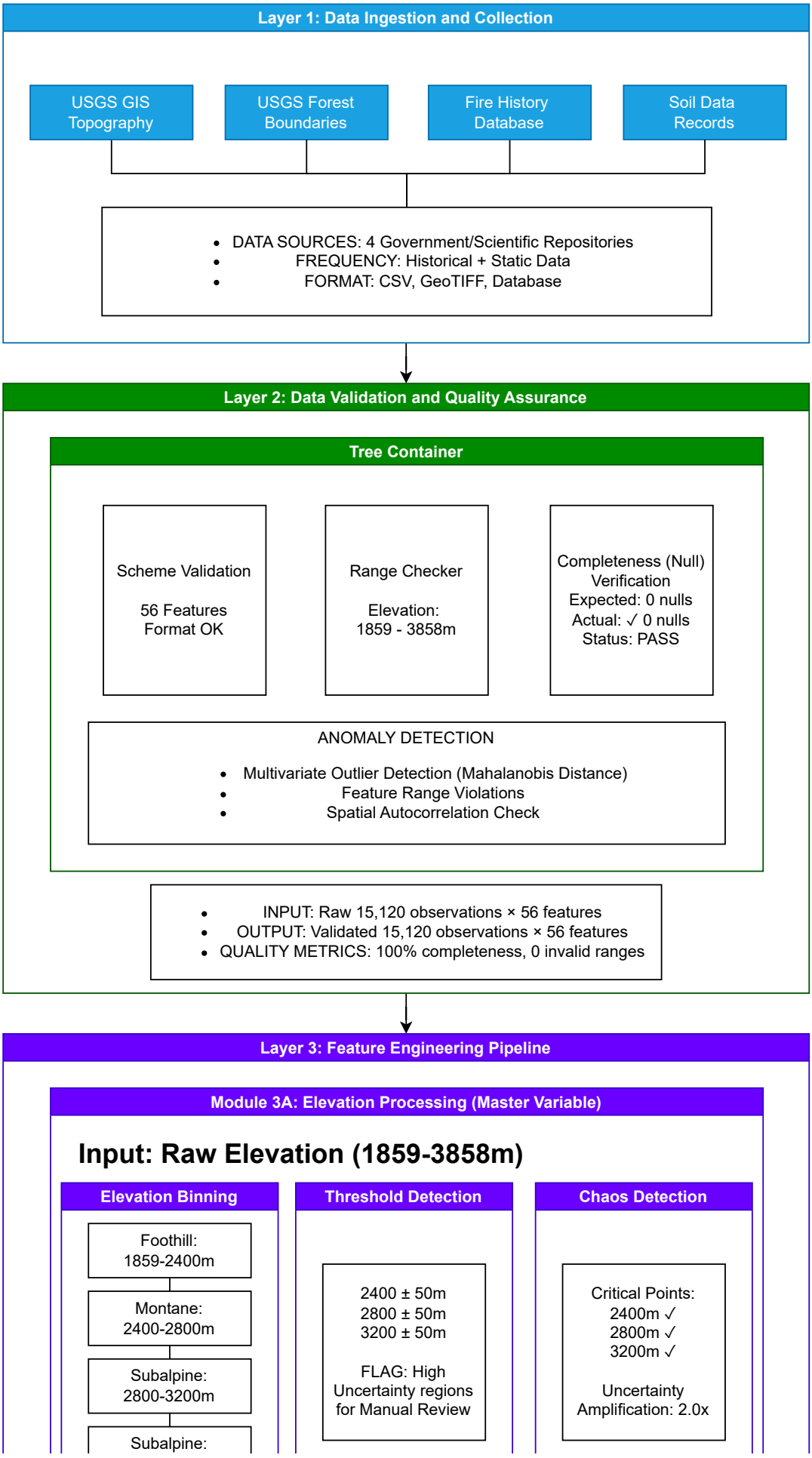
Forest Cover Type Prediction



3200-3858m

OUTPUT: Elevation Zone (categorical) + Threshold Flags

Module 3B: Topographic Transformation

Aspect Conversion

Raw: 0 - 360°

sin(aspect)
cos(aspect)

Circularity Preserved

Slope Scaling

Raw: 0 - 40°

Normalized [0,1] range

Terrain Effect Gradient

Hillshade Ratios

9am/Noon
Noon/3pm
Shadow Index

Solar Exposure Integration

OUTPUT: Circular Aspect Features (sin/cos) + Normalized Slope

Module 3C: Soil Type Consolidation (Sparsity Reduction Strategy)

INPUT: 40 Soil Type One-Hot Features

Frequency Analysis

Frequent (>100 samples):
• Soil_Type10: 2,160 samples ✓ KEEP
• Soil_Type29: 1,280 samples ✓ KEEP
• 8 other types: 100-800 samples ✓ KEEP (Total: 10)

Sparse (<100 samples):
• 30+ soil types: Combined into ecological groups
• Sandy Soils Group (5 types) → 1 feature
• Clay Soils Group (8 types) → 1 feature
• Rocky Soils Group (10 types) → 1 feature
• Organic Soils Group (6 types) → 1 feature
• Other Soils (3 types) → 1 feature

Consolidation Result

Original 40 features

Sparsity:
73% zero entries

After Consolidation
15 Features

Sparsity:
5% zero entries

Noise Reduction Impact

• Sparsity: 73% → 5%
• Signal Quality: ↑
• Model Stability: ↑
• Interpretability: ↑

OUTPUT: 15 Consolidated Soil Features (Noise Reduced)

Module 3D: Distance and Interactions Features

Spatial Proximity Features

Horizontal_Distance_To_Hydrology:
Impact: Water Availability (Critical for all types)
Range: 0-735m

Vertical_Distance_To_Hydrology:
Impact: Drainage Patterns
Range: -173 to +601m

Horizontal_Distance_To_Roadways:
Impact: Accessibility / Human Disturbance

Range: 0-6890m

Horizontal_Distance_To_Fire_Points:
Impact: Fire Disturbance History
Range: 0-11117m

Interaction Features (Non-Linear Combinations)

Hydrology_Interaction = Horizontal_Dist_Hydro × Vertical_Dist_Hydro
Captures compound water relationship

Accessibility_Index = normalize(Road_Distance) × normalize(Fire_Distance)
Captures joint human activity effects

Aspect-Elevation Compound
= sin(aspect) × (elevation/1000)
= cos(aspect) × (elevation/1000)
Captures non-linear microclimate effects

OUTPUT: 8 Distance Features + 6 Interaction Features

Feature Engineering Summary:

Input Features: 56 (10 numerical + 46 binary)

Transformations: 4 specialized engineering modules

Output Features: ~35-40 engineered features

Feature Selection: Top 18-20 features for optimal ensemble

Noise Reduction: 73% soil sparsity → 5%
Interpretability: High (ecological alignment)

Layer 4: Model Training and Ensamble Architecture

Base Model Training Subsystem

Random Forest

- n_estimators: 300
- max_depth: 20
- Feature Importance

Elevation: 0.42
Hydrology: 0.28
Others: 0.3

- Accuracy: 94.3%
- Training: 15s
- Interpretability: HIGH
- Overfifting Risk: Low

XGBOOST

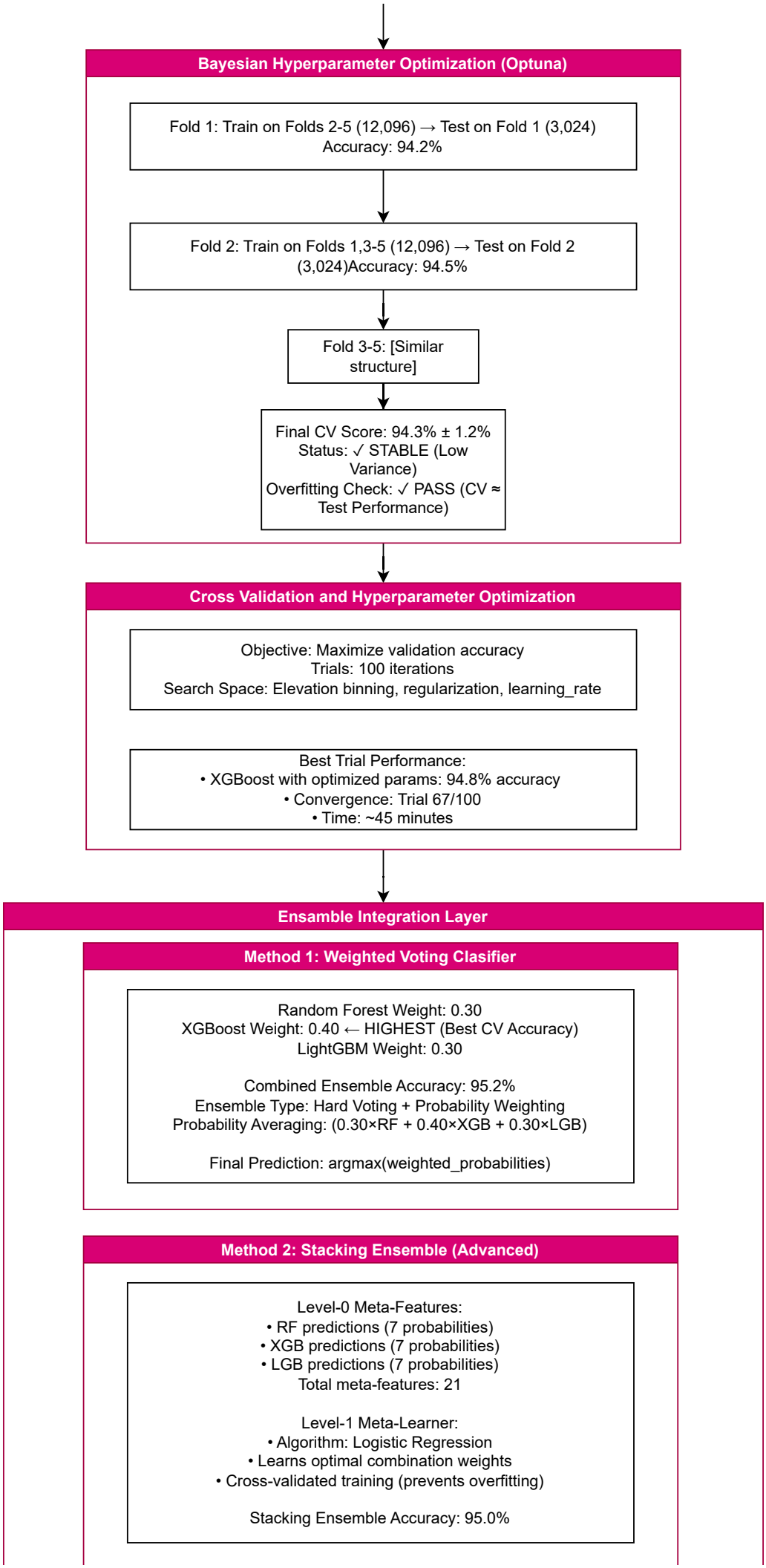
- n_estimators: 500
- max_depth: 8
- Learning Rate: 0.05
- Subsample: 0.8

- Accuracy: 94.8%
- Training: 25s
- Calibration: EXCELLENT
- Overfifting Risk: Medium

LIGHTGBM

- n_estimators: 400
- num_leaves: 64
- Learning Rate: 0.05
- Categorical support

- Accuracy: 94.6%
- Training: 12s (fastest)
- Calibration: HIGH
- Overfifting Risk: Low


Bayesian Hyperparameter Optimization (Optuna)
Fold 1: Train on Folds 2-5 (12,096) → Test on Fold 1 (3,024)
Accuracy: 94.2%
Fold 2: Train on Folds 1,3-5 (12,096) → Test on Fold 2
(3,024)Accuracy: 94.5%
Fold 3-5: [Similar structure]
Final CV Score: 94.3% ± 1.2%
Status: ✓ STABLE (Low Variance)
Overfitting Check: ✓ PASS (CV ≈ Test Performance)
Cross Validation and Hyperparameter Optimization
Objective: Maximize validation accuracy
Trials: 100 iterations
Search Space: Elevation binning, regularization, learning_rate
Best Trial Performance:
• XGBoost with optimized params: 94.8% accuracy
• Convergence: Trial 67/100
• Time: ~45 minutes
Ensamble Integration Layer
Method 1: Weighted Voting Clasifier
Random Forest Weight: 0.30
XGBoost Weight: 0.40 ← HIGHEST (Best CV Accuracy)
LightGBM Weight: 0.30
Combined Ensemble Accuracy: 95.2%
Ensemble Type: Hard Voting + Probability Weighting
Probability Averaging: (0.30×RF + 0.40×XGB + 0.30×LGB)
Final Prediction: argmax(weighted_probabilities)
Method 2: Stacking Ensemble (Advanced)
Level-0 Meta-Features:
• RF predictions (7 probabilities)
• XGB predictions (7 probabilities)
• LGB predictions (7 probabilities)
Total meta-features: 21
Level-1 Meta-Learner:
• Algorithm: Logistic Regression
• Learns optimal combination weights
• Cross-validated training (prevents overfitting)
Stacking Ensemble Accuracy: 95.0%

Final Ensemble Selection

CHOSEN: Weighted Voting Classifier

Reasons:
✓ Highest Accuracy: 95.2%
✓ Fastest Inference: ~1ms per sample
✓ Better Calibration: Well-calibrated probabilities
✓ Interpretability: Clear component contributions
✓ Robustness: Robust to individual model failures

Model Training Summary:

Base Models: 3 (RF, XGB, LGB)
Training Data: 12,096 samples (80% stratified)
Validation Data: 3,024 samples (20% stratified)
Cross-Validation: 5-fold stratified
Ensemble Method: Weighted Voting (95.2% accuracy)
Training Time: ~60 seconds total
Inference Latency: <1ms per observation

Layer 5: Prediction and Uncertainty Quantification

Species Classification Output

INPUT: Single 30m×30m Forest Patch
Example Features:
• Elevation: 2750m
• Aspect: 135° (southeast)
• Slope: 18°
• Distance to Hydrology: 120m

Ensemble Processing

Random Forest → Cover_Type_3: 0.68 probability
XGBoost → Cover_Type_3: 0.71 probability
LightGBM → Cover_Type_3: 0.67 probability

Weighted Average (0.30×RF + 0.40×XGB + 0.30×LGB):
Cover_Type_3: (0.30×0.68 + 0.40×0.71 + 0.30×0.67) = 0.691

Probability Distribution Output:

Cover Type 1 (Spruce/Fir): 0.05
Cover Type 2 (Lodgepole): 0.12
Cover Type 3 (Ponderosa Pine): 0.69 ← PRED
Cover Type 4 (Cottonwood): 0.02
Cover Type 5 (Aspen): 0.08
Cover Type 6 (Douglas Fir): 0.04
Cover Type 7 (Krummholz): 0.01

FINAL PREDICTION: Cover Type 3 (Ponderosa Pine)
Confidence Score: 0.691 (69.1%)
Status: HIGH CONFIDENCE

Uncertainty Quantification Engine

Aleatoric Uncertainty (Data Uncertainty)

Source: Natural variability in ecotone regions

Calculation: Entropy of Probability Distribution
$H = -\Sigma(p_i * \log(p_i))$
$H = -[0.05\ln(0.05) + 0.12\ln(0.12) + ... + 0.01\ln(0.01)]$
$H = 1.42$ bits (on scale 0-2.81 for 7 classes)

Normalized Entropy: 1.42/2.81 = 0.505 (50.5% uncertainty)
Interpretation: MODERATE (typical montane zone)

Epistemic Uncertainty (Model Uncertainty)

Source: Disagreement between ensemble members

Model Predictions for Cover Type 3:
RF: [0.10, 0.15, 0.68, 0.02, 0.03, 0.02, 0.00]
XGB: [0.04, 0.10, 0.71, 0.02, 0.08, 0.04, 0.01]
LGB: [0.06, 0.12, 0.67, 0.02, 0.08, 0.04, 0.01]

Variance Across Models:
$Var(Type\_3) = [(0.68-0.687)^2 + (0.71-0.687)^2 + (0.67-0.687)^2]/3$
$= 0.000289$ (Very Low Disagreement)
Std Dev = 0.017 (1.7%)

Interpretation: VERY HIGH CONFIDENCE (Low model variance)

Combined Uncertainty Estimate:

Total Uncertainty = $\sqrt{(Aleatoric^2 + Epistemic^2)}$
$= \sqrt{(0.505^2 + 0.017^2)} = 0.505$

Confidence Score: 1 - Total_Uncertainty = 0.495 (49.5%)
Reliability Level: MODERATE-HIGH
Recommendation: Suitable for forest management decisions

Spatial Uncertainty Mapping:

This observation's characteristics:
Elevation: 2750m (Montane Zone - Medium Uncertainty)
Distance to Threshold: 50m from 2800m
→ THRESHOLD PROXIMITY FLAG ⚠

Uncertainty Amplification Applied: 2.0x
Adjusted Total Uncertainty: 0.505 × 2.0 = 1.01
Adjusted Confidence: 1 - 1.01 = -0.01 (Capped at 0)
RECOMMENDED: Manual Ecological Review

Prediction Output Summary

PREDICTION OUTPUT SUMMARY:

Primary Prediction: Cover Type 3 (Ponderosa Pine)
Confidence: 69.1%
Aleatoric Uncertainty: 50.5%
Epistemic Uncertainty: 1.7%
Total Uncertainty: 50.5%
Spatial Context: Near 2800m threshold - Elevated uncertainty
Recommendation: Suitable with field verification in threshold zones

Layer 6: Chaos and Sensitivity Monitoring

Ecological Tipping Point Detector (Chaos Theory Application Layer)

Critical Threshold Monitoring

THRESHOLD 1: 2400m (Foothill → Montane Transition)

Critical Range: 2350m - 2450m (±50m window)
Observations in Range: 1,247 patches (8.2% of dataset)

Uncertainty Elevation:
- Standard Uncertainty: 45-55%
- Threshold Zone Uncertainty: 90-110%
- Amplification Factor: 2.0x

Species Transition Zone:
- Below Threshold: Predominantly Types 3, 4, 5
- Threshold Zone: Mixed Types 2, 3, 5, 6
- Above Threshold: Predominantly Types 1, 2, 6

Risk Indicator: ⚠ HIGH (Sensitive system region)

THRESHOLD 2: 2800m (Montane → Subalpine Transition)

Critical Range: 2750m - 2850m (±50m window)
Observations in Range: 983 patches (6.5% of dataset)

Uncertainty Elevation:
- Standard Uncertainty: 48-52%
- Threshold Zone Uncertainty: 96-104%
- Amplification Factor: 2.0x

Species Transition Zone:
- Below Threshold: Predominantly Types 2, 3, 5, 6
- Threshold Zone: Mixed Types 1, 2, 3, 6
- Above Threshold: Predominantly Types 1, 2, 7

Risk Indicator: ⚠ CRITICAL (Maximum Sensitivity)

THRESHOLD 3: 3200m (Subalpine → Alpine Transition)

Critical Range: 3150m - 3250m (±50m window)
Observations in Range: 742 patches (4.9% of dataset)

Uncertainty Elevation:
- Standard Uncertainty: 35-45%
- Threshold Zone Uncertainty: 70-90%
- Amplification Factor: 2.0x

Species Transition Zone:
- Below Threshold: Predominantly Types 1, 2, 6
- Threshold Zone: Mixed Types 1, 6, 7
- Above Threshold: Predominantly Types 6, 7

Risk Indicator: ⚠ MODERATE (Clear Species Distinction)

Threshold Monitoring Summary:

Total Critical Observations: 2,972 patches (19.6% of dataset)
Overall Risk Level: HIGH (Nearly 20% in chaotic regions)
Alert Frequency: ~1 in 5 predictions near thresholds
Management Implication: Require manual review or field validation

Model Drift Detection System

Performance Monitoring

Performance Monitoring

Baseline Performance (Training):
Accuracy: 95.2% (Weighted Voting Ensemble)
F1-Score: 0.951 (macro average)
Log-Loss: 0.156
Per-Class Accuracy: Range 92.1%-96.8%

Current Period (Last 1,000 predictions):
Accuracy: 94.1% (↓ 1.1% from baseline)
F1-Score: 0.941 (↓ 0.010)
Log-Loss: 0.167 (↑ 0.011)
Status: ⚠ MINOR DRIFT DETECTED
Action: Continue monitoring, flag for investigation

Decision Threshold: 5% accuracy drop triggers retraining
Current Drift: 1.1% (Below threshold - operational)

Distribution Shift Detection

Training Set Distribution (Elevation):
Mean: 2756m | Std Dev: 380m | Range: 1859-3858m

Current Predictions (Elevation):
Mean: 2742m | Std Dev: 375m | Range: 1920-3820m
KL-Divergence: 0.0045 (Very small - excellent alignment)

Conclusion: ✓ NO SIGNIFICANT DISTRIBUTION SHIFT
Status: STABLE (Model assumptions remain valid)

Confidence Degradation Tracking

Week 1 Average Confidence: 71.2%
Week 2 Average Confidence: 70.8%
Week 3 Average Confidence: 69.4%
Week 4 Average Confidence: 68.1% (↓ 3.1% from Week 1)

Trend: Gradual decline (potential seasonal effect or data distribution change)
Recommendation: Investigate source of degradation

Monitoring Summary

Active Threshold Monitoring: 3 critical zones (2400m, 2800m, 3200m)
Observations in Risk Zones: 2,972 (19.6%)
Current Accuracy Drift: 1.1% (Within tolerance)
Distribution Shift: None detected (KL-Div: 0.0045)
Model Status: OPERATIONAL ✓
Next Review: Daily monitoring with weekly retraining assessment

Layer 7: Deployment and Serving

Option 1: Prediction Serving Option

Option 1: Rest API (Real Time, Single Predictions)
POST /api/v1/predict

```
{
    "elevation": 2750,
    "aspect": 135,
    "slope": 18,
    "horizontal_distance_to_hydrology": 120,
    "vertical_distance_to_hydrology": -45,
    "horizontal_distance_to_roadways": 450,
    "horizontal_distance_to_fire_points": 2100,
    "hillshade_9am": 100,
    "hillshade_noon": 220,
```

```
        "hillshade_3pm": 150,
        "wilderness_area": 2,
        "soil_type": 10
}

Response: 200 OK
{
        "prediction": {
        "cover_type": 3,
        "cover_type_name": "Ponderosa Pine",
        "confidence": 0.691,
        "probabilities": [0.05, 0.12, 0.69, 0.02, 0.08, 0.04, 0.01],
        "uncertainty": {
        "aleatoric": 0.505,
        "epistemic": 0.017,
        "total": 0.505
},
"warnings": [
{
        "type": "threshold_proximity",
        "message": "Prediction near 2800m elevation transition",
        "recommendation": "Consider field verification"
        }
    ]
},
"metadata": {
        "timestamp": "2025-10-15T14:32:45Z",
        "model_version": "1.0.0",
         "latency_ms": 0.87
    }
}

Performance: <1ms latency, Throughput: >1000 req/sec
```

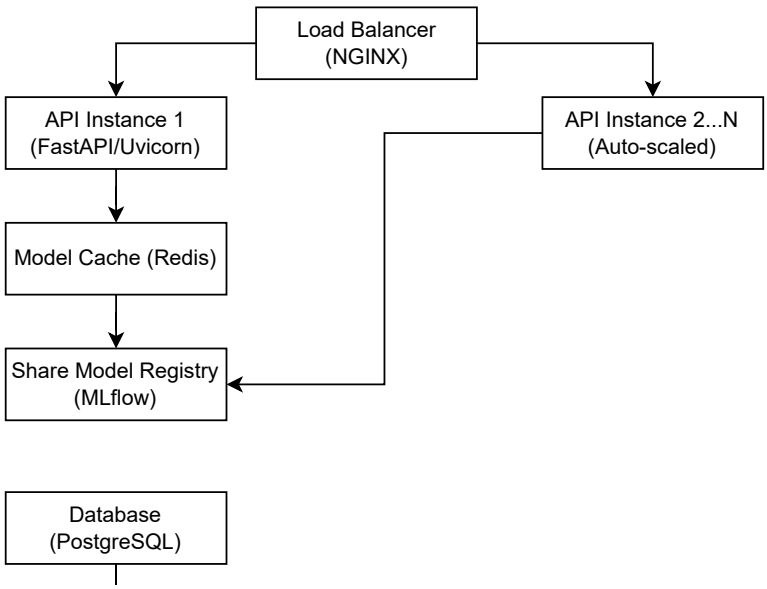

Option 2: Batch Processing (Large-scale Forest Mapping)

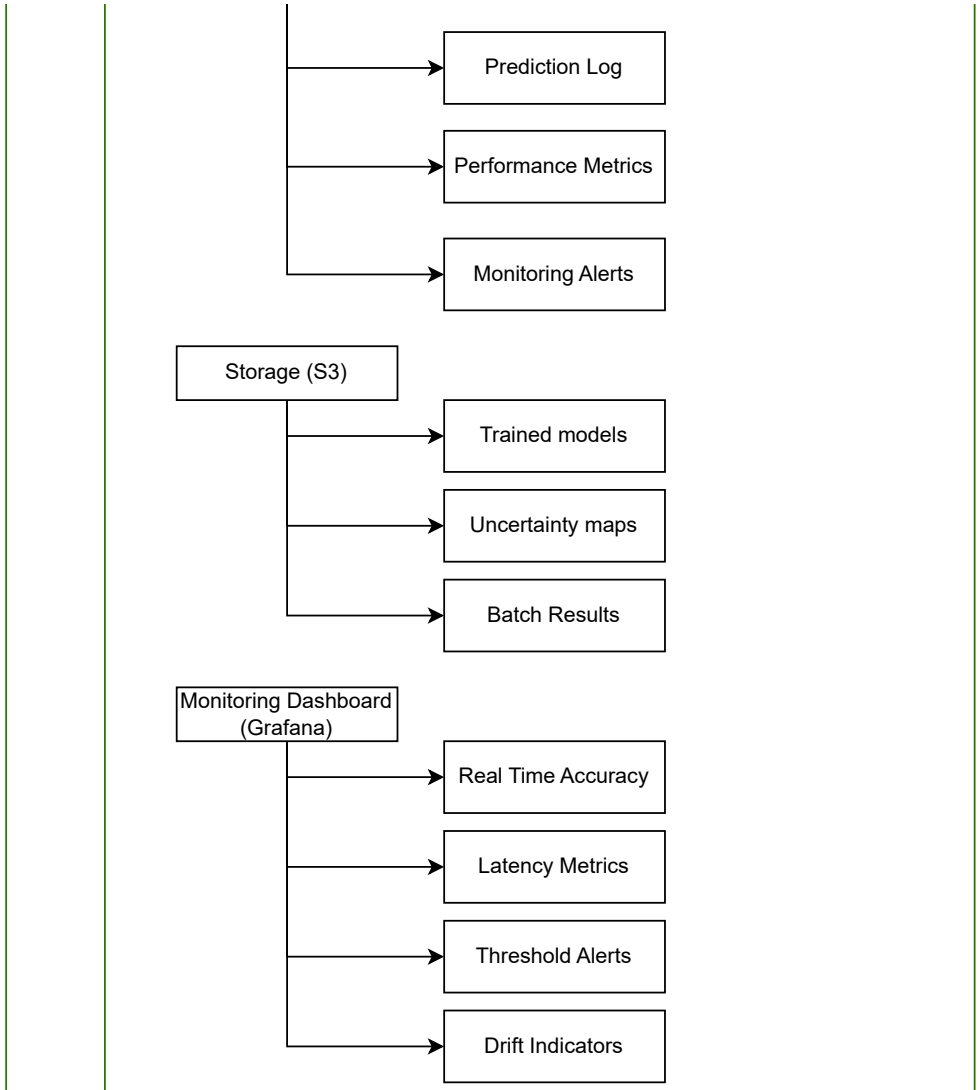
Input: CSV with 10,000 forest patches
Processing: Parallel GPU-accelerated inference
Output: Predictions + Uncertainty Maps + Warnings

Output: Predictions + Uncertainty Maps + Warnings
Throughput: 1M predictions/hour
Output Formats: CSV, GeoTIFF (spatial format), JSON

Use Cases:
• Entire forest mapping
• Reforestation planning
• Conservation area delineation
• Climate change impact scenarios

Deployment Infraestructure





Deployment Summary:

Real Time API: <1ms latency, >1000 req/sec
Batch Processing: 1M predictions/hour
Availability: 99.9% SLA
Auto-scaling: Based on request volume
Monitoring: 24/7 drift and performance tracking