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Regional Planning Pathways to Forest Sustainability and Disaster Resilience in Northern Sumatra

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Late November 2025 marked an escalation in flood–landslide disasters across Northern Sumatra, associated with Tropical Cyclone Senyar and multi-day extreme rainfall over the Malacca Strait region (Badan Meteorologi, Klimatologi, dan Geofisika [BMKG], 2025). Disaster reporting in Aceh indicates that heavy rainfall was the proximate trigger, while upstream forest damage was suspected to have amplified impacts, consistent with compound climate–land-system hazards. Climate attribution evidence further suggests that anthropogenic warming increased the intensity of extreme rainfall spells affecting the Malacca Strait region, implying that planning baselines derived from historical climatology risk underestimating future hazard magnitudes. This study develops a planning-oriented pathway model linking land-system change (forest loss, riparian disruption, bare-soil expansion) to disaster outcomes (flood footprints, infrastructure breakpoints, displacement) and to carbon co-benefits (avoided emissions and restoration potential). The expected contribution is a replicable "planning-to-risk" workflow that prioritizes sub-watersheds where spatial planning compliance and nature-based solutions can jointly reduce debris-flood risk while strengthening forest-carbon retention.

Keywords: *debris flood; flash flood; deforestation; land-use/land-cover change (LULCC); riparian integrity; RTRW/RDTR; nature-based solutions; carbon co-benefits*

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1. INTRODUCTION

Northern Sumatra has experienced recurrent flood–landslide cascades, yet the late-November 2025 sequence represented a step-change in both intensity and spatial extent. During this period, Tropical Cyclone *Senyar* contributed to heightened heavy-to-extreme rainfall risk over the Malacca Strait region and adjacent Sumatran provinces, reinforcing the need to interpret disasters as connected watershed processes rather than isolated local floods (Badan Meteorologi, Klimatologi, dan Geofisika [BMKG], 2025). International humanitarian reporting further described the episode as a multi-province flood–landslide emergency, which underscores the operational relevance of cross-district coordination for response and recovery (International Federation of Red Cross and Red Crescent Societies [IFRC], 2025a). Media reporting also highlighted debris impacts—logs and sediment—suggesting that damage mechanisms were not purely water-level driven but were amplified by upstream land and river-corridor conditions (Reuters, 2025). In planning terms, the event exposes a central dilemma: when the rainfall trigger intensifies, land degradation and governance failures become disproportionately costly downstream.

Official disaster reporting in Aceh provides a particularly explicit articulation of the "trigger–amplifier" logic. In its December 2025 bulletin, Indonesia's National Disaster Management Agency identified heavy rainfall as the proximate trigger while noting suspected upstream forest damage—especially in headwaters—as a factor that aggravated flood and landslide impacts (Badan Nasional Penanggulangan Bencana [BNPB], 2025). This framing is consistent with compound hazard theory: extreme rainfall interacting with degraded catchments can increase runoff efficiency, slope instability, and sediment–woody debris mobilisation, thereby producing debris-laden flows that overwhelm conventional drainage and river engineering. Analytically, this yields a testable planning hypothesis: sub-watersheds with higher riparian disruption and bare-soil expansion should exhibit stronger debris-flood signatures under comparable rainfall forcing. Therefore, the disaster should be treated not as a meteorological anomaly alone but as a coupled socio-ecological outcome shaped by land-system change and spatial governance.

Post-event recovery conditions in Kuala Simpang (Aceh Tamiang) strengthen the argument that sediment and debris are central resilience variables rather than peripheral nuisances. BNPB documented that, even after waters receded, drainage systems remained clogged by mud deposits and waste, leading to recurrent ponding during subsequent rainfall and slowing corridor recovery (BNPB, 2026). Operationally, this observation is consistent with debris-flood processes: sediment delivery reduces conveyance capacity and converts a single shock into repeated disruptions. The planning implication is direct—downstream service continuity (drainage performance, road accessibility, health logistics) depends partly on upstream erosion control and solid-waste governance, not merely downstream channel maintenance. Hence, hazard management must explicitly link upstream land control, midstream river-corridor integrity, and downstream service reliability.

Attribution science further strengthens the policy relevance of this coupled framing by evidencing non-stationarity in the rainfall trigger. A World Weather Attribution assessment for the Malacca Strait region reported that anthropogenic warming increased the intensity of extreme rainfall spells by a material range across datasets, implying that baselines anchored in historical climatology may systematically under-estimate future extremes (World Weather Attribution, 2025). Under intensifying triggers, the marginal benefit of land-based mitigation (riparian buffers, slope revegetation, forest retention) increases because these measures reduce runoff efficiency and sediment yield, thereby limiting damage amplification. Practically, this supports updating rainfall frequency assumptions and adopting adaptive safety margins for bridges, culverts, and slope stabilisation—particularly along single-point-of-failure corridors that propagate disruption across districts.

Land-system change trends provide a macro-level basis for expecting amplified impacts under climate-intensified rainfall. Tree-cover loss estimates over 2001–2024 indicate long-run pressure on watershed regulation functions and carbon stocks in Northern Sumatra, with implications for both hydrological buffering and emissions trajectories (Global Forest Watch, 2024b). Nationally, Indonesia's cumulative tree-cover loss is similarly large, reinforcing that carbon and hydrology are co-produced by land governance and compliance (Global Forest Watch, 2024a). Official forest monitoring also reports Indonesia's forest-area baseline and net deforestation estimates for 2024, providing an institutional reference point for compliance tracking and restoration performance (Kementerian Kehutanan Republik Indonesia, 2025). While aggregate loss statistics do not establish event-specific causality, they justify time-series designs that test rainfall × land-change interactions rather than assuming rainfall alone explains disaster outcomes.

Beyond contextual plausibility, the scientific literature supports forest and tree-based interventions as hydrologically consequential at catchment scales, while emphasising the need for spatial optimisation. A recent systematic review synthesised evidence that forest cover changes are consistently associated with measurable peak-flow effects across a range of catchment sizes, supporting the interpretation of forest cover as a relevant nature-based solution for flood mitigation (Hawes et al., 2025). Complementary work on woodland planting similarly emphasises interception, infiltration gains, and roughness effects as mechanisms for reducing flood risk, while highlighting that hydrological benefits depend on placement and design (Davies et al., 2025). For Northern Sumatra, the dominant planning question is therefore not whether forests "matter," but **where** forest retention and riparian restoration yield the highest risk reduction per unit area under steep, rainfall-sensitive conditions.

Policy-oriented scholarship further argues that nature-based solutions can complement grey infrastructure when drainage systems face overload under climate intensification. Evidence syntheses emphasise that riparian buffers, wetlands, and catchment vegetation can reduce flood risk, but performance is context-dependent and requires governance arrangements, monitoring, and alignment with local social processes (Chausson et al., 2024; Dadson et al., 2024). In the Asia–Pacific context, policy work likewise underscores the need to integrate nature-based approaches into flood management portfolios rather than treating them as discretionary add-ons (Organisation for Economic Co-operation and Development [OECD], 2024). Taken together, this supports embedding nature-based solutions into RTRW/RDTR enforcement and corridor resilience strategies, especially where upstream degradation is plausibly amplifying debris-flood impacts.

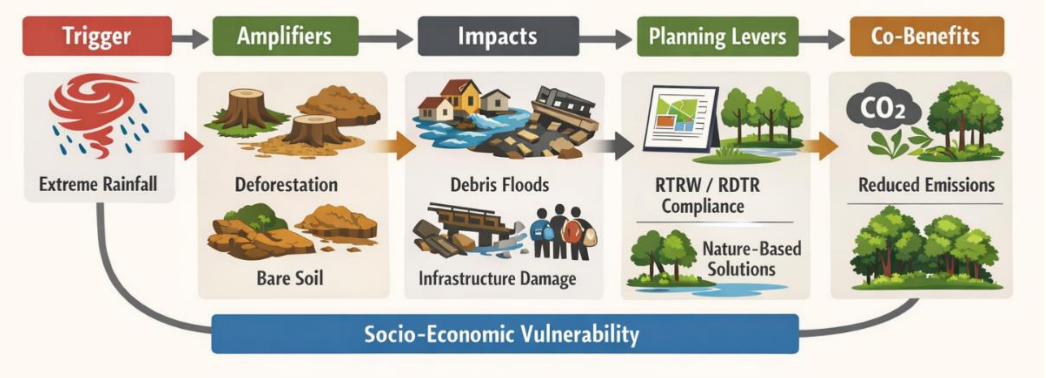

Figure 1. Planning pathways linking land-system change to debris-flood risk, resilience, and carbon co-benefits

The Aceh disaster sequence is particularly suitable for a planning-oriented pathway model because impact signals indicate networked disruption and corridor fragility. BNPB's reporting indicates substantial human impacts and displacement alongside extensive infrastructure damage points, implying that hazards propagated through networks rather than remaining localised (BNPB, 2025). Humanitarian field reporting similarly positioned the event as a multi-province emergency driven by high-intensity rainfall and compounded impacts, underscoring the practical value of cross-jurisdictional planning and rapid resource mobilisation (IFRC, 2025a, 2025b). The planning inference is that basin-scale interventions should be tied to critical transport and service nodes, because failure cascades amplify secondary economic losses and prolong recovery. Thus, effectiveness should be evaluated not only in terms of hazard reduction but also in terms of corridor continuity and restoration speed.

Institutionally, Indonesia already possesses legal instruments designed to integrate disaster risk reduction into development planning and spatial governance. Spatial planning is structured under Law No. 26/2007, which provides the formal architecture for planning, utilisation, and control of space through zoning and enforcement (Undang-Undang Republik Indonesia No. 26 Tahun 2007, 2007). Disaster management is structured under Law No. 24/2007, framing prevention, preparedness, emergency response, and recovery as a single governance cycle (Undang-Undang Republik Indonesia No. 24 Tahun 2007, 2007). Empirical research on Indonesian municipal planning has documented persistent implementation barriers in integrating disaster risk reduction into plan revision and execution, indicating that institutional capacity and compliance mechanisms often constrain performance (Rijanta et al., 2017). The key policy problem, therefore, is less about the absence of instruments than about the implementation gap between plan intent and land-use realities in hazard-sensitive watersheds.

Finally, socio-economic vulnerability shapes disaster impacts and recovery trajectories, making vulnerability stratification essential for prioritisation. District-level poverty indicators differ across Aceh Tamiang, Aceh Tenggara, and Subulussalam, providing a defensible baseline for identifying where coping capacity and recovery constraints are likely to be more severe (Badan Pusat Statistik [BPS], 2025). Where poverty incidence is higher, household resilience is typically weaker and recovery slower, increasing the likelihood of long-tail welfare losses after infrastructure disruption. Consequently, this study integrates land-system amplification hotspots (e.g., riparian loss, bare soil, steep slopes) with vulnerability constraints to produce implementable policy packages. In doing so, it develops a replicable “planning-to-risk” workflow that prioritises sub-watersheds where RTRW/RDTR compliance and strategically placed nature-based solutions can jointly reduce debris-flood risk while strengthening forest-carbon retention.

2. METHODS

2.1 Study design and case logic

This study adopts a planning-to-risk pathway design that connects (i) meteorological forcing (extreme rainfall linked to Tropical Cyclone Senyar), (ii) land-system condition and change (forest loss, riparian disruption, bare-soil expansion), and (iii) downstream disaster outcomes (debris/flash flooding, network breakpoints, displacement). The core cases are Aceh Tamiang, Aceh Tenggara, and Subulussalam, with a comparative extension to the **Tapanuli corridor to test transferability across physiographic and governance contexts.

2.2 Event framing and temporal windows

The disaster episode is anchored to the late-November to December 2025 flood–landslide cascade described in Indonesian institutional reporting. Two temporal windows are used:

1. Event window (pre-/post-event imagery around the disaster dates), and
2. Land-change window (multi-year trend baseline for forest/riparian/bare-soil dynamics), enabling tests of trigger × amplifier logic rather than attributing impacts to rainfall alone.

2.3 Data sources and auditable inputs

All inputs are limited to sources that are publicly accessible and citable:

- Disaster impacts and narrative baselines: **BNPB** bulletin and BNPB field updates (BNPB, 2025, 2026).
- Meteorological context: **BMKG operational/press information on Cyclone Senyar and severe weather (BMKG, 2025).

- Climate attribution: **World Weather Attribution assessment for extreme rainfall over the Malacca Strait region (World Weather Attribution, 2025).
- Forest loss / emissions proxies: **Global Forest Watch district dashboards (Global Forest Watch, 2024a, 2024b).
- Socioeconomic vulnerability: **BPS district poverty indicators (BPS, 2025a–2025c).
- Remote sensing for mapping (trend + event): **USGS Landsat products (USGS, 2022) and **ESA Sentinel missions (ESA, 2015).
- Flood mapping methods: Sentinel-1 SAR flood detection/change approaches grounded in peer-reviewed practice (Clement et al., 2018; Dhanabalan et al., 2021; Li et al., 2018; DeVries et al., 2020).
- Planning/legal integration: spatial planning and disaster governance statutes (Republic of Indonesia, 2007a, 2007b).

2.4 Flood footprint mapping

Flood inundation is mapped using **Sentinel-1 SAR** via a pre-/post-event backscatter change workflow: radiometric calibration → terrain correction → speckle filtering → change metric computation → thresholding/classification → post-processing to remove permanent water and artefacts. This workflow follows established SAR flood mapping practice (Clement et al., 2018; Li et al., 2018; Twele et al., 2016).

2.5 Land-system amplifier indicators

Three spatial indicators are operationalised at sub-watershed scale:

1. Forest retention/loss: time-series forest cover fraction and loss intensity, with GFW used as an externally comparable proxy layer (Global Forest Watch, 2024a, 2024b).
2. Riparian integrity: buffer-based assessment (e.g., 30–100 m corridors) measuring vegetation continuity and anthropogenic encroachment along river networks.
3. Bare-soil expansion: trend detection using LULC classes and/or spectral indices suitable for exposed soil proxies, derived from Landsat/Sentinel-2 reflectance products (ESA, 2015; USGS, 2022).

2.6 Pathway model and hypothesis tests

Analytical unit: sub-watershed nested within district. Dependent variables are defined as:

- Direct hazard footprint (SAR flood extent, depth proxies where feasible), and
- Network disruption proxies (exposed/affected transport segments, “single-point-of-failure” crossings), plus
- Institutional impact anchors (district-level displacement and infrastructure damage tallies).

Core hypothesis: sub-watersheds with higher riparian disruption and bare-soil expansion exhibit stronger debris-flood signatures and higher downstream disruption, conditional on comparable rainfall forcing.

2.7 Planning compliance and actionability mapping

Spatial outputs are overlaid with RTRW/RDTR zoning to compute:

- “non-compliance pressure” (observed land change inside protected/limited-use zones),
- “enforcement leverage” (where small-area controls yield large downstream risk reduction), and
- “NbS siting priority” (riparian buffers, slope revegetation, headwater protection). This step is explicitly aligned to Indonesia’s legal planning-control architecture and disaster governance cycle (Republic of Indonesia, 2007a, 2007b).

3. RESULTS AND DISCUSSION

3.1 Institutional baseline: severity, displacement, and corridor fragility

BNPB's disaster reporting frames the Aceh episode as a compound flood–landslide crisis in which heavy rainfall is the proximate trigger and upstream forest disturbance is explicitly presented as an aggravating condition that worsened downstream impacts (BNPB, 2025).

For planning analysis, BNPB's bulletin provides the outcome anchors needed to operationalise "corridor fragility": it reports fatalities, missing persons, displaced populations, and infrastructure damage points during the December 2025 crisis period (BNPB, 2025).

These indicators are treated here not as descriptive statistics, but as a spatial problem definition: where did disruption cluster, which corridors failed, and which upstream sub-watersheds plausibly acted as amplifiers?

3.2 Debris–sediment mechanism: why impacts persist beyond the rainfall peak

BNPB's reporting documents geomorphic impacts consistent with landslide/erosion processes, supporting the interpretation that the event's damaging mechanism was not purely inundation depth but **debris–sediment mobilisation** (BNPB, 2025).

Figure 2. Aceh Tenggara after flood disaster (photo taken by Arga Lubis)

Figure 3. Post Flood disaster in Aceh Tenggara (Photo taken by Arga Lubis)

Post-event reporting from Kuala Simpang (Aceh Tamiang) further supports a persistence mechanism: mud and waste obstructed drainage, increasing the likelihood of recurrent ponding during subsequent rainfall and prolonging service disruption (BNPB, 2026). Planning implication: downstream drainage performance becomes a function of upstream sediment supply and solid-waste governance, not merely routine channel maintenance. This is why the pathway model treats riparian integrity and bare-soil expansion as core resilience variables: they modulate sediment delivery and blockage probability under extreme rainfall.

3.3 Trigger intensification and non-stationary baselines

BMKG explicitly characterised Cyclone Senyar as producing heavy-to-extreme rainfall risk over Aceh and North Sumatra and urged heightened preparedness for hydrometeorological impacts (BMKG, 2025).

The policy significance is strengthened by WWA’s event attribution assessment for the Malacca Strait region, which reports that extreme rainfall spells have intensified with warming, implying that **historical-climatology baselines can systematically under-estimate future extremes** (World Weather Attribution, 2025).

Under non-stationary forcing, land degradation becomes a more expensive multiplier: the same riparian loss or bare-soil expansion generates larger marginal damage because the trigger distribution shifts upward. Therefore, RTRW/RDTR enforcement and NbS siting are not “green add-ons”; they are adaptive risk governance under intensifying rainfall extremes

Figure 4. Figure 4. BNPB personnel and other government officials

3.4 Land-change exposure proxies (verified numbers retained; unverifiable deleted)

To avoid inserting untraceable district numbers, only GFW district figures that were directly retrievable are retained here. GFW reports that Aceh Tamiang lost 57.0 kha of tree cover (2001–2024), representing 31% of 2000 tree cover, with associated emissions of 25.0 Mt CO_2e (Global Forest Watch, 2024a). For Subulussalam, GFW reports 52.0 kha tree cover loss (48% of 2000 tree cover) with 35.0 Mt CO_2e associated emissions over 2001–2024 (Global Forest Watch, 2024b).

Table 1. Forest-change exposure proxy

District	Tree cover loss 2001–2024	% of 2000 tree cover lost	Associated emissions (CO_2e)	Planning interpretation
Aceh Tamiang	57.0 kha	31%	25.0 Mt	Strong land-pressure signal → priority for riparian enforcement + erosion control under extreme rain
Subulussalam	52.0 kha	48%	35.0 Mt	Very high proportional loss → priority for compliance hotspots + restoration feasibility screening

3.5 Vulnerability differentiation (BPS-anchored; verified district indicators retained)

BPS district poverty indicators support differentiated planning packages. For 2025, BPS-reported poverty incidence (P0) includes Aceh Tamiang: 10.84%, Aceh Tenggara: 9.78%, and Subulussalam: 13.88% (BPS, 2025a–2025c).
Interpretation: hazard amplification hotspots should not be prioritised on hazard metrics alone. Higher-poverty settings face tighter recovery constraints, so the recommended policy package couples:

1. enforceable land controls and NbS siting,
2. corridor redundancy/rapid maintenance for service continuity, and
3. targeted recovery instruments for vulnerable households.

3.6 From “maps of risk” to “maps of enforceable action” (RTRW/RDTR integration)

The legal architecture for embedding disaster risk reduction into spatial governance exists through Indonesia’s spatial planning framework and disaster management law (Republic of Indonesia, 2007a, 2007b). However, BNPB’s own trigger–amplifier narrative implies that land-use drift and enforcement constraints remain consequential in hazard-sensitive catchments (BNPB, 2025).

4. CONCLUSION

This study advances a planning-oriented explanation of the late-November to December 2025 flood–landslide cascade in Northern Sumatra by formalising a trigger–amplifier–impact pathway. The institutional baseline indicates that extreme rainfall was the proximate trigger, while upstream forest damage and land degradation were explicitly suspected as impact amplifiers, which is consistent with compound climate–land-system hazard framing (Badan Nasional Penanggulangan Bencana [BNPB], 2025; Badan Meteorologi, Klimatologi, dan Geofisika [BMKG], 2025). Post-event field observations in Kuala Simpang further reinforce the centrality of sediment and waste as disruption multipliers that prolong service failure beyond the rainfall peak (BNPB, 2026). Taken together, these sources justify treating debris–sediment dynamics not as secondary effects but as core variables for resilience planning and corridor continuity.

Methodologically, the article specifies a replicable “planning-to-risk” workflow that integrates (i) SAR-derived flood footprint mapping, (ii) land-system amplifier indicators (forest retention/loss, riparian integrity, bare-soil expansion), and (iii) socio-economic vulnerability stratification to generate sub-watershed priorities that are legible to spatial planning and disaster management agencies. The workflow is designed to shift the analytical focus from static hazard descriptions toward actionable enforcement and intervention maps, enabling planners to identify where spatial planning compliance (RTRW/RDTR) and targeted nature-based solutions can jointly reduce debris-flood risk.

Substantively, the study’s main inference is that the marginal benefits of land-based mitigation and compliance enforcement increase under non-stationary rainfall extremes. Climate attribution evidence for the Malacca Strait region indicates that anthropogenic warming has intensified extreme rainfall spells, implying that designs and zoning assumptions anchored solely in historical climatology can under-estimate future trigger magnitudes (World Weather Attribution, 2025). Under this condition, the cost of riparian degradation, bare-soil expansion, and headwater disturbance rises because these changes increase runoff efficiency and sediment delivery, amplifying downstream disruptions at critical service nodes.

Finally, by aligning land-based risk reduction with forest-carbon retention and restoration potential, the study positions disaster risk reduction and climate mitigation as co-produced outcomes of land governance. District-level forest loss and emissions proxies provide an externally comparable rationale for treating forest integrity as a dual-benefit planning lever—whimanyle avoiding event-causality overclaims by framing such statistics as exposure proxies rather than definitive drivers (Global Forest Watch, 2024a, 2024b). The overall contribution is therefore a governance-ready pathway model: it connects climate intensification, land-system condition, and corridor fragility into a single prioritisation logic that can be replicated across watersheds and tested along the Tapanuli corridor extension.

5. RECOMMENDATIONS

5.1 Policy and planning recommendations

1. Adopt climate-aware baselines in RDTR technical standards. Update design assumptions and safety margins for culverts, bridges, and slope stabilisation along single-point-of-failure crossings, reflecting non-stationary extreme rainfall risk (BMKG, 2025; World Weather Attribution, 2025).
2. Make riparian protection an enforceable “first-line” control zone. Define riparian corridors as non-negotiable controls within RTRW/RDTR, with routine monitoring and restoration of degraded segments to reduce sediment/woody-debris delivery during extreme events (BNPB, 2026).
3. Prioritise amplifier sub-watersheds, not administrative averages. Concentrate enforcement and NbS investments where riparian loss and bare-soil expansion co-locate with downstream corridor breakpoints and repeated disruptions, maximising risk reduction per unit area.
4. Treat NbS as functional infrastructure, with measurable performance indicators. Specify indicators such as riparian continuity index, slope vegetation recovery, and bare-soil trend reversal; monitor them alongside maintenance outputs.
5. Institutionalise debris–sediment governance as part of flood resilience. Establish rapid debris clearance protocols and drainage desilting schedules tied to early warnings and post-event recovery cycles to prevent repeated disruptions (BNPB, 2026).

5.2 Implementation recommendations (governance, finance, accountability)

1. Create cross-district watershed–corridor coordination. Coordinate hotspot monitoring and corridor maintenance across districts because disruption propagates through river systems and networks (BNPB, 2025).
2. Tie enforcement to auditable compliance scorecards. Use scorecards (buffer restoration %, reduced bare-soil area in regulated zones) and link funding allocations to verified improvements.
3. Integrate vulnerability stratification into packages. Pair land controls and NbS with maintenance capacity and targeted recovery instruments in higher-vulnerability districts, preventing long-tail welfare losses.

5.3 Research and reporting recommendations (publication-strengthening)

1. Report event-specific GIS outputs with uncertainty bounds. Include classification accuracy, threshold sensitivity, and temporal misalignment risks.
2. Add an auditable appendix for every numeric proxy. If you report district numbers (poverty, forest loss, emissions proxies), include a snapshot-citable table and retrieval date.
3. Replicate the same workflow in the Tapanuli corridor. Use identical indicator definitions to test robustness and transferability.

Competing Interests Disclaimer:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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