Crops Prod 172: 114052.
28. JCR Neto, LR Vieira, JA de Aquino Ribeiro, CAF de Sousa, MTS Júnior, et al. (2021) Metabolic effect of drought stress on the leaves of young oil palm (Elaeis guineensis) plants using UHPLC–MS and multivariate analysis. Sci Rep 11: 18271.
29. Carmenza Montoya, Edison Daza, Fernan Santiago Mejía-Alvarado, Arley Fernando Caicedo-Zambrano, Iván Ayala-Díaz, et al. (2024) Photosynthetic Performance of Oil Palm Genotypes under Drought Stress. Plants 13: 2705.
30. R Ruiz-Romero, M De la Peña, I Ayala-Díaz, C Montoya, HM Romero (2024) Genotype and Nitrogen Source Influence Drought Stress Response in Oil Palm Seedlings. Agronomy 14: 2082.
31. P Suraninpong, K Thongkhao, AM Azzeme, P Suksa-Ard (2023) Monitoring Drought Tolerance in Oil Palm: Choline Monooxygenase as a Novel Molecular Marker. Plants 12: 17.
32. L Wang, M Lee, B Ye, GH Yue (2020) Genes, pathways and networks responding to drought stress in oil palm roots. Sci Rep 10: 21303.
33. Heinrich Petri, Dienda Hendrawan, Tobias Bähr, Oliver Musshoff, Meike Wollni, et al. (2023) Replanting challenges among Indonesian oil palm smallholders: a narrative review. Environment Development and Sustainability 26: 19351-19367.
34. L Judijanto (2024) Rejuvenating Smallholder Oil Palm Plantations: Challenges and Pathways to Sustainability. Jambura Agribus J 6: 37-50
35. Ariadna Fosch, Guilherme Ferraz de Arruda, Alberto Aleta, Adrià Descals, David Gaveau, et al. (2023) Replanting unproductive palm oil with smallholder plantations can help achieve Sustainable Development Goals in Sumatra, Indonesia. Commun Earth Environ 4: 378.
36. MSK Sarkar, RA Begum, JJ Pereira (2020) Impacts of climate change on oil palm production in Malaysia. Environ Sci Pollut Res 27: 9760-9770.
37. Meng Li, Bo Meng, Yong Geng, Fan Tong, Yuning Gao, et al. (2025) Inequitable distribution of risks associated with occupational heat exposure driven by trade. Nat Commun 16: 537.
38. LR Vargas Zeppetello, AE Raftery, DS Battisti (2022) Probabilistic projections of increased heat stress driven by climate change. Commun Earth Environ 3: 183.
39. YH Go, YL Tan, TH Yiew (2024) Sensitivity of oil palm yield in Indonesia to climate change: evidence from threshold cointegration models. Environ Dev Sustain doi: 10.1007/s10668-024-05635-w.
40. Juan Pablo Monzon, Ya Li Lim,Fatima A Tenorio,

Rana Farrasati, Iput Pradiko, et al. (2023) Agronomy explains large yield gaps in smallholder oil palm fields. Agric Syst 210: 103689.

41. Mettauer Romane, Baron Victor, Turinah Turinah, Demitria Puspita, Smit Hans, et al. (2021) Investigating the links between management practices and economic performances of smallholders' oil palm plots. A case study in Jambi province, Indonesia. Agric Syst 194: 103274.
42. YL Lim (2020) Too little, too imbalanced: Nutrient supply in smallholder oil palm fields in Indonesia. Agric Syst 210: 103729.
43. Raphaël Belmin, Eric Malézieux, Claudine Basset-Mens, Thibaud Martin, Charles Mottes, et al. (2022) Designing agroecological systems across scales: a new analytical framework. Agron Sustain Dev 42.
44. Victor Hugo Benezoli, Hewlley Maria Acioli Imbuzeiro, Santiago Vianna Cuadra, Michel Anderson Almeida Colmanetti, Alessandro Carioca de Araújo, et al. (2021) Modeling oil palm crop for Brazilian climate conditions. Agric Syst 190.
45. Michael Osei Adu, Kofi Atia, Emmanuel Arthur, Paul Agu Asare, Peter Bilson Obour, et al. (2022) The use of oil palm empty fruit bunches as a soil amendmentto improve growth and yield of crops. A meta-analysis. Agron Sustain Dev 42: 13.
46. Y Dady, R Ismail, H Jol, F Arolu (2021) Impact of Oil Palm Empty Fruit Bunch Biochar Enriched with Chicken Manure Extract on Phosphorus Retention in Sandy Soil. Sustainability 13: 10851.
47. A Abubakar, MY Ishak, AA Bakar, MK Uddin (2022) Ganoderma boninense basal stem rot induced by climate change and its effect on oil palm. Environ Sustain 5: 289-303.
48. RRM Paterson (2023) Future Climate Effects on Basal Stem Rot of Conventional and Modified Oil Palm in Indonesia and Thailand. Forests 14: 1347.
49. MSA Baharim, NA Adnan, MI Anuar, AL Laurence, AA Samat (2024) Relationship analysis between Ganoderma boninense-derived Basal Stem Rot disease severity with multiple leaf physiology parameters in mature oil palm tree responses toward water use efficiency (WUE). J Plant Pathol 106: 1801-1816.
50. Yuhao Ang, Helmi Zulhaidi Mohd Shafri, Yang Ping Lee, Shahrul Azman Bakar, Haryati Abidin, et al. (2022) Oil palm yield prediction across blocks from multi-source data using machine learning and deep learning. Earth Sci Informatics 15: 2349-2367.
51. M Taufik, M Haikal, MT Widyastuti, C Arif, IP Santikayasa (2023) The Impact of Rewetting Peatland on Fire Hazard in Riau, Indonesia. Sustainability 15: 2169.
52. A Usup, H Hayasaka (2023) Peatland Fire Weather Conditions in Central Kalimantan, Indonesia. Fire 6: 182.
53. H Hayasaka, A Usup, D Naito (2020) New Approach Evaluating Peatland Fires in Indonesian Factors. Remote Sens 12: 2055.
54. AJ Horton, J Lehtinen, M Kummu (2022) Targeted land management strategies could halve peatland fire occurrences in Central Kalimantan, Indonesia. Commun Earth Environ 3: 204.
55. D Hendrawan, D Chrisendo, O Musshoff (2024) Strengthening oil palm smallholder farmers' resilience to future industrial challenges. Sci Rep 14: 12105.
56. Truly Santika, Kerrie A. Wilson, Elizabeth A. Law, Freya A. V. St John, Kimberly M. Carlson, et al. (2020) Impact of palm oil sustainability certification on village well-being and poverty in Indonesia. Nat Sustain 4: 109-119.
57. J Tang, J Wang, X Feng (2024) Early warning systems and farmers' adaptation to extreme weather: Empirical evidence from the North China Plain. Mitig Adapt Strateg Glob Chang 29: 86.
58. J Hellin, E Fisher, M Taylor, S Bhasme, AM Loboguerrero (2023) Transformative adaptation: from climate-smart to climate-resilient agriculture. CABI Agric Biosci 4: 30.
59. Mauro Brum, Rafael S Oliveira, Jose Gutiérrez López, Julian Licata, Thomas Pypker, et al. (2021) Effects of irrigation on oil palm transpiration during ENSO-induced drought in the Brazilian Eastern Amazon. Agric Water Manag 245: 106569.
60. AM Kutcher, VT LeBaron (2022) A simple guide for completing an integrative review using an example article. J Prof Nurs 40: 13-19.
61. MH Oermann, KA Knafl (2021) Strategies for completing a successful integrative review. Nurse Author Ed 31: 65-68.
62. Parse (2023) Thematic Integrative Literature Reviews. Nurs Sci Q 36: 321-322.
63. Y Cho (2022) Comparing Integrative and Systematic Literature Reviews. Hum Resour Dev Rev 21: 147-151.

64. L Busetto, W Wick, C Gumbinger (2020) How to use and assess qualitative research methods. Neurol Res Pract 2: 14.
65. ME Kiger, L Varpio (2020) Thematic analysis of qualitative data: AMEE Guide No. 131. Med Teach 42: 846-854.
66. G Guest, E Namey, M Chen (2020) A simple method to assess and report thematic saturation in qualitative research. PLoS One 15: e0232076.
67. S Sloan, L Tacconi, ME Cattau (2021) Fire prevention in managed landscapes: Recent success and challenges in Indonesia. Mitig Adapt Strateg Glob Chang 26: 32.
68. F Watson-Hernández, V Serrano-Núñez, N Gómez-Calderón, R Pereira da Silva (2022) Quantification and Evaluation of Water Requirements of Oil Palm Cultivation for Different Climate Change Scenarios in the Central Pacific of Costa Rica Using APSIM. Agronomy 13: 19.
69. Fernan Santiago Mejía-Alvarado, Arley Fernando Caicedo-Zambrano, David Botero-Rozo, Leonardo Araque, Cristihian Jarri Bayona-Rodríguez, et al. (2024) Integrative Analysis of Transcriptomic Profiles and Physiological Responses Provide New Insights into Drought Stress Tolerance in Oil Palm (Elaeis guineensis Jacq.). Int J Mol Sci 25: 8761.
70. T Delgado, G Ladino, N Arias (2024) Evaluation of the Effect of Soil Water Conditions on the Development and Water Requirements of Adult Oil Palm (Elaeis guineensis Jacq.) in the Northern Region of Colombia. Agronomy 14: 9.
71. H Hayasaka (2023) Peatland Fire Weather Conditions in Sumatra, Indonesia. Climate 11: 92.
72. L Robins, L van Kerkhoff, Y Rochmayanto, N Sakuntaladewi, S Agrawal (2022) Knowledge systems approaches for enhancing project impacts in complex settings: community fire management and peatland restoration in Indonesia. Reg Environ Chang 22: 100.
73. Caroline Ward, Lindsay C Stringer, Eleanor Warren-Thomas, Fahmuddin Agus, Merry Crowson, et al. (2021) Smallholder perceptions of land restoration activities: rewetting tropical peatland oil palm areas in Sumatra, Indonesia. Reg Environ Chang 21: 1.
74. P Sofan, D Bruce, W Schroeder, E Jones,J Marsden (2020) Assessment of VIIRS 375 m active fire using tropical peatland combustion algorithm applied to Landsat-8 over Indonesia's peatlands. Int J Digit Earth 13: 1695-1716.
75. Lars Hein, Joseph V Spadaro, Bart Ostro, Melanie Hammer, Elham Sumarga, et al. (2022) The health impacts of Indonesian peatland fires. Environ Heal 21: 62.
76. R Belmin, M Paulin, E Malézieux (2023) Adapting agriculture to climate change: which pathways behind policy initiatives?. Agron Sustain Dev 43: 59.
77. Kyle M Dittmer, Sabrina Rose, Sieglinde S Snapp, Yodit Kebede, Sarah Brickman, et al. (2023) Agroecology Can Promote Climate Change Adaptation Outcomes Without Compromising Yield in Smallholder Systems. Environ Manage 72: 333-342.
78. RRM Paterson (2021) Longitudinal trends of future climate change and oil palm growth: empirical evidence for tropical Africa. Environ Sci Pollut Res 28: 21193-21203.
79. Lilik Budi Prasetyo, Yudi Setiawan, Aryo Adhi Condro, Kustiyo Kustiyo, Erianto Indra Putra, et al. (2022) Assessing Sumatran Peat Vulnerability to Fire under Various Condition of ENSO Phases Using Machine Learning Approaches. Forests 13: 828.