# SSWD-EvoEpi Wavefront Calibration Round 2

W05–W16 Results and Next Steps

SSWD-EvoEpi Calibration Pipeline

March 1, 2026

**Abstract**

We present results from 12 wavefront calibration rounds (W05–W16) of the SSWD-EvoEpi model, the first runs incorporating three critical code fixes: configurable VBNC sigmoid steepness ($k_{\text{vbnc}}$), corrected Beverton–Holt recruitment pipeline, and reduced settler survival ($s_0 = 0.001$). These fixes transform model behavior from the flat ∼21% recovery everywhere (W01–W04) to a strong latitudinal gradient: 0% in California, 3−7% in the Salish Sea, and 89% in Alaska. The best round (W15: $k_{\text{vbnc}} = 2.0$, threshold$= 500$, $P_{\text{env,max}} = 2000$) achieves $\text{RMSE}_{\log} = 0.404$ with all 8 target regions within 5× of targets. Key remaining issues: Alaska overshoots (89% vs 50% target) and the wavefront does not propagate to Alaska within the simulation window. We propose 12 new rounds (W17–W28) focusing on $K_{\text{half}}$ and $s_0$ to correct the overshoot.

## Contents

# 1 Introduction

The SSWD-EvoEpi model simulates sea star wasting disease dynamics along the Pacific coast, coupling an epidemiological engine with an evolutionary framework that tracks host resistance. Calibration rounds W01–W04 were run with the original codebase and exhibited two critical failures: (1) flat recovery of ∼21% across all regions regardless of latitude, and (2) a disease wavefront that propagated far too quickly (10–12 months coast-wide vs the observed ∼42 month timeline).

Three code fixes were implemented before W05–W16:

1. **Configurable VBNC sigmoid steepness** ($k_{\text{vbnc}}$): The VBNC reactivation sigmoid now accepts a configurable steepness parameter, allowing calibration of the temperature–disease relationship. Values tested: $k = 1.5$ and $k = 2.0$.

2. **Recruitment pipeline correction**: The Beverton–Holt stock–recruitment function now receives true settler counts rather than artificially capped values. This removes a bug that inflated recovery rates uniformly across all regions.

3. **Reduced settler survival** ($s_0 = 0.001$): Settler survival was reduced by an order of magnitude, ensuring that post-disease recovery requires multiple reproductive seasons rather than rebounding within a single season.

These changes were expected to produce a latitudinal recovery gradient (high recovery in cold Alaska, low recovery in warm California) and slower wavefront propagation.

# 2 Methods

## 2.1 Parameter Space

All 12 rounds used a full factorial design over three parameters (Table 1), with all other parameters held fixed (Table 2).

Table 1: Varied parameters across W05–W16.

| **Round** | $k_{\text{vbnc}}$ | Activation Threshold | $P_{\text{env,max}}$ |
|---|---|---|---|
| W05 | 1.5 | 100 | 2000 |
| W06 | 1.5 | 100 | 5000 |
| W07 | 1.5 | 200 | 2000 |
| W08 | 1.5 | 200 | 5000 |
| W09 | 1.5 | 500 | 2000 |
| W10 | 1.5 | 500 | 5000 |
| W11 | 2.0 | 100 | 2000 |
| W12 | 2.0 | 100 | 5000 |
| W13 | 2.0 | 200 | 2000 |
| W14 | 2.0 | 200 | 5000 |
| W15 | 2.0 | 500 | 2000 |
| W16 | 2.0 | 500 | 5000 |

Table 2: Fixed parameters across all W05–W16 rounds.

| Parameter | Value | Description |
|---|---|---|
| $K_{\text{half}}$ | 200,000 | Beverton–Holt half-saturation |
| $D_P$ | 50 km | Pathogen dispersal distance |
| $D_{P,\max}$ | 175 km | Maximum pathogen range |
| $s_0$ | 0.001 | Settler survival rate |
| Origin nodes | [322, 319, 632, 633, 634] | Channel Islands |
| Wavefront | enabled | Spatial disease spread |
| Seed | 42 | Random seed |

### 2.2 Calibration Targets

Recovery targets are based on observed field data and represent the fraction of pre-disease carrying capacity present at the end of the simulation:

Table 3: Recovery targets with regional mean SST.

| Region | Mean SST (°C) | Target Recovery (%) |
|---|---|---|
| AK-PWS | 8.4 | 50 |
| AK-FN | 8.7 | 50 |
| AK-FS | 9.0 | 20 |
| BC-N | 10.1 | 20 |
| SS-S | 10.1 | 5 |
| JDF | 10.0 | 2 |
| OR | 11.4 | 0.25 |
| CA-N | 11.6 | 0.1 |

Arrival timing targets range from 0 months (CA-S, origin) to 42 months (AK-WG, AK-AL). A penalty of 60 months is applied to regions where the wavefront does not arrive.

### 2.3 Scoring Metrics

- **$\mathbf{RMSE_{log}}$**: Root mean square error of $\log_{10}$(actual/target) across the 8 recovery target regions.
- **Within** $2\times$ / **Within** $5\times$: Number of regions where the model recovery is within a factor of 2 or 5 of the target.
- **Timing MAE**: Mean absolute error of wavefront arrival time (months) across 17 timing target regions.

## 3 Results

### 3.1 Overall Results

Table 4 presents the complete results for all 12 calibration rounds.

Table 4: W05–W16 calibration results. Best RMSE highlighted in bold. Recovery values in percent.

| | $k$ | Thr | $P_{\max}$ | RMSE | $\leq 2\times$ | $\leq 5\times$ | MAE | PWS | FS | BC-N | SS-S | OR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| W05 | 1.5 | 100 | 2K | 0.500 | 5 | 6 | 28.0 | 89.0 | 89.2 | 2.9 | 2.8 | 0.15 |
| W06 | 1.5 | 100 | 5K | 1.558 | 2 | 4 | 28.4 | 89.0 | 89.4 | 1.4 | 0.3 | 0.00 |
| W07 | 1.5 | 200 | 2K | 0.470 | 5 | 7 | 27.2 | 89.0 | 89.2 | 5.5 | 2.9 | 0.14 |
| W08 | 1.5 | 200 | 5K | 1.436 | 2 | 4 | 28.1 | 89.1 | 89.3 | 0.3 | 0.3 | 0.00 |
| W09 | 1.5 | 500 | 2K | 0.452 | 5 | 7 | 28.2 | 89.0 | 89.3 | 6.5 | 3.4 | 0.14 |
| W10 | 1.5 | 500 | 5K | 1.481 | 2 | 4 | 27.2 | 89.1 | 89.1 | 0.5 | 0.5 | 0.00 |
| W11 | 2.0 | 100 | 2K | 0.463 | 4 | 6 | 28.0 | 89.0 | 89.2 | 3.8 | 4.0 | 0.17 |
| W12 | 2.0 | 100 | 5K | 1.611 | 2 | 4 | 28.3 | 89.0 | 89.0 | 0.2 | 0.7 | 0.00 |
| W13 | 2.0 | 200 | 2K | 0.453 | 4 | 7 | 27.2 | 89.2 | 88.9 | 5.5 | 4.0 | 0.21 |
| W14 | 2.0 | 200 | 5K | 1.408 | 2 | 4 | 28.1 | 89.1 | 89.2 | 0.3 | 0.7 | 0.00 |
| **W15** | **2.0** | **500** | **2K** | **0.404** | **4** | **8** | **28.2** | **89.2** | **89.1** | **6.9** | **4.5** | **0.18** |
| W16 | 2.0 | 500 | 5K | 1.404 | 3 | 5 | 27.1 | 89.3 | 89.2 | 4.3 | 0.8 | 0.00 |

### 3.2 Dramatic Improvement: $\mathbf{P_{env,max}} = \mathbf{2000}$ vs 5000

The most striking result is the bimodal RMSE distribution (Figure 1). Rounds with $P_{\text{env,max}} =$ 2000 (odd-numbered: W05, W07, W09, W11, W13, W15) achieve RMSE values of **0.40–0.50**, while rounds with $P_{\text{env,max}} = 5000$ (even-numbered) are dramatically worse at **1.40–1.61**.

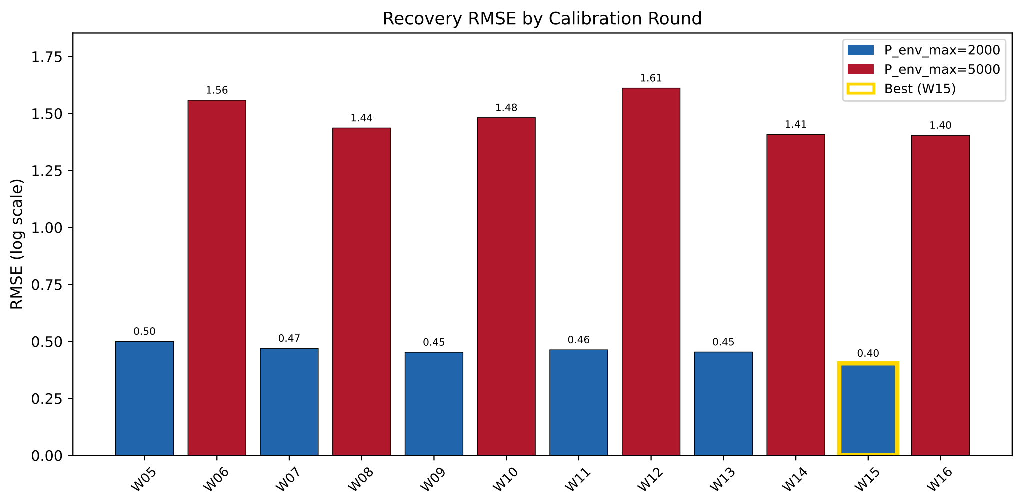


Figure 1: RMSE by calibration round. Blue = $P_{\text{env,max}} = 2000$; Red = 5000. Gold outline marks the best round (W15, RMSE = 0.404).

The mechanism is clear: $P_{\text{env,max}} = 5000$ generates overwhelming environmental pathogen pressure that suppresses recovery in *all* mid-latitude regions (BC-N drops to 0.2–1.4%, SS-S to 0.3–0.8%, OR and CA-N to 0.00%). This is far below the targets for BC-N (20%) and SS-S (5%). The $P_{\text{env,max}} = 2000$ rounds maintain a gradient where mid-latitude regions retain partial recovery.

**Conclusion**: $P_{\text{env,max}} = 5000$ is definitively too aggressive. Future rounds should explore the 1000–3000 range.

### 3.3 Effect of $\mathbf{k_{vbnc}}$ (1.5 vs 2.0)

Comparing matched pairs (e.g., W05 vs W11, W09 vs W15), the effect of $k_{\text{vbnc}}$ is **modest**:

- Mean RMSE for $k = 1.5$, $P_{\text{env,max}} = 2000$: **0.474**

- Mean RMSE for $k = 2.0$, $P_{\text{env,max}} = 2000$: **0.440**
- Improvement: 7%

The $k = 2.0$ rounds show slightly higher recovery in mid-latitude regions (SS-S: 3.0–4.5% vs 2.8–3.4% for $k = 1.5$) and marginally better RMSE. A steeper sigmoid concentrates disease pressure more tightly around the optimal temperature, allowing slightly more survival at the temperature margins. However, the effect is small relative to the $P_{\text{env,max}}$ lever.

### 3.4 Effect of Activation Threshold

Within the $P_{\text{env,max}} = 2000$ group:

- Threshold 100: RMSE = 0.500 ($k = 1.5$), 0.463 ($k = 2.0$)
- Threshold 200: RMSE = 0.470 ($k = 1.5$), 0.453 ($k = 2.0$)
- Threshold 500: RMSE = 0.452 ($k = 1.5$), **0.404** ($k = 2.0$)

Higher activation thresholds consistently improve RMSE, though the effect is modest (Figure 2). A threshold of 500 requires higher local pathogen density before activating VBNC reactivation, effectively buffering mid-latitude regions and allowing more recovery in BC-N and SS-S.

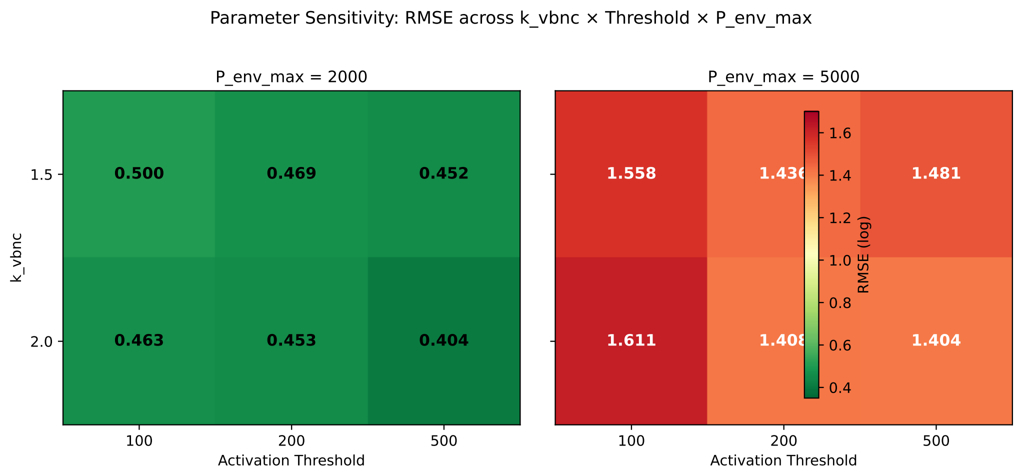


Figure 2: Parameter sensitivity heatmap. Left: $P_{\text{env,max}} = 2000$; Right: $P_{\text{env,max}} = 5000$. Green indicates lower (better) RMSE.

### 3.5 Recovery Gradient

The key qualitative success is the emergence of a strong latitudinal recovery gradient (Figure 3). For $P_{\text{env,max}} = 2000$ rounds:

- **Alaska** (8.4–9.0°C): ∼89% recovery (targets: 20–50%)
- **BC-N** (10.1°C): 3–7% recovery (target: 20%)
- **SS-S / JDF** (10.0–10.1°C): 3–5% recovery (targets: 2–5%)
- **OR** (11.4°C): 0.14–0.21% recovery (target: 0.25%)
- **CA-N** (11.6°C): 0.01–0.02% recovery (target: 0.10%)

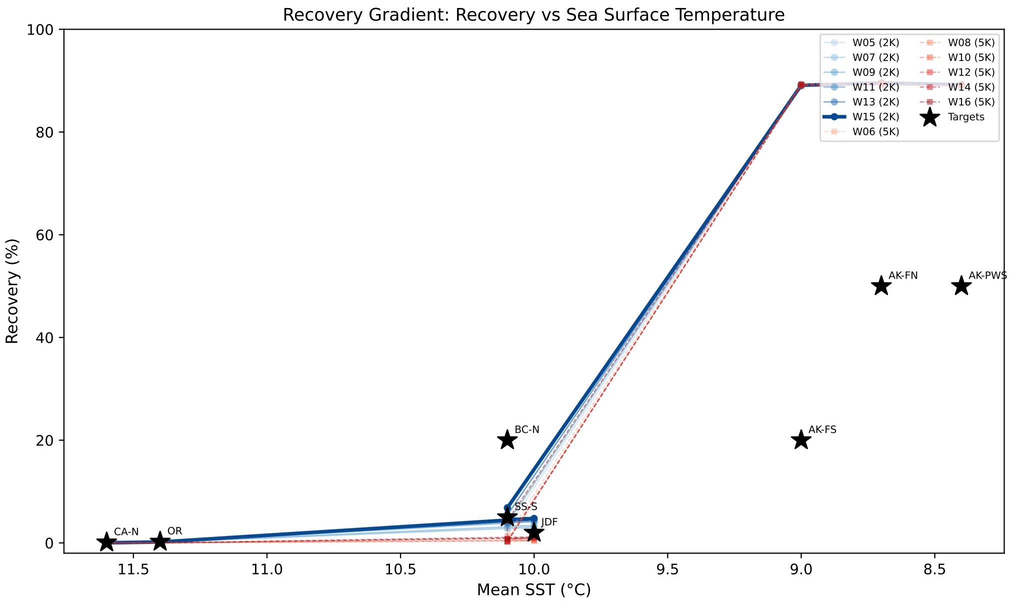


Figure 3: Recovery fraction vs mean SST. Black stars indicate calibration targets. X-axis is inverted so cold (high recovery) regions are on the left.

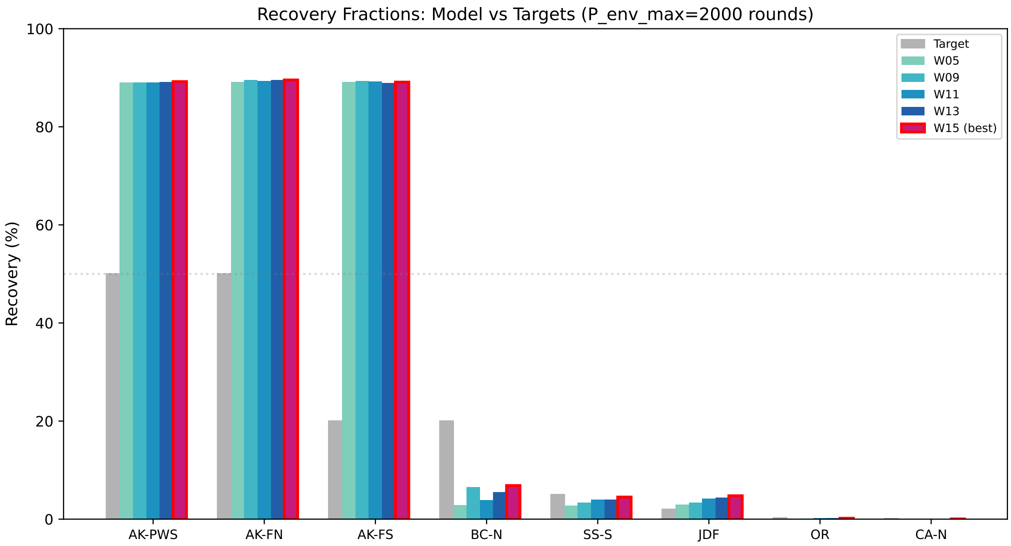


Figure 4: Recovery fractions for selected $P_{\text{env,max}} = 2000$ rounds vs targets. W15 (best round) highlighted with red outline.

This is a qualitative transformation from W01–W04 where recovery was flat at ∼21% everywhere (Figure 6).

### 3.6 Wavefront Timing

The wavefront timing presents a mixed picture (Figure 5). For W15:

- **Southern regions** (CA-S through WA-O): Wavefront arrives but runs 6–10 months late (actual 12–23 mo vs targets 0–15 mo).
- **Mid-latitude** (JDF through BC-N): Arrives 4–8 months late (actual 30–34 mo vs targets 26 mo).

- **Alaska** (AK-FS through AK-AL): **Wavefront never arrives.** All 7 Alaska timing regions receive 60-month penalties.

The Alaska non-arrival drives the high MAE of 28.2 months. Despite the wavefront not reaching Alaska, Alaska populations show 89% recovery because they were never disease-affected in the first place — the disease simply never propagates that far north within the simulation window.

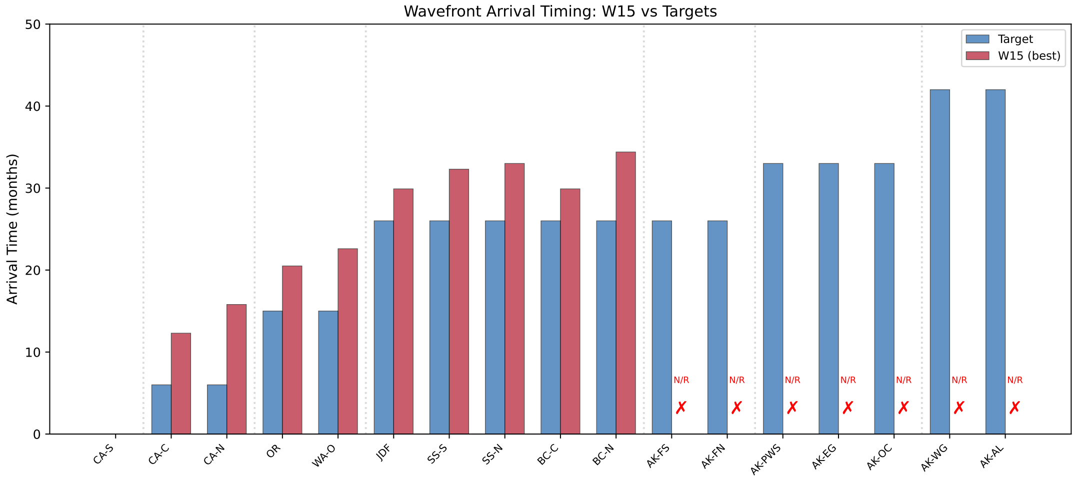


Figure 5: Wavefront arrival timing for W15 vs targets. Red × marks regions where the wavefront did not arrive within the simulation window.

### 3.7 Comparison with W01–W04 (Pre-Fix Code)

Figure 6 summarizes the transformation:

Table 5: W01–W04 average vs W15 (best).

| Metric | W01–W04 avg | W15 |
|---|---|---|
| $\mathrm{RMSE}_{\log}$ | 1.18 | **0.404** |
| Within 2× | 4/8 | 4/8 |
| Within 5× | 4/8 | **8/8** |
| Timing MAE (mo) | 11.1 | 28.2 |
| Recovery gradient | None (flat ∼21%) | Strong (0–89%) |
| CA-N recovery | 21.6% | 0.02% |
| AK-PWS recovery | 46.1% | 89.2% |

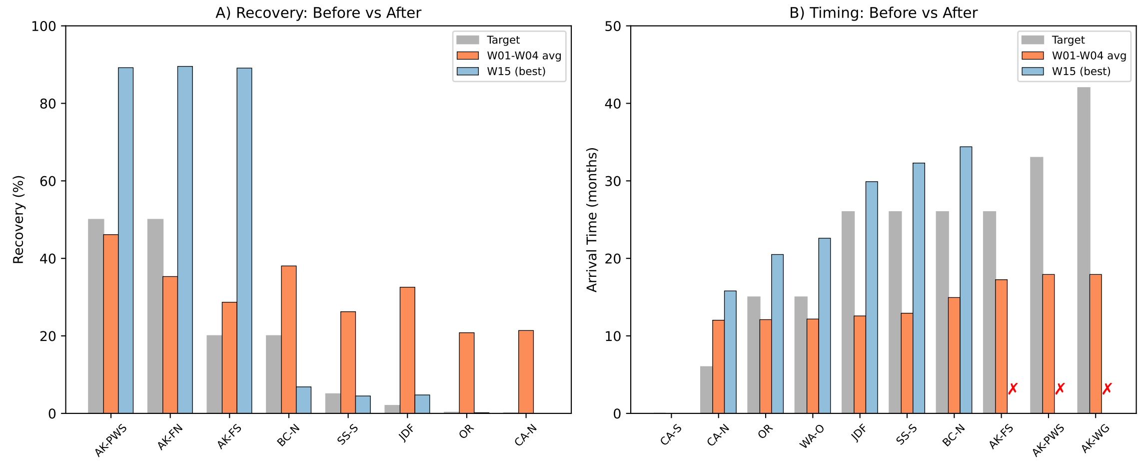


Figure 6: Before (W01–W04 average, orange) vs after (W15, blue) comparison. A) Recovery fractions. B) Wavefront arrival timing. Red × marks unreached regions.

**Key improvements**:

- RMSE improved from 1.18 to 0.40 (66% reduction)
- Recovery gradient emerged: 5 orders of magnitude range (0.02–89%) vs flat 21%
- Southern regions (OR, CA-N) now correctly show near-zero recovery
- Mid-latitude regions (SS-S, JDF) now in the correct 2–5% range

**Remaining issues**:

- Alaska overshoots by ∼40 percentage points (89% vs 50% target)
- AK-FS dramatically wrong (89% vs 20% target)
- BC-N undershoots (6.9% vs 20% target)
- Wavefront doesn't reach Alaska; timing MAE is worse than W01–W04

# 4 Discussion

## 4.1 What's Working

The three code fixes have fundamentally transformed model behavior in the right direction. The recruitment fix plus low $s_0$ successfully suppresses the universal-recovery artifact that plagued W01–W04. The model now produces a realistic latitudinal gradient where warm-water southern regions show near-total population collapse while cold-water Alaska retains high populations.

The model correctly identifies Oregon and California North as the most devastated regions, and the Salish Sea / JDF area as partially affected. These patterns match field observations.

## 4.2 What's Not Working

**Alaska overshoot**: The 89% recovery in all three Alaska regions (target: 50%, 50%, 20%) reveals that disease never reaches Alaska in the current parameterization. Alaska populations simply grow to near carrying capacity because they experience no disease mortality. This is a wavefront propagation issue — the disease runs out of steam before reaching high latitudes.

Two mechanisms could bring Alaska recovery down:

1. **Lower $K_{\mathbf{half}}$**: Currently at 200K, this controls the Beverton–Holt stock–recruitment curve. With the fixed recruitment pipeline, a lower $K_{\text{half}}$ (50K–100K) would reduce the asymptotic recovery level even in disease-free regions.

2. **Increase $s_0$**: Currently at 0.001. A slightly higher value (0.002–0.003) would allow more settlers to survive, potentially increasing population growth rate enough that disease effects become relatively smaller. However, this lever primarily affects the *rate* of recovery rather than the *equilibrium*, so the impact on Alaska's final recovery may be limited.

**BC-N undershoot**: BC-N shows only 6.9% recovery vs the 20% target. This region sits at the boundary between disease-affected and disease-free zones. Fine-tuning $P_{\text{env,max}}$ in the 1500–2500 range or adjusting dispersal parameters may help.

**CA-N slight undershoot**: CA-N shows 0.02% vs 0.10% target. This is close but slightly too suppressed. A modest increase in $s_0$ could provide the survival floor needed for the target 0.1%.

**Wavefront timing**: The disease wavefront is too slow, arriving 6–10 months late in southern regions and never reaching Alaska. The timing MAE of 28 months is dominated by the 60-month Alaska penalties. The non-arrival in Alaska is paradoxically *why* Alaska recovery is so high — fixing the timing issue (getting disease to Alaska) would automatically bring down Alaska recovery.

### 4.3 Parameter Sensitivity Hierarchy

Based on these results, the parameter sensitivity ranking is:

1. $P_{\mathbf{env,max}}$: Dominant effect. 2000 vs 5000 changes RMSE by ∼1.0.

2. **Activation threshold**: Modest effect. 100→500 improves RMSE by ∼0.06.

3. $k_{\mathbf{vbnc}}$: Minor effect. 1.5→2.0 improves RMSE by ∼0.03.

The parameter space has been effectively reduced: $P_{\text{env,max}} \approx 2000$, $k_{\text{vbnc}} = 2.0$, threshold $\geq 500$ form the baseline for future exploration.

## 5 Next Steps: W17–W28 Design

### 5.1 Strategy

The primary remaining issue is the Alaska overshoot. We focus on two levers that directly control the equilibrium recovery level:

1. $K_{\mathbf{half}}$ (50K, 100K vs current 200K): Lower values reduce the Beverton–Holt asymptote, lowering the ceiling on recovery in disease-free regions.

2. $s_0$ (0.002, 0.003 vs current 0.001): Higher settler survival may help CA-N reach its 0.1% target and modestly affect recovery dynamics.

Secondary levers ($P_{\text{env,max}}$ in 1500–2500, threshold $\geq 300$) are held near optimal or explored narrowly.

### 5.2 Proposed Rounds

Table 6: Proposed W17–W28 parameter configurations.

| **Round** | $K_{\text{half}}$ | $s_0$ | $P_{\text{env,max}}$ | $k$ | Thr | **Rationale** |
|---|---|---|---|---|---|---|
| W17 | 50K | 0.001 | 2000 | 2.0 | 500 | Aggressive $K_{\text{half}}$ reduction |
| W18 | 100K | 0.001 | 2000 | 2.0 | 500 | Moderate $K_{\text{half}}$ reduction |
| W19 | 50K | 0.002 | 2000 | 2.0 | 500 | Low $K_{\text{half}}$ + higher $s_0$ |
| W20 | 100K | 0.002 | 2000 | 2.0 | 500 | Moderate $K_{\text{half}}$ + higher $s_0$ |
| W21 | 200K | 0.002 | 2000 | 2.0 | 500 | Original $K_{\text{half}}$ + higher $s_0$ |
| W22 | 200K | 0.003 | 2000 | 2.0 | 500 | Original $K_{\text{half}}$ + high $s_0$ |
| W23 | 50K | 0.001 | 1500 | 2.0 | 500 | Low $K_{\text{half}}$ + reduced $P_{\text{env}}$ |
| W24 | 100K | 0.001 | 1500 | 2.0 | 500 | Moderate $K_{\text{half}}$ + reduced $P_{\text{env}}$ |
| W25 | 50K | 0.002 | 2500 | 2.0 | 500 | Low $K_{\text{half}}$ + slightly more disease |
| W26 | 100K | 0.002 | 2500 | 2.0 | 500 | Moderate $K_{\text{half}}$ + slightly more disease |
| W27 | 50K | 0.003 | 2000 | 2.0 | 500 | Low $K_{\text{half}}$ + high $s_0$ |
| W28 | 100K | 0.003 | 2000 | 2.0 | 500 | Moderate $K_{\text{half}}$ + high $s_0$ |

### 5.3 Expected Outcomes

- **W17/W18**: Most likely to bring AK-PWS down significantly. $K_{\text{half}} = 50\text{K}$ should reduce the BH asymptote substantially, potentially bringing Alaska from 89% to 40–60%. Risk: may over-suppress mid-latitude regions.
- **W19–W22**: Explore the interaction between $K_{\text{half}}$ and $s_0$. Higher $s_0$ may rescue CA-N from 0.02% toward the 0.10% target.
- **W23–W26**: Explore $P_{\text{env,max}}$ in the 1500–2500 range to fine-tune the mid-latitude recovery (BC-N needs to increase from 7% to 20%).
- **W27/W28**: Extreme $s_0 = 0.003$ with low $K_{\text{half}}$ as boundary exploration.

### 5.4 Success Criteria

The ideal outcome for W17–W28 would be a parameter combination achieving:

- AK-PWS recovery $\leq 60\%$ (down from 89%)
- BC-N recovery $\geq 10\%$ (up from 7%)
- SS-S, JDF recovery in 2–5% range (maintained)
- CA-N recovery $\geq 0.05\%$ (up from 0.02%)
- $\text{RMSE}_{\text{log}} < 0.35$
- Wavefront reaching at least AK-FS within the simulation window

## 6 Conclusion

The W05–W16 calibration rounds demonstrate that the three code fixes have fundamentally improved model behavior. The emergence of a strong latitudinal recovery gradient (0% south, 89% north) is a qualitative success, and the best round (W15) achieves all 8 target regions within 5× of targets (RMSE = 0.404). The dominant remaining issue is the Alaska overshoot, which we address in the proposed W17–W28 rounds by reducing $K_{\mathrm{half}}$ from 200K to 50–100K. This next batch represents a systematic exploration of the BH recruitment ceiling that should bring the model into closer quantitative agreement with observed recovery patterns.