A Single Puma's Shadow

Fear-Mediated Trophic Cascades and the Minimum Viable Size of Suburban Preserves

A dynamical-model assessment of whether encouraging apex predators into small suburban preserves is a credible restoration strategy — written for park managers and conservation journalists.

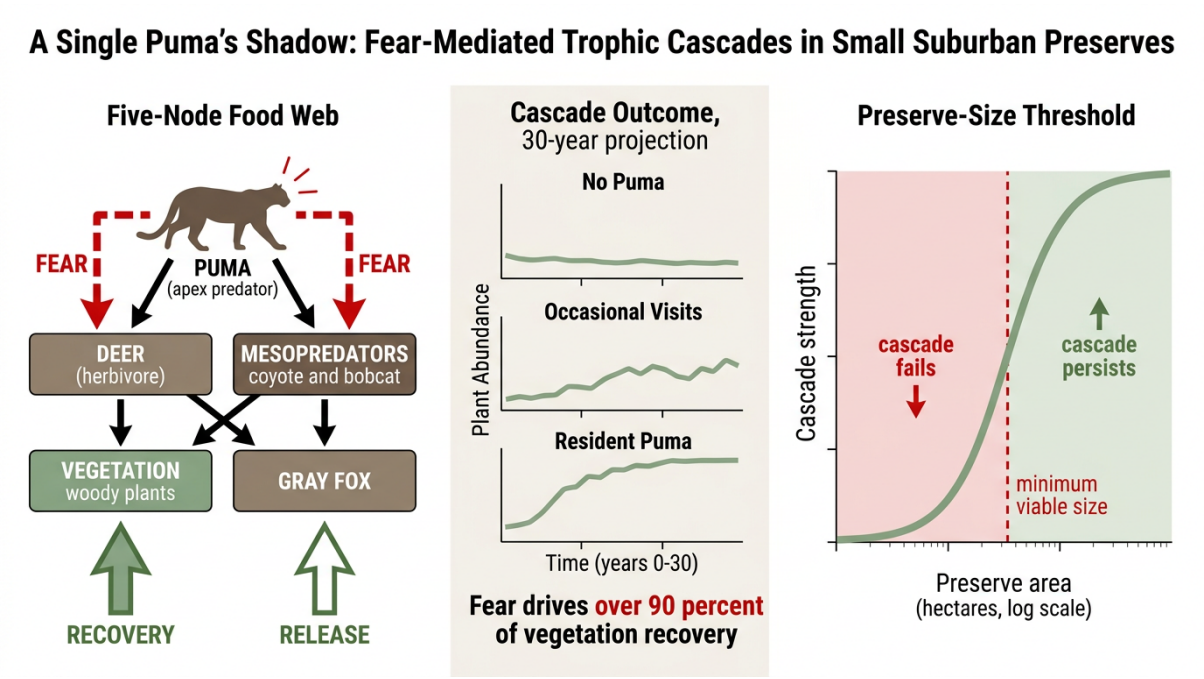

Figure 1. Graphical abstract. A five-node food web links the apex predator (puma) to deer, mesopredators (coyote, bobcat), gray fox, and woody vegetation. Solid arrows are consumption; red dashed arrows are the non-consumptive "landscape of fear" pathway. As puma presence rises from absent, to occasional visits, to an established resident, woody vegetation recovers and gray foxes are released, while mesopredators decline. Whether this cascade fires at all depends on preserve area: below a minimum viable size the cascade fails, and above it the cascade persists.

1 Executive Summary and Key Takeaways

In 2026, ecologists reported that the return of a *single* mountain lion (*Puma concolor*) to a small suburban nature preserve in the San Francisco Bay Area was followed by measurable, community-wide change: deer and mesopredators became less active by day and shifted their activity away from the predator, and the density of woody plants increased over the study window [24]. That observation crystallises a question park managers now face across fragmented, human-dominated landscapes: *is deliberately encouraging apex predators into small suburban preserves a credible ecological restoration strategy, or is the preserve simply too small for the effect to take hold?*

This brief answers that question with a transparent, reproducible dynamical model rather than anecdote. We built a five-node predator–prey food web calibrated to a California oak-woodland / chaparral preserve, projected it over 30 years under three puma regimes (no pumas, occasional transient visits, and an established resident), decomposed the mechanism driving any

cascade into lethal predation versus fear, and stress-tested the whole system against preserve size and habitat-edge effects. The model reproduces the documented "no-puma" signature — released deer, dominant mesopredators, suppressed foxes, and over-browsed vegetation — before any predator is introduced, which gives us confidence that its response to predator return is meaningful.

Four findings stand out. First, a *resident* puma can genuinely flip a degraded preserve: in our calibrated system woody vegetation rises by 223% relative to the predator-free baseline, gray foxes increase by 320%, mesopredator abundance falls by 65%, and total browsing pressure drops by 55%. Second, the engine of this recovery is *fear, not killing*: paired counterfactual simulations attribute more than 91% of both the vegetation and gray-fox response to the non-consumptive, behaviourally-mediated pathway, consistent with experimental demonstrations that the mere perception of a predator can cascade through a food web [23, 25]. Third, *occasional visits are not a substitute for residency*: a roving puma that passes through intermittently delivers only partial recovery (vegetation +49%, foxes +166%) and, in our simulations, never restores vegetation or foxes to even half of their full-residency ceiling. Fourth, and most important for planning, *preserve size is decisive*. Below roughly 400–500 ha the cascade fails outright regardless of puma regime, because edge-subsidised mesopredators remain dominant and gray foxes stay suppressed. A resident puma needs on the order of 1,000 ha to return foxes halfway and about 1,600 ha to return vegetation halfway within 30 years.

Bottom line for decision-makers. Encouraging apex predators is a credible restoration lever, but a *conditional* one. Its power comes from re-instating a landscape of fear, so it acts fastest on mobile animals (foxes recover in ∼1.5–3 years) and slowest on vegetation (partial in years, full recovery beyond a 30-year horizon). The strategy pays off primarily where a preserve is large enough — or, more realistically, *connected* enough to a larger habitat network — to support a resident predator rather than the occasional visitor. For a preserve of only a few hundred hectares, predator return should be expected to shift mammal behaviour and mesopredator balance (as reported at the Bay Area site) without, on its own, delivering deep vegetation recovery. The realistic management goal is landscape connectivity and large protected cores, not the small fragment as a stand-alone predator refuge.

The remainder of this brief documents the model and its equations (Section 2), the 30-year scenario projections (Section 3), the quantitative cascade-strength and recovery-time analysis (Section 4), the preserve-size tipping points and edge-effect stress tests (Section 5), and actionable recommendations with an explicit statement of assumptions and uncertainty (Section 6).

2 Ecological Food-Web Framework and Dynamical Model Equations

2.1 The five interacting nodes

We represent the preserve community with five state variables whose interactions capture the two routes by which a returning apex predator can restructure an ecosystem (Figure 2). The apex predator (P) is the puma; the large herbivore (D) is black-tailed / mule deer (*Odocoileus hemionus*); the mesopredator guild (M) is coyote and bobcat (*Canis latrans*, *Lynx rufus*); the small carnivore (F) is the gray fox (*Urocyon cinereoargenteus*); and the basal resource (V) is the woody-vegetation browse layer (oak recruitment and chaparral). This structure is deliberately chosen to embed two classical phenomena at once: a herbivore-mediated *green* cascade (puma → deer → vegetation) and *mesopredator release* of a fragmentation-sensitive small carnivore (puma → mesopredator → fox), the latter being the canonical outcome of apex-predator loss in fragmented Californian landscapes [6, 14, 19].

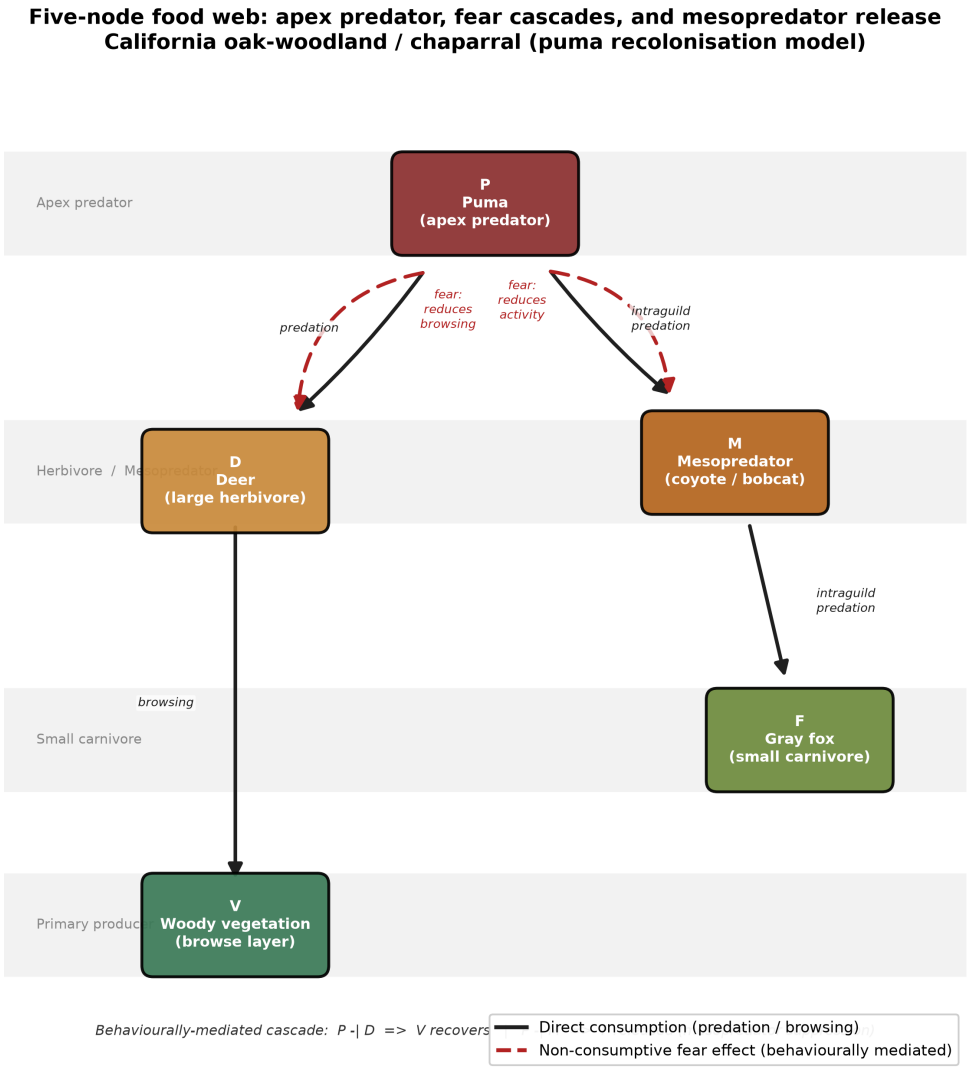

Figure 2. Five-node food-web structure. Solid black arrows denote direct consumption (Holling Type II functional responses): puma→deer and puma→mesopredator (a shared multi-prey response), deer→vegetation (browsing), and mesopredator→fox (intraguild predation). Red dashed arrows denote the non-consumptive "fear" pathway: puma presence lowers deer browsing efficiency (releasing vegetation) and lowers mesopredator activity and reproduction (releasing gray foxes). The behaviourally-mediated cascade $P \dashv D \Rightarrow V$ operates even when the predator kills almost nothing.

2.2 Governing equations

The community evolves according to five coupled ordinary differential equations (state ordered P, D, M, F, V). Direct feeding links use saturating Holling Type II functional responses [10], and the predator's attack on its two prey shares a single handling-time denominator (a multi-prey Type II response):

$$\frac{dV}{dt} = r_V\,V\!\left(1-\frac{V}{K_V}\right) - g_{DV}\,D, \tag{1}$$

$$\frac{dD}{dt} = e_{DV}\,g_{DV}\,D - m_D\,D - f_{PD}\,P, \tag{2}$$

$$\frac{dM}{dt} = r_M\,\mu_M\,M - \frac{r_M}{K_M}M^2 + e_{MF}\,g_{MF}\,M - f_{PM}\,P, \tag{3}$$

$$\frac{dF}{dt} = r_F\,F\!\left(1-\frac{F}{K_F}\right) - g_{MF}\,M, \tag{4}$$

$$\frac{dP}{dt} = e_{PD}\,f_{PD}\,P + e_{PM}\,f_{PM}\,P - m_P\,P, \tag{5}$$

with the per-capita interaction terms

$$g_{DV} = \mu_D(P)\,\frac{a_{DV}\,V}{1+a_{DV}h_{DV}V}, \qquad g_{MF} = \mu_M(P)\,\frac{a_{MF}\,F}{1+a_{MF}h_{MF}F}, \tag{6}$$

$$f_{PD} = \frac{a_{PD}\,D}{1+a_{PD}h_{PD}D+a_{PM}h_{PM}M}, \qquad f_{PM} = \frac{a_{PM}\,M}{1+a_{PD}h_{PD}D+a_{PM}h_{PM}M}. \tag{7}$$

The heart of the model is the pair of *fear multipliers* that couple the predator's mere presence to prey behaviour,

$$\mu_D(P) = \frac{1}{1+\beta_D P}, \qquad \mu_M(P) = \frac{1}{1+\beta_M P}, \tag{8}$$

which reduce deer browsing efficiency and mesopredator activity/reproduction as puma pressure P rises. This is the mathematical expression of the "landscape of fear" [8, 11, 15] and follows the now-standard approach of building anti-predator behaviour directly into predator–prey dynamics [28]. Because μ_M also multiplies the mesopredator's own predation on foxes (g_{MF}), fear both suppresses mesopredators and eases their pressure on foxes, so gray-fox release in this model is itself largely fear-driven.

2.3 Parameterisation and the no-predator baseline

Rates are per year and densities are relative indices loosely scaled to the per-km^2 figures reported for Bay Area and Santa Cruz Mountains preserves; the parameter set (Table 1) is order-of-magnitude calibrated to reproduce the documented qualitative predator-free signature rather than fit to a single time series. With the predator absent ($P = 0$), the fear multipliers equal one and the system settles to a single, globally stable equilibrium (Table 2): deer are released to a high density, mesopredators are dominant (exceeding their own reference carrying capacity through the fox subsidy), gray foxes are suppressed to roughly a fifth of their ceiling, and vegetation is held at roughly a quarter of its potential by chronic over-browsing. All six qualitative checks that define this degraded, mesopredator-dominated baseline are satisfied. This is precisely the state that apex-predator loss produces in the real fragmentation literature [6, 7, 27], which is why we treat it as the honest starting point against which any restoration must be measured.

Two modelling choices deserve emphasis. First, the deer–vegetation interaction is deliberately kept in the stable regime: because $1/(a_{DV}h_{DV}) = 250$ exceeds $K_V = 100$, the prey isocline declines monotonically over the biologically relevant range, so the system does not exhibit the destabilising limit cycles of the paradox of enrichment [21, 22]. Second, in the calibrated parameter set the puma's own per-capita growth rate at baseline prey densities is negative ($e_{PD}f_{PD} + e_{PM}f_{PM} - m_P \approx 0.124 - 0.20 < 0$), so a locally prey-limited puma cannot self-establish. This is realistic for a wide-ranging carnivore whose local presence is set by regional

territory and dispersal dynamics rather than by local prey [1, 2]. We therefore treat puma density as an externally prescribed pressure $P(t)$ and integrate the four responding layers with the identical equations above; the three management scenarios differ only in the temporal pattern of $P(t)$.

Table 1. Baseline parameter set (per-year rates; densities are relative indices). Fear coefficients β_D, β_M set the strength of the landscape-of-fear response and are the model's most consequential — and least directly measured — parameters.

Symbol	Meaning	Value	Symbol	Meaning	Value
r_V	vegetation growth rate	1.0	a_{MF}	meso attack on fox	0.23
K_V	vegetation ceiling	100	h_{MF}	meso handling (fox)	0.15
a_{DV}	deer attack on veg.	0.02	e_{MF}	meso conversion (fox)	0.20
h_{DV}	deer handling (veg.)	0.20	r_F	fox growth rate	1.5
e_{DV}	deer conversion (veg.)	0.40	K_F	fox ceiling	10
m_D	deer mortality	0.20	a_{PD}	puma attack on deer	0.05
r_M	meso growth rate	1.0	h_{PD}	puma handling (deer)	0.80
K_M	meso ceiling	5.0	e_{PD}	puma conversion (deer)	0.15
m_P	puma mortality	0.20	a_{PM}	puma attack on meso	0.10
β_D	deer fear coefficient	1.5	h_{PM}	puma handling (meso)	0.50
β_M	meso fear coefficient	2.0	e_{PM}	puma conversion (meso)	0.10

Table 2. Predator-free ($P = 0$) baseline equilibrium — a single global attractor reached from eight random starts. This over-browsed, mesopredator-dominated state is the starting condition for every restoration scenario.

Node	Variable	Equilibrium	Interpretation
Deer	D	40.12	high — herbivore released (no apex predation)
Mesopredator	M	5.47	dominant — 109% of its reference ceiling K_M
Gray fox	F	2.20	suppressed — 22% of its ceiling K_F
Vegetation	V	27.78	over-browsed — 28% of its ceiling K_V

3 Thirty-Year Scenario Projections

3.1 Three puma regimes

We integrate the community for 30 years from the predator-free baseline under three regimes of the exogenous puma pressure $P(t)$. In **Scenario A (no pumas)** the predator is permanently absent, $P(t) = 0$; this scenario is a control that must — and does — remain exactly at baseline, validating the numerical engine. In **Scenario B (occasional visits)** a roving, non-resident puma passes through intermittently: visits arrive as a Poisson process (rate drawn per realisation between 1 and 2 per year), each lasting a uniformly random 2–6 months, during which $P = 1$ and otherwise $P = 0$. Because this regime is stochastic, we run 50 Monte-Carlo realisations and report the ensemble mean and 95% confidence interval; across the ensemble a typical trajectory sees about 27 visits over 30 years (mean rate $1.47\,\mathrm{yr}^{-1}$, mean occupancy 0.39). In **Scenario C (resident puma)** an established animal maintains constant pressure $P = 1$. The chosen pressure makes βP of order one, so the landscape-of-fear effect is ecologically meaningful ($\mu_D \approx 0.40$, $\mu_M \approx 0.33$ at $P = 1$). All scenarios are integrated segment-by-segment with a stiff solver (LSODA, rtol $= 10^{-8}$, atol $= 10^{-10}$) so that the step discontinuities in $P(t)$ at visit boundaries remain solver-safe, and a fixed random seed guarantees reproducibility.

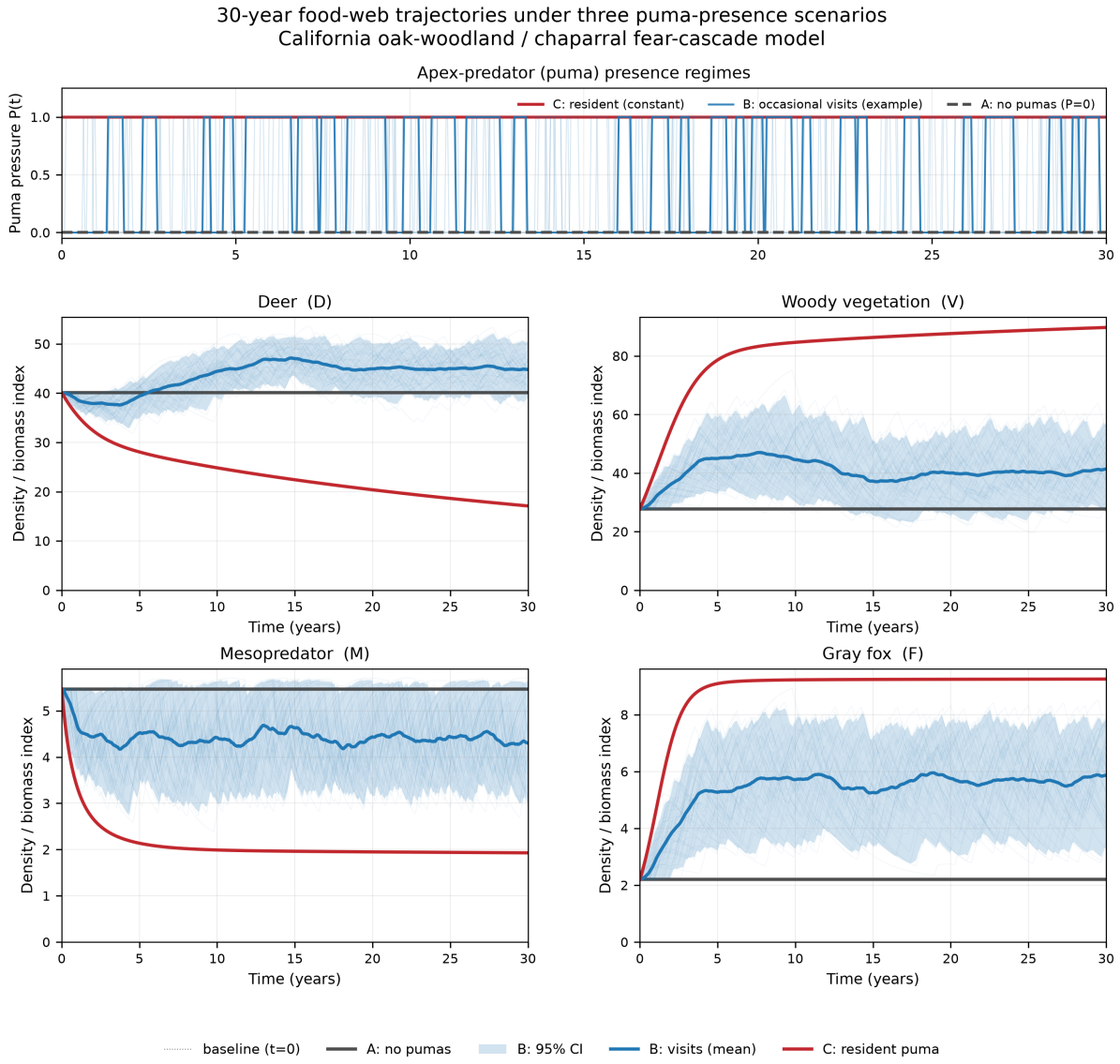

Figure 3. Thirty-year trajectories under the three puma regimes. Top strip: the prescribed puma-pressure signal $P(t)$ — flat zero (A, grey dashed), stochastic pulses (B, blue), and constant residency (C, red). Panels: deer (D), woody vegetation (V), mesopredators (M) and gray fox (F). Scenario B is shown as the Monte-Carlo mean (blue) with its 95% confidence band; Scenario C is the deterministic red curve. A clean, monotonic $A \to B \to C$ gradient of vegetation and fox recovery with mesopredator decline is the signature of a behaviourally-mediated trophic cascade plus mesopredator release.

3.2 What the trajectories show

The projections (Figure 3, endpoints in Table 3) reveal a clean, monotonic gradient of ecological recovery as puma presence intensifies from A to B to C. Under residency (C), deer fall from 40.1 to 17.1 as the combination of direct predation and, more importantly, fear-driven reductions in foraging take hold; released from chronic browsing, woody vegetation more than triples, climbing from 27.8 toward its ceiling at 89.7. Simultaneously the mesopredator guild is pushed down from 5.47 to 1.93, and the gray fox — freed from intraguild predation — more than quadruples from 2.20 to 9.25, approaching its own ceiling. This dual response, a green cascade to the vegetation and a mesopredator-release cascade to the small carnivore, mirrors the field evidence that cougars can drive herbivore-mediated recovery of woody plants [3] and that apex predators structure mesopredator and small-carnivore communities in fragmented California habitats [6, 19].

The occasional-visit regime (B) is the most policy-relevant, because it is what a small, poorly connected preserve is most likely to receive. Here the community responds, but only partially and in pulses: vegetation rises to about 41 and the gray fox to about 5.9 on average, with wide confidence bands reflecting the luck of the visitation draw. Notably, mean deer abundance in Scenario B actually edges *upward* (to 44.8) rather than down — transient fear pulses briefly depress browsing and let the deer's own resource base (and thus the deer) grow between visits, without the sustained mortality and fear that residency imposes. This is a concrete illustration that a predator glimpsed now and then is ecologically very different from a predator that lives there. It also cautions against reading a single early field observation as evidence of a durable cascade: apparent recoveries can be transient, context-dependent, or confounded, as re-analyses of even the most famous cascades have shown [4, 12].

Table 3. Thirty-year endpoint densities (Scenario B is the Monte-Carlo mean). Every scenario begins at the predator-free baseline in the first column.

Node	Baseline ($t = 0$)	A: no pumas	B: visits (mean)	C: resident
Deer D	40.12	40.12	44.79	**17.10**
Mesopredator M	5.47	5.47	4.30	**1.93**
Gray fox F	2.20	2.20	5.87	**9.25**
Vegetation V	27.78	27.78	41.41	**89.73**

4 Quantitative Cascade Strength and Recovery Time

4.1 How strong is the cascade?

A trophic cascade, in its modern synthesis, is the downward propagation of indirect effects from predators through a food web, arising either from consumption of prey or from prey responses to perceived risk [17]; our indices are designed to capture exactly this signature. To make the recovery comparable across scenarios we express each 30-year endpoint as a relative change from the common predator-free baseline (Table 4, Figure 4A). The contrast is stark. A resident puma produces a 223% gain in vegetation, a 320% release of gray foxes, a 65% reduction in mesopredators, and a 55% reduction in total browsing pressure. Occasional visits achieve a meaningful but far smaller cascade: 49% more vegetation, 166% more foxes, and only a 21% mesopredator reduction with a 6% browsing reduction. The no-puma control sits, as it must, at exactly zero on every index. The magnitude ordering $A < B < C$ holds for every response variable, and the gap between B and C is large — residency is not merely "more of the same" as visitation, it is a qualitatively deeper restructuring of the food web.

Table 4. Cascade-strength and mesopredator-release indices at 30 years (relative change versus the predator-free baseline).

Index	A (no puma)	B (visits, mean)	C (resident)
Vegetation gain $\Delta V/V_0$	0%	+49.1%	**+223.0%**
Gray-fox release $\Delta F/F_0$	0%	+166.3%	**+319.8%**
Mesopredator reduction $-\Delta M/M_0$	0%	+21.4%	**+64.8%**
Browsing-pressure reduction	0%	+6.1%	**+55.0%**

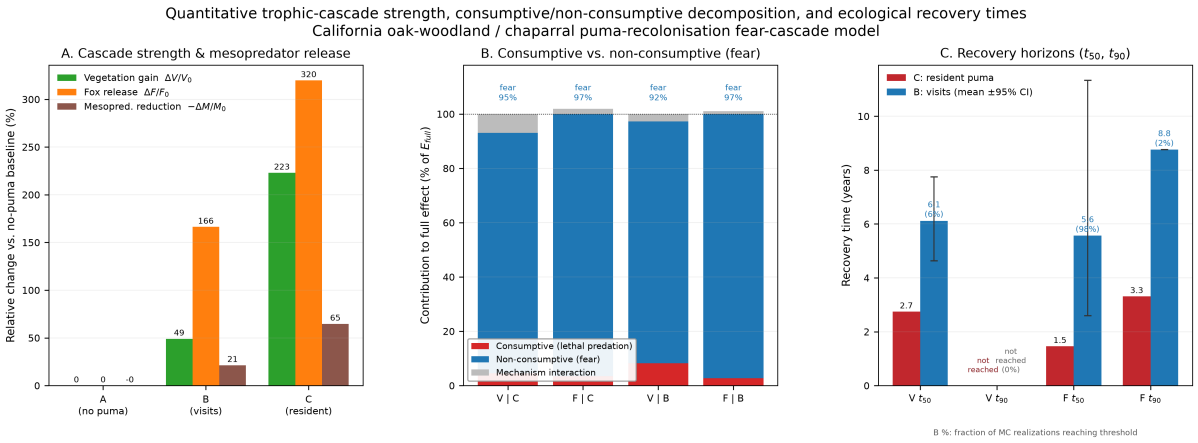

Figure 4. Cascade strength, mechanism decomposition, and recovery horizons. (A) Relative change versus baseline for vegetation gain, fox release, and mesopredator reduction across the three scenarios. (B) Paired counterfactual decomposition of the vegetation (V) and gray-fox (F) responses into consumptive (lethal predation), non-consumptive (fear), and interaction contributions; the fear share exceeds 91% in every case. (C) Recovery horizons: time to reach 50% (t_{50}) and 90% (t_{90}) of the resident-puma equilibrium ceiling; percentages for Scenario B give the fraction of Monte-Carlo realisations that reach each threshold.

4.2 Fear, not killing, drives the recovery

The most important scientific result for interpreting real observations is the mechanism decomposition (Figure 4B). We ran paired counterfactual simulations that switch single mechanisms off under identical visitation schedules: a *density-only* world with fear disabled ($\beta_D = \beta_M = 0$, leaving only lethal predation) and a *fear-only* world with predation disabled ($a_{PD} = a_{PM} = 0$, leaving only the behavioural response). Comparing each against the full model, and carrying an explicit interaction term because the two mechanisms are not additive, yields an unambiguous verdict: the non-consumptive fear pathway accounts for 95% of the resident-puma vegetation response and 97% of the gray-fox response, with lethal predation contributing only a few percent (Table 5). The same dominance holds under occasional visits. In other words, in this system the predator restructures the community mainly by frightening its prey into foraging less and moving differently, not by killing enough animals to thin their numbers. This is exactly the mechanism that controlled experiments have isolated — fear of a large carnivore, even without lethal contact, is sufficient to cascade to lower trophic levels [25] — and it is consistent with field work showing that California pumas alter their own and their prey's behaviour under human-induced fear [13, 23, 29, 31].

This mechanistic insight matters for managers because it explains *why* the effect can appear quickly and at low predator density: a single animal, or even the intermittent scent and sign of one, can reshape prey behaviour far out of proportion to the number of kills it makes. It is the plausible mechanism behind the rapid mammal-behaviour shifts reported when one puma returned to a Bay Area preserve [24].

Table 5. Mechanism decomposition of the 30-year vegetation and gray-fox responses (share of the full-model effect). Fear is the dominant driver throughout.

Scenario	Response	Consumptive (lethal)	Non-consumptive (fear)	Interaction
C — resident	Vegetation V	4.9%	**95.1**%	+7.0%
C — resident	Gray fox F	3.4%	**96.6**%	−1.9%
B — visits	Vegetation V	8.5%	**91.5**%	+2.8%
B — visits	Gray fox F	2.6%	**97.4**%	−1.1%

4.3 How long until recovery?

Speed of recovery differs sharply between the mobile animal and the slow-growing plants (Figure 4C), measured as the time to reach 50% (t_{50}) and 90% (t_{90}) of the resident-puma equilibrium ceiling ($V \to 100$, $F \to 9.3$). Under residency (C), the gray fox rebounds fast — half-recovery in about 1.5 years and 90% recovery in about 3.3 years — because its release is behavioural and its intrinsic growth rate is high. Vegetation is far slower: it reaches half of its ceiling in about 2.7 years, but the final approach is protracted and it does not reach 90% within the 30-year horizon. This asymmetry is ecologically honest — browse layers, oak recruitment, and woody biomass accumulate over decades, and even celebrated large-carnivore restorations show woody recovery playing out over many years and constrained by other factors such as hydrology and herbivore history [12, 16, 18]. Under occasional visits (B), the picture is bleaker still: the fox half-recovery threshold is reached in 98% of realisations (mean ∼5.6 years) but almost no realisation reaches 90%, and the vegetation half-recovery threshold is essentially never reached. Transient visitation buys partial, reversible gains; it does not deliver the sustained recovery that residency does.

5 Preserve-Size Tipping Points and Edge-Effect Stress Testing

5.1 Why size changes everything

The scenarios above assume a preserve large enough for the intrinsic community dynamics to play out. Real suburban preserves are small and edge-dominated, and it is well established that small fragments lose apex predators first, become subsidised havens for mesopredators, and drive edge-sensitive small carnivores toward local extinction [5, 6, 9, 30]. To test whether predator return can *reverse* that fragmentation syndrome, we added an explicit preserve-area dimension A (in hectares) on top of the verified community model, without altering any of the core equations. Area enters through four physically motivated channels. First, edge/core geometry: a square preserve of area A has an interior core $A_{\text{core}} = (\sqrt{A} - 2e)^2$ after subtracting an edge buffer of depth $e \approx 200\,\text{m}$, so the interior fraction $\phi = A_{\text{core}}/A$ collapses in small preserves. Second, carrying-capacity scaling: vegetation and fox ceilings are interior-favouring and degrade toward an edge floor as ϕ falls, while the mesopredator ceiling is *edge-subsidised* and inflates in fragments. Third, fox edge mortality: an extra loss term $m_F^{\text{edge}} = \varepsilon(1 - \phi)$ injects matrix and boundary mortality on gray foxes near small-preserve edges. Fourth, and crucially, the puma forcing itself scales with area: the transient-visit rate saturates with size, $\lambda(A) = \lambda_{\max} A^n/(A_{\text{half}}^n + A^n)$, and the probability of supporting a resident follows a logistic function of $\log_{10} A$ centred near 1,200 ha — capturing the basic fact that a wide-ranging carnivore needs a large area (or connectivity to one) to reside [1, 2, 30].

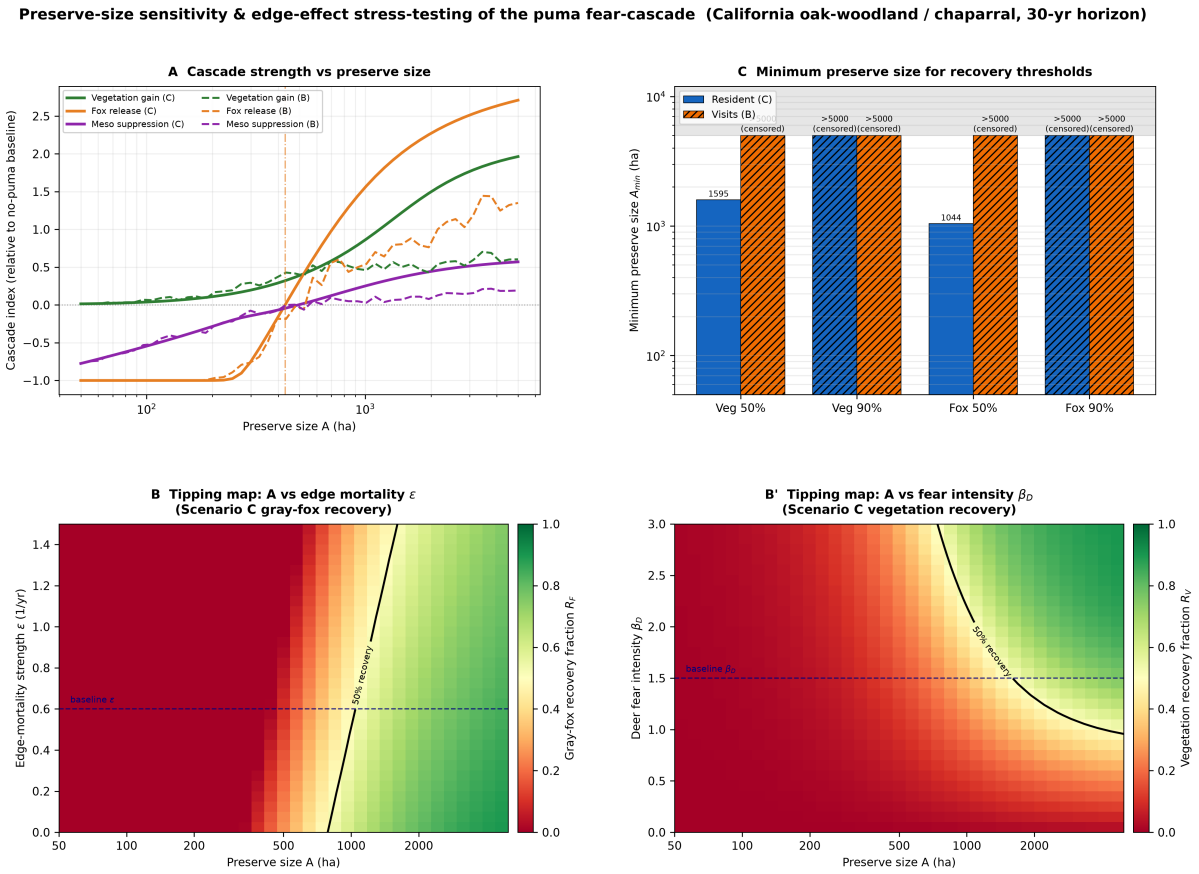

Figure 5. Preserve-size sensitivity and edge-effect stress tests (30-year horizon). (A) Cascade indices versus preserve area for resident (solid) and visiting (dashed) pumas; the cascade is negligible in small preserves and strengthens with size. (B) Gray-fox recovery across the joint space of preserve area and fox edge-mortality ε — stronger edge mortality pushes the minimum viable size upward. (B′) Vegetation recovery across preserve area and deer-fear intensity β_D — a stronger landscape of fear pulls the minimum viable size downward. (C) Minimum preserve size $A_{\min}$ to reach 50% and 90% vegetation and fox recovery; hatched bars mark thresholds not reached within the tested range (censored beyond 5,000 ha).

5.2 The tipping points

Sweeping preserve area from 50 to 5,000 ha reveals sharp thresholds rather than a gentle gradient (Figure 5A, Table 6). Below roughly **400–500 ha** the cascade fails almost entirely under any puma regime: edge-subsidised mesopredators remain dominant, gray-fox release stays at or below zero, and there is no vegetation recovery to speak of. The first thing to turn positive as preserves grow is the sign of the mesopredator and fox response — a resident puma flips fox release positive at about 430 ha and mesopredator suppression positive at about 494 ha. But flipping the sign is not the same as delivering recovery. To restore gray foxes to half of their ceiling a resident puma needs about **1,044 ha**, and to restore vegetation to half its ceiling it needs about **1,595 ha**. The 90% thresholds for both vegetation and foxes are not reached anywhere within the tested range at 30 years — consistent with the Section 4 finding that even full residency leaves vegetation short of 90% at three decades. Occasional visits never reach any 50% recovery threshold at any preserve size we tested; a visiting puma can nudge the mesopredator and fox balance in preserves above ∼440–530 ha, but it cannot substitute for residency at any size.

Table 6. Critical preserve-size thresholds $A_{\min}$ (30-year horizon). "Censored" means the threshold is not reached within the tested range of 50–5,000 ha.

Threshold	Resident puma (C)	Occasional visits (B)
Positive fox release ($\Delta F/F_0 > 0$)	**430 ha**	531 ha
Mesopredator suppression ($-\Delta M/M_0 > 0$)	**494 ha**	441 ha
50% gray-fox recovery	**1,044 ha**	> 5,000 ha (censored)
50% vegetation recovery	**1,595 ha**	> 5,000 ha (censored)
90% gray-fox recovery	> 5,000 ha (censored)	> 5,000 ha (censored)
90% vegetation recovery	> 5,000 ha (censored)	> 5,000 ha (censored)

5.3 Stress-testing the thresholds

Because these thresholds depend on the two least-certain parts of the model — how badly edges kill foxes (ε) and how strongly deer respond to fear (β_D) — we mapped the recovery surface across both (Figure 5B, B′). The two levers move the tipping point in opposite and intuitive directions. Stronger fox edge mortality pushes the fox minimum viable size *upward*: over the tested range the fox 50% threshold shifts from roughly 790 ha (benign edges) to about 1,610 ha (harsh edges), because more edge loss demands a larger protected interior to compensate. Conversely, a stronger deer landscape of fear pulls the vegetation minimum viable size *downward*, from well over 3,500 ha when fear is weak to about 740 ha when fear is strong — a more potent behavioural response achieves the browsing-release cascade in a smaller preserve. This is the single most actionable sensitivity in the whole analysis: the effectiveness of predator restoration in small preserves hinges on how frightening the predator actually is to deer, and on how permeable (or lethal) the surrounding matrix is to foxes. The structural implication mirrors the fragmentation literature: apex predators fail first in small, edge-dominated, poorly connected fragments [6, 7, 9, 27, 30], and reversing that syndrome is chiefly a problem of area and connectivity, not of the predator's intrinsic ecological potential.

6 Management Recommendations and Uncertainty Bounds

6.1 What this means for decisions

Translating the analysis into guidance, the central message is that predator return is a credible restoration lever whose payoff is strongly conditional on scale and permanence. **Treat residency, not visitation, as the objective.** Every result shows a large gap between the pulsed, partial, reversible gains of an occasional visitor and the deep restructuring a resident predator delivers; management that produces only intermittent visitation should expect only intermittent benefits. **Prioritise area and connectivity over the isolated fragment.** Because a wide-ranging carnivore cannot self-establish on local prey in a small preserve, the practical route to residency is a large protected core or — far more achievable in suburban settings — robust corridors linking the preserve into a network large enough to sustain a home range, an approach the fragmentation and reserve-design literature has long endorsed [1, 2, 9, 30]. This emphasis on total protected area and connectivity should nonetheless be applied as a functional target rather than a rigid cut-off, since networks of smaller, well-connected patches can also carry substantial conservation value and inflexible minimum-patch-size rules risk discarding it [20]. **Set expectations by trophic level and time.** Managers and journalists should anticipate rapid, visible shifts in mammal behaviour and mesopredator/fox balance within a few years — exactly the kind of early signal reported at the Bay Area preserve [24] — but should treat deep woody-vegetation recovery as a multi-decadal outcome that a 30-year horizon may only partly reveal. **Manage**

the edge and the matrix, not just the predator. Since fox recovery is throttled by edge mortality and vegetation recovery is amplified by a strong landscape of fear, complementary actions — reducing hard edges, limiting matrix mortality of small carnivores, and minimising human disturbance that blunts the predator's fear effect [13, 23, 26, 29] — can lower the effective minimum viable size. **Do not oversell a single observation.** The prudent posture, given how readily transient or confounded signals can masquerade as durable cascades [4, 12], is to pair any predator-return program with monitoring designed to distinguish a temporary behavioural blip from a sustained cascade.

6.2 Assumptions, limitations, and uncertainty bounds

Honesty about what the model does and does not represent is essential for a decision brief. The state variables are relative indices, not absolute densities, and the parameter set is order-of-magnitude calibrated to reproduce the documented predator-free signature rather than fitted to a specific preserve's time series; the numbers should be read as internally consistent comparisons across scenarios, not as site-specific forecasts. The community core is deterministic and treats a single, well-mixed preserve; real preserves have spatial structure, and we approximate it only through the aggregate edge/core geometry of Section 5. The puma is prescribed as an exogenous forcing because it cannot self-establish on local prey — a defensible simplification that nonetheless means we do not model puma population dynamics, dispersal, or the genetic and demographic "extinction vortex" risks that threaten isolated cougar populations in southern California [1, 2]. The landscape-of-fear coefficients β_D and β_M are the model's most influential and least directly measured parameters; the Section 5 stress tests exist precisely because the tipping points move substantially with them (the vegetation minimum viable size ranges from about 740 to over 3,500 ha as deer fear varies, and the fox minimum viable size from about 790 to 1,610 ha as edge mortality varies). The stochastic visitation results carry real spread: the Scenario B ensemble recovery fraction is 0.19 (95% CI −0.01 to 0.40) for vegetation and 0.51 (95% CI 0.17 to 0.80) for foxes, so the "partial recovery" verdict for visitation is robust to visitation luck. Finally, the 30-year horizon censors the slow tail of woody recovery, so vegetation t_{90} values and the corresponding 90% preserve-size thresholds are lower bounds; a longer simulation would resolve them but would not change the qualitative ordering.

6.3 Conclusion

Encouraging apex predators into a degraded landscape can, in principle, restart a powerful, fear-driven trophic cascade that recovers vegetation and releases suppressed small carnivores — and it can do so quickly for mobile animals and largely through behaviour rather than killing. But for the small suburban preserve, the honest answer is qualified. A few hundred hectares is generally too small for the cascade to take hold on its own, and it is far too small to host the resident predator that the deepest recovery requires; the intermittent visitor such a preserve is likely to receive delivers only partial, reversible gains. The strategy becomes credible when the preserve is embedded in a habitat network large and connected enough to support a resident predator and to buffer its edges. Predator restoration, in short, is not a small-fragment quick fix but a landscape-scale commitment — and, framed that way, it is one of the most ecologically leveraged investments a conservation program can make.

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