Forest Carbon Lite Simulator: A Transparent Model for Restoration and Management Decision Support Under Climate Change

Version 0.1 - Professional Review Draft

Seeking feedback on logical consistency and practical utility

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Abstract

The Forest Carbon Lite Simulator (FCL v0.1) presents an open-source, scientifically-grounded framework for projecting carbon sequestration outcomes under climate change and management scenarios. Designed for rapid scenario exploration, the model addresses the gap between time intensive national carbon models and simple growth calculations. FCL enables practitioners to quickly create and compare multiple strategies, evaluating reforestation versus restoration approaches, management interventions, and climate adaptation pathways. Key features include orthogonal separation of climate and management effects to prevent double-counting, modular scenario generation, and integrated economic analysis aligned with carbon credit markets. Built on FullCAM's validated Tree Yield Formula and incorporating stochastic mortality and disturbance processes, FCL supports critical professional decisions such as site selection, management intensity optimisation, and climate adaptation planning. The model is designed for preliminary screening and scenario exploration, with field validation required before operational deployment for investment decisions.

Keywords: forest carbon modelling, professional decision support, climate adaptation, carbon crediting, FullCAM, adaptive forest management

1 Introduction: The Challenge

Forest carbon professionals face a fundamental challenge: how to make credible, defensible projections of carbon sequestration in a changing climate. This requires navigating complex interactions between forest growth, management interventions, and economic viability. Existing tools fall into two categories:

1. **National inventory models** (e.g. FullCAM): Rigorous but offering limited flexibility for scenario exploration.
2. **Simple calculators**: Easy to use but lack the sophistication to capture climate impacts and management effects.

The Forest Carbon Lite Simulator addresses this gap by providing a transparent, mid-complexity model that professionals can understand, validate, and adapt to their specific contexts.

Practical Note:
This model is designed for forest managers, carbon project developers, policy makers, researchers, and conservation professionals who need to evaluate carbon outcomes but may not have access to complex modelling infrastructure or want to explore hypothetical scenarios.

Key Terminology

Forest types: ETOF = Eucalypt Tall Open Forest, EOF = Eucalypt Open Forest, AFW = Acacia Forest Woodland
Management codes: l/m/i = light/moderate/intensive AFM applied to standing forest, lr/mr/ir = light/moderate/intensive AFM applied to standing forest and reforestation site
Model components: TYF = Tree Yield Formula (growth engine), FPI = Forest Productivity Index (climate metric), ACCU = Australian Carbon Credit Unit

2 Core Model Logic

2.1 Modular Scenario Design

FCL's core innovation is its modular scenario builder that enables rapid, systematic exploration of forest carbon outcomes. Rather than running single scenarios in isolation, practitioners can systematically combine forest types, climate projections, and management approaches to create comprehensive decision support matrices. Economic parameters are also fully customizable, allowing users to test different carbon prices, discount rates, and cost assumptions across all scenarios.

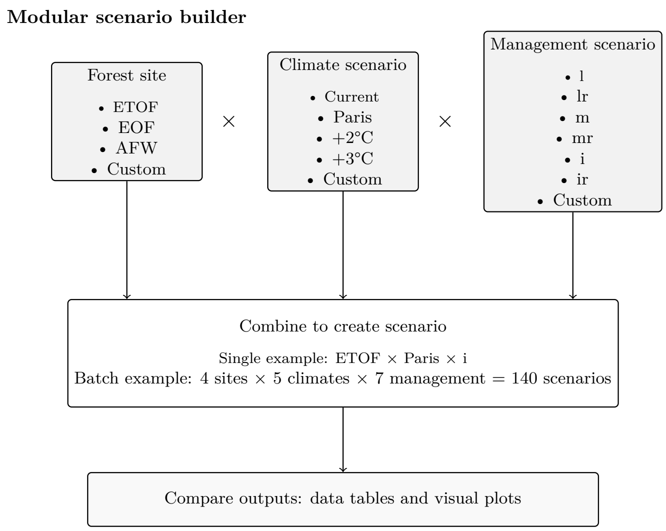


Figure 1: Logical design of the modular scenario builder.

Key Benefits of Modular Design:

- **Rapid Exploration**: Generate 140 scenarios in minutes versus weeks with traditional tools
- **Systematic Coverage**: Ensure no critical combinations are missed in decision analysis
- **Visual Comparison**: Side-by-side scenario analysis with comprehensive carbon and management outcomes
- **Decision Support**: Direct translation from scenarios to investment and management decisions
- **Scalability**: Add new forest types, climate projections, or management options without rebuilding the model

Practical Applications:

The modular approach enables practitioners to answer complex questions systematically:

- Which forest type performs best under Paris Agreement scenarios?
- What management intensity optimizes carbon returns under different climate futures?
- How do different forest types respond to climate change across management intensities?
- Which combinations provide the most robust outcomes across climate uncertainty?

This systematic exploration capability addresses a critical gap in forest carbon decision-making: the ability to rapidly evaluate multiple strategies and identify optimal approaches under uncertainty.

2.2 Mathematical Foundation: The FullCAM Tree Yield Formula

FCL implements the FullCAM Tree Yield Formula (TYF) as its core growth engine. This formula has been progressively developed and validated through multiple research efforts over two decades (Waterworth et al., 2007; Paul and Roxburgh, 2020; Forrester et al., 2025) and forms the basis for Australia's official forest carbon accounting under UNFCCC reporting requirements.

2.2.1 Growth Engine Implementation

Annual biomass increment is calculated as:

$$\Delta \mathrm{AGB}(t) = y \times M \times \left(e^{-k/t} - e^{-k/(t-1)}\right) \times \mathrm{FPI}_{\mathrm{ratio}} \quad (1)$$

where:

- $\Delta\mathrm{AGB}(t)$ = annual increment in aboveground biomass (t/ha/yr)
- t = forest age (years)
- M = maximum aboveground biomass potential (t/ha)
- G = age of maximum growth rate (years)
- $k = 2G - 1.25$ (growth curve shape parameter)
- y = management multiplier (1.0 = baseline, >1.0 = enhanced)
- $\mathrm{FPI}_{\mathrm{ratio}}$ = climate productivity adjustment ($\mathrm{FPI}/\mathrm{FPI}_{\mathrm{ave}}$)

Mortality and disturbance events are applied stochastically on an annual basis, with chronic mortality reducing existing biomass multiplicatively and disturbances creating variable biomass losses based on event severity. Detailed mathematical formulations for mortality, disturbance, and carbon pool dynamics are provided in Appendix B.

2.2.2 Parameter Sources for Australian Forest Types

Default parameters for FCL v0.1 are from published FullCAM calibrations:

Table 1: Model parameters for Australian forest types (FCL v0.1 defaults)

Parameter	ETOF	EOF	AFW
FullCAM TYF Growth Parameters			
M - Max biomass (t/ha)	290	170	49
G - Age max growth (yr)	12.53	12.53	12.53
y - Management multiplier	1.0–1.35	1.0–1.35	1.0–1.35
k - Shape parameter	23.81	23.81	23.81
Ecosystem Process Parameters			
Root:shoot ratio	0.25	0.30	0.40
Mortality (%/yr)	0.75	1.15	1.75
Fire return interval (yr)	35	20	15
Carbon fraction	0.47	0.47	0.47

Parameter sources and notes:

- **M (Maximum biomass):** ETOF and EOF values from Roxburgh et al. (2019) spatial layer (national coverage); AFW value from Paul and Roxburgh (2020) mulga calibration. Site-specific values available from Roxburgh spatial layer.

- **G (Age at maximum growth):** G calibrated for each forest type (Paul and Roxburgh, 2020; Forrester et al., 2025).
- **y (Management multiplier):** Baseline = 1.0 (no intervention). Enhanced values (1.0–1.35) based on management intensity levels: light (1.10), moderate (1.20), and intensive (1.35).
- **k (Shape parameter):** Derived as $k = 2G - 1.25 = 23.81$.
- **Root:shoot ratios:** From Mokany et al. (2006).
- **Mortality rates:** FullCAM default values for forest types.
- **Fire return intervals:** Based on historical fire frequency records for each forest type.
- **Carbon fraction:** 0.47 IPCC default (IPCC, 2006; IPPC, 2019).

2.3 Carbon Conversions

We adopt the IPCC default carbon fraction of 0.47 for woody biomass (IPCC, 2006; IPPC, 2019), which has been validated across multiple forest types globally (Martin and Thomas, 2011; Thomas and Martin, 2012). While Australian eucalypts may vary from 0.45-0.49 (Ximenes and Wright, 2006), the 0.47 default introduces acceptable uncertainty (±4%) and maintains consistency with national carbon accounting protocols.

$$\text{Carbon} = \text{Dry Matter} \times 0.47 \tag{2}$$

$$\text{CO}_2\text{e} = \text{Carbon} \times 3.67 \tag{3}$$

3 Climate-Management Separation

A critical challenge in forest carbon modelling is avoiding double-counting when combining climate and management effects.

3.1 Orthogonal Effects Safeguard

We implement strict separation through orthogonal parameterisation:

$$\text{Growth} = \text{Base} \times \underbrace{\left(\frac{\text{FPI}_t}{\text{FPI}_{\text{baseline}}}\right)}_{\text{Climate only}} \times \underbrace{y}_{\text{Management only}} \tag{4}$$

This ensures:

- Climate effects modify FPI ratios exclusively
- Management effects modify y-multiplier exclusively
- Combined effects are multiplicative, not compounded

3.2 Implementation Logic

Implementation: The orthogonal effects are calculated independently then multiplied:

$$\text{FPI}_{\text{ratio}} = 1 - 0.1 \times (\Delta T) \tag{5}$$

$$y = 1 + 0.2 \times I \quad \text{where } I \in [0, 1] \tag{6}$$

$$G = G_0 \times \text{FPI}_{\text{ratio}} \times y \tag{7}$$

where ΔT is temperature change (°C), I is management intensity (0 = none, 1 = maximum), and G_0 is baseline growth rate.

Practical Note:
This separation allows professionals to evaluate climate and management scenarios independently, then combine them with confidence that effects aren't being double-counted.

3.3 Active Forest Management: Restoration Context

The management multiplier (y) in our framework can represent Active Forest Management (AFM), which treats interventions as temporary restoration activities rather than perpetual commercial forestry. Following Bennett et al. (2024), AFM treats management as ecosystem medicine that works toward obsolescence: interventions decrease as forests regain autonomous function.

AFM principles in FCL: Management multipliers enhance growth while reducing disturbance impacts. Interventions target restoration rather than commercial production, with success measured by declining intervention needs over time as forests regain reslience and ecoystem function.

AFM interventions include strategic thinning to reduce fuel loads and prevent mortality cascades (Ameray et al., 2021; Weston et al., 2020), cultural burning to restore fire regimes (Bradstock et al., 2012), and assisted regeneration following international restoration standards (Gann, 2020). These interventions are particularly important given that high-severity fires can combust nearly twice the carbon of moderate-severity fires in eucalypt forests (Volkova et al., 2022).

4 Intended Application

Forest carbon professionals, researchers, and policymakers face recurring decisions that require rapid, defensible carbon projections: Which sites offer the best return? What management intensity optimizes outcomes? How will climate change affect strategy viability? FCL is designed to answer these questions through systematic scenario comparison.

The model currently supports education, research, and policy scenario exploration, enabling users to understand carbon projection methods and evaluate management trade-offs. Once field validation is complete (Section 5.1), FCL could support decision domains such as site selection, management intensity and approach, climate adaptation and risk management, and financial carbon project planning.

Economic projections integrate reforestation costs ($1,500-3,000/ha establishment), management costs ($25-100/ha/yr), and carbon market dynamics ($35-70/t$\text{CO}_2$e), informed by recent Australian and global assessments (Austin et al., 2020; Busch et al., 2024; Evans, 2018; Jonson and Freudenberger, 2011; Pacheco et al., 2024).

Detailed economic parameters are provided in Appendix B.

Figure 2 illustrates how FCL integrates into adaptive forest management through four decision stages: initial site assessment establishes baseline carbon potential; scenario comparison informs management strategy development; performance monitoring tracks realized outcomes against projections; and adaptive revision adjusts strategies when thresholds are breached. This structured approach enables practitioners to navigate from evaluation through ongoing adaptation using consistent projection methods.

Decision Flowchart

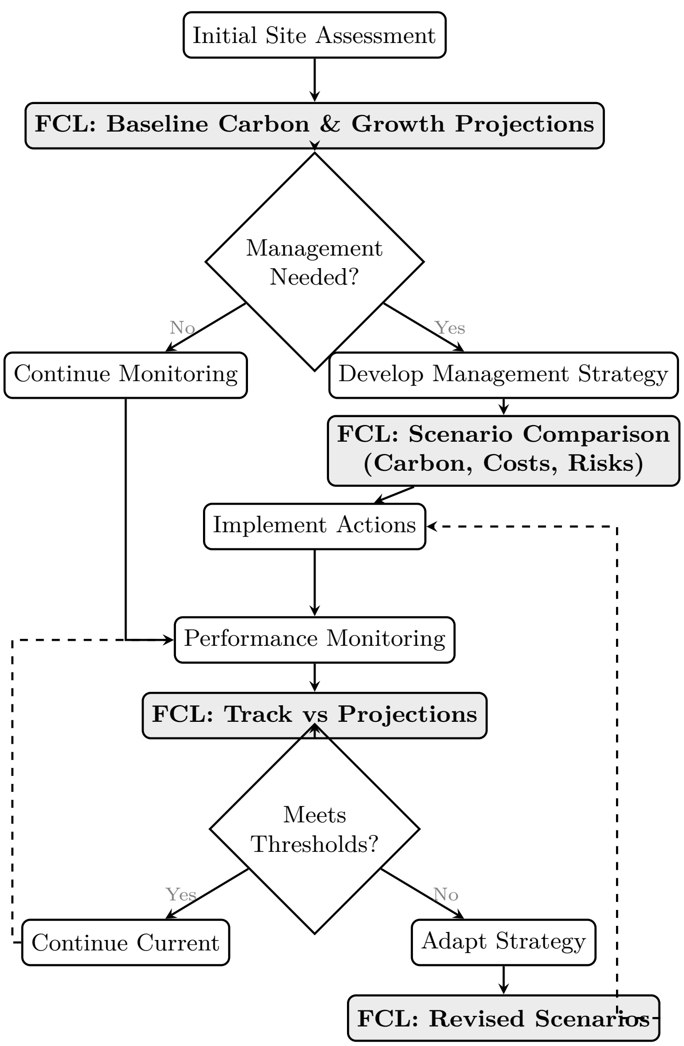


Figure 2: Conceptual integration of Forest Carbon Lite in adaptive management workflows. Grey boxes indicate where the model will provide quantitative decision support once field-validated.

5 Model Validation, Limitations and Assumptions

5.1 Validation Status

Validated Foundation: The core Tree Yield Formula has undergone extensive validation across Australian forest types (Waterworth et al., 2007; Paul and Roxburgh, 2020; Forrester et al., 2025) and serves as Australia's official carbon accounting methodology. Modelled sequestration rates align with published Australian data: 8.5 tCO_2e/ha/yr for eucalypt woodland restoration (Jonson and Freudenberger, 2011), 12 tCO_2e/ha/yr for intensive mixed-species reforestation (Paul et al., 2018), and 4.5 tCO_2e/ha/yr for natural regeneration (Cook-Patton et al., 2020).

FCL Implementation: While we have correctly implemented the validated TYF, our complete model system has not been independently validated against field measurements. The model's validated components (TYF implementation, IPCC carbon accounting framework, economic calculation logic) enable preliminary applications, but integrated carbon pool transfers, climate sensitivity responses, management effect magnitudes, and multi-year projection accuracy require field validation.

Critical Limitation: Without field validation, FCL should be used for preliminary screening and scenario comparison only, not as the sole basis for project investment decisions or MRV reporting. We are actively seeking validation partnerships to test FCL against multi-year carbon stock measurements, ACCU issuance records, and realized project economics.

These validation constraints inform the following known limitations and key assumptions that reviewers should evaluate.

5.2 Model Limitations

We acknowledge several important limitations:

1. **Spatial simplification**: No landscape connectivity or edge effects
2. **Static parameters**: Climate and management effects don't vary with forest age
3. **Linear climate response**: May underestimate threshold effects
4. **Simplified mortality**: Doesn't capture pest/disease dynamics
5. **Carbon pool transfers**: Fixed rates don't respond to environmental conditions
6. **Constant management intensity**: Version 0.1 applies constant management intensity throughout simulations, overestimating long-term costs and underestimating forest autonomy gains. Temporal de-escalation (intensive → targeted → minimal over 25+ years) is planned for v0.2

5.3 Key Assumptions for Review

Key Assumption:

Climate sensitivity parameter: Forest Productivity

Index adjustment uses a linear response: $\text{FPI}_{\text{ratio}} = 1 - 0.1 \times (\Delta T)$. This 10% per degree parameter represents a central estimate from literature showing high variability: 5-15% for temperate forests (Wood et al., 2015), 3-8% for drought-adapted systems (Choat et al., 2018), and up to 20% for moisture-limited forests (Wardlaw, 2021). We acknowledge this simplification may underestimate non-linear threshold responses (McDowell et al., 2018).

Key Assumption:
Management effectiveness parameters: Growth improvements from forest management are highly context-dependent and vary by intervention type, forest condition, and degradation status. Published studies show:

- Thinning in eucalypt forests: 15-50% growth improvement (Forrester and Baker, 2012; Forrester et al., 2013)
- Restoration thinning in degraded forests: 10-25% improvement (Dwyer et al., 2010)
- Environmental plantings: 20-35% with moderate intensity (Paul et al., 2018)

Our parameters represent mid-range estimates: light management (1.10 = 10%), moderate (1.20 = 20%), and intensive (1.35 = 35%). Site-specific responses may vary ±50% from these values depending on initial forest condition.

Key Assumption:
Disturbance return intervals: Fire frequencies based on historical data may not reflect future climate-driven changes.

5.4 Comparison with Other Models

Table 2: Model comparison

Feature	FCL	FullCAM	Simple calc
Transparency	High	Low	High
Complexity	Medium	High	Low
Climate effects	Yes	Yes	No
Management	Yes	Limited	No
Uncertainty	Yes	Yes	No
Accessibility	High	Low	High

Having outlined the model's capabilities, limitations, and assumptions, we now seek professional input to guide further development and validation efforts.

6 Feedback Questions for Reviewers

We seek professional feedback on five critical areas:

1. **Model Logic**: Is the separation of climate and management effects (Equation 4) logical and useful? Do the growth curve formulations and carbon pool transfers align with field observations?
2. **Parameters**: Are the climate sensitivity values (10% per degree warming), management effectiveness estimates (10-35% uplift), and mortality rates (0.75-1.75% annually) reasonable for your forest types?
3. **Validation Gap**: Do you have multi-year carbon monitoring data we could use to validate the integrated model? What minimum validation would you require before using this operationally?
4. **Practical Utility**: What additional scenarios or economic adjustments would be valuable? Are there critical factors we haven't captured?
5. **Implementation**: Would you use this tool for preliminary screening, education, or policy analysis? What features would improve operational utility?

We value constructive criticism over endorsement. This is a working draft seeking to improve before wider release.

7 Conclusions and Next Steps

7.1 Summary

FCL provides a transparent mid-complexity framework that bridges the gap between rigid national models and oversimplified calculators. By implementing validated FullCAM algorithms within a modular scenario builder, the model enables rapid exploration of forest carbon outcomes under climate change and management interventions. Version 0.1 is suitable for education, policy analysis, and preliminary screening; operational deployment requires field validation.

7.2 Priorities for Development

Version 0.2 will address:

1. Field validation protocols and data integration guides
2. Dynamic parameters (age-dependent climate/management responses)
3. Non-linear climate thresholds and enhanced disturbance modelling
4. Additional forest types with regional calibration
5. Hydrological and biodiversity co-benefits

7.3 Call for Collaboration

We invite professionals to share validation data, test with local parameters, and contribute to open-source development. We acknowledge Traditional Owners as the original forest managers.

Acknowledgments

We thank the forest professionals who provided early feedback. We acknowledge Traditional Owners as the original forest managers and incorporate their knowledge where culturally appropriate and with permission.

Data and Code Availability

- **Code repository**: https://github.com/forestsystemtransformation/forest-carbon-lite for inspection and testing. Users should

review the validation status (Section 5.1) before operational deployment.
- **Documentation**: Comprehensive user guide and API documentation
- **Example data**: Test scenarios with known outputs for validation
- **License**: MIT (open source)

Author Contributions

PA designed the model framework, implemented the scenario builder, conducted validation analysis, and wrote the manuscript.

Competing Interests

The author declares no competing financial or non-financial interests.

A Visual Decision Support Outputs

The model generates five core visualization types for scenario analysis. Representative examples demonstrate analytical capabilities; complete interpretation protocols available in repository documentation.

Interpreting model outputs: These visualizations demonstrate FCL's analytical framework using representative scenarios. Projections are generated using validated FullCAM algorithms with literature-based parameters; quantitative estimates (e.g., "40% decline under +3°C") should be interpreted as scenario comparisons rather than site-specific predictions. Operational applications benefit from local parameter calibration and field validation.

A.1 Output Types and Key Findings

Time series analysis (Fig. 3): Carbon accumulation trajectories show management effectiveness declining approximately 40% under +3°C scenarios relative to current climate across all forest types.

Additionality comparison (Fig. 4): Management interventions project 15-25% additional carbon per degree warming, with intensive management maintaining highest relative gains across climate scenarios.

Strategy optimization (Fig. 5): AFW scenarios show reforestation outperforming management (positive crossover by year 8), while ETOF Paris scenarios show management priority (management benefits exceed reforestation losses throughout projection period).

Economic projections (Fig. 6): Management scenarios show 8-12 year break-even periods; reforestation extends to 12-15 years due to establishment costs and growth lag.

Forest type comparison (Fig. 7): ETOF demonstrates highest absolute carbon accumulation but EOF shows better cost-effectiveness ($/t$CO_2$e) under moderate management intensity.

Uncertainty quantification (Fig. 8): Maximum biomass (M) and growth multiplier (y) explain 68% of output variance. 90% confidence intervals span ±30% of mean projections at year 25.

A.2 Representative Visualizations

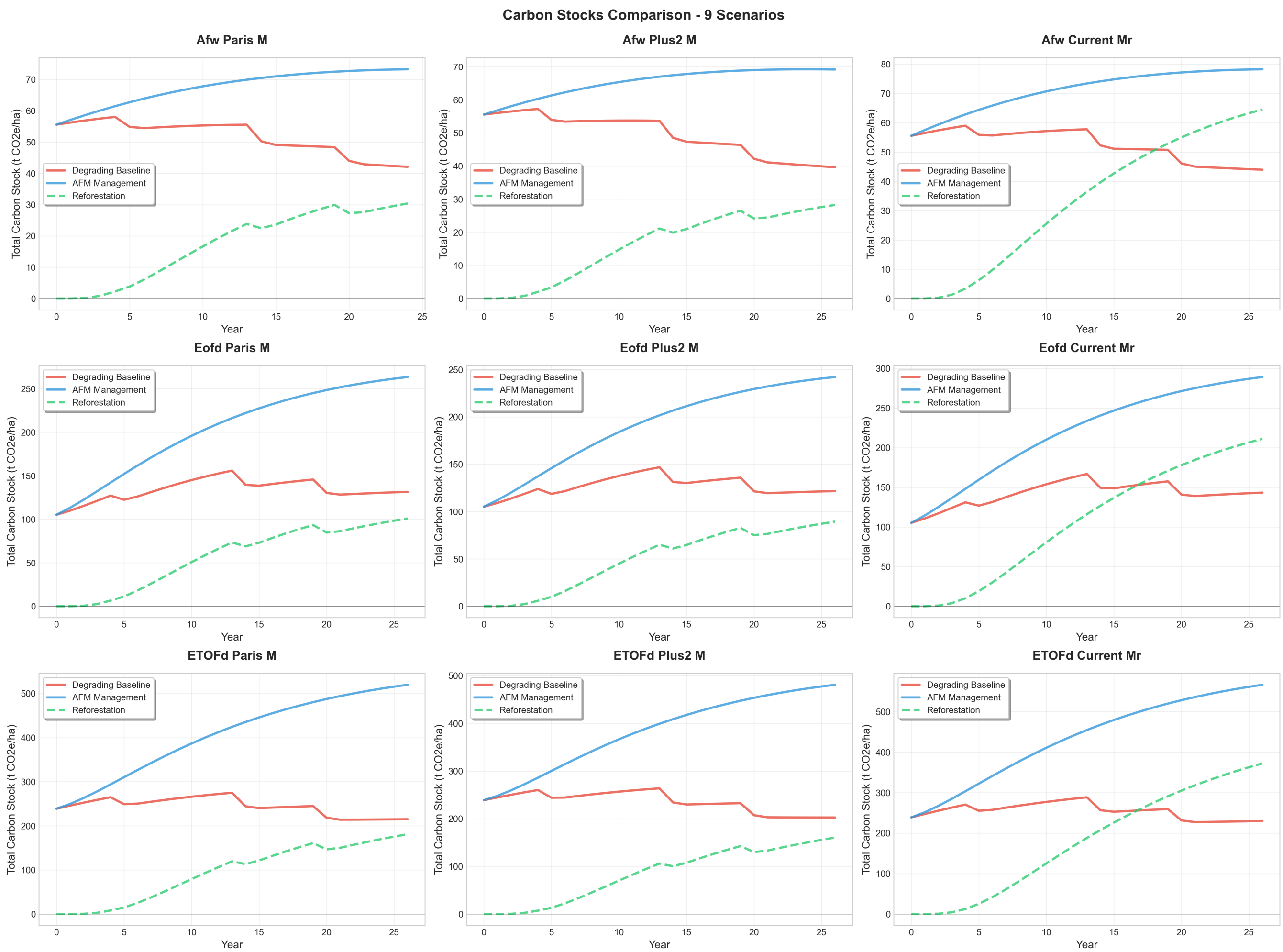


Figure 3: Carbon stock time series across forest types, climate scenarios, and management approaches.

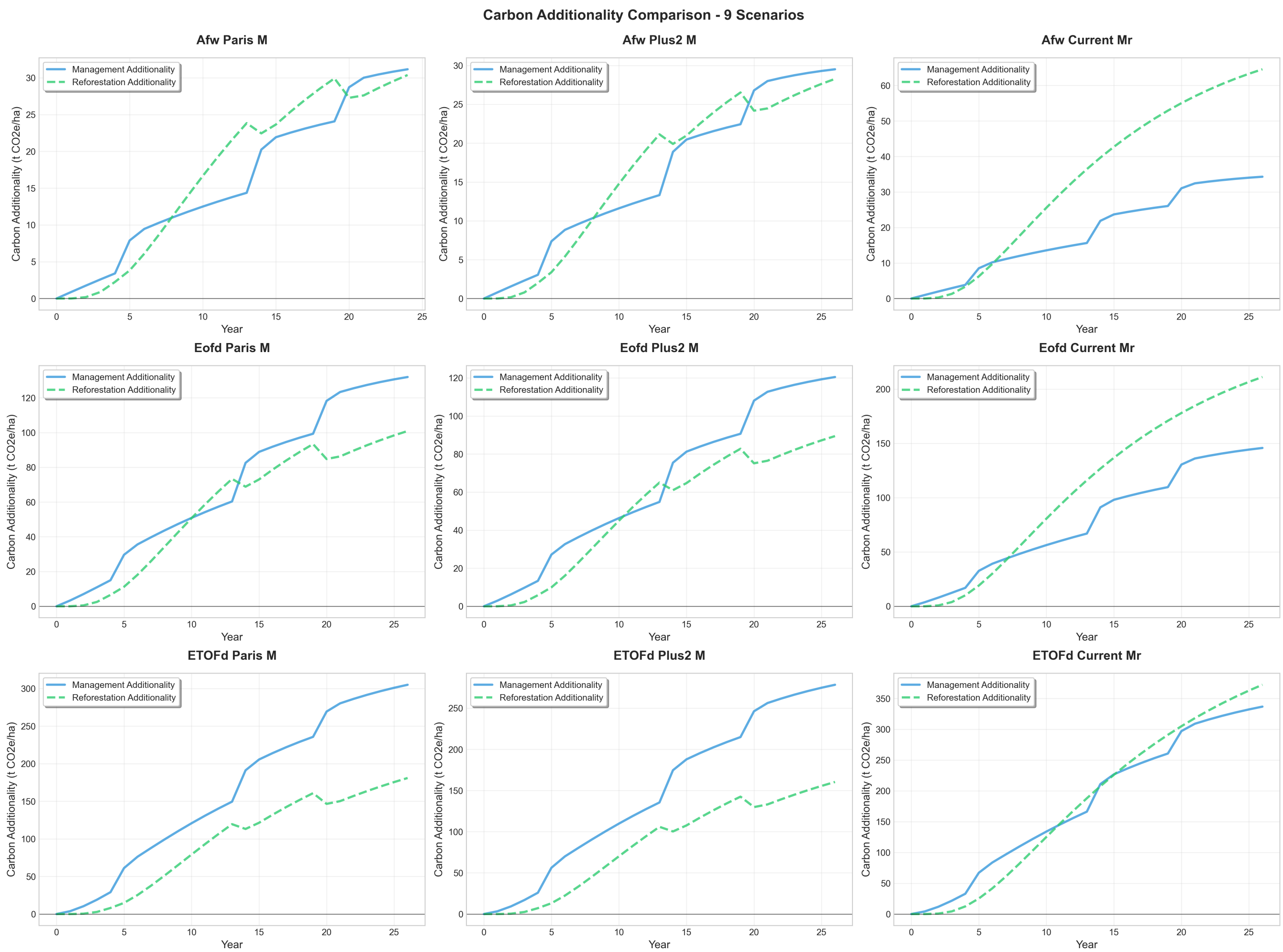
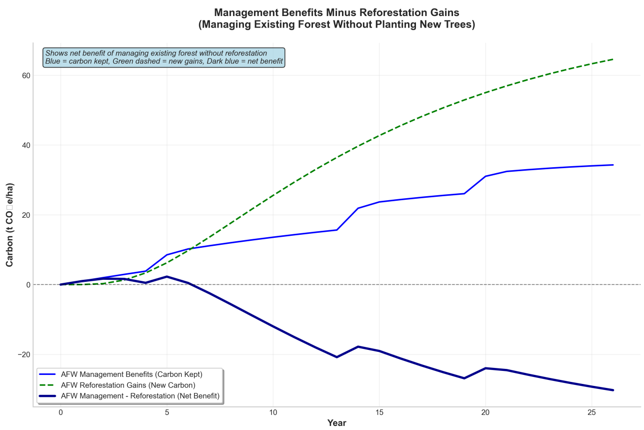
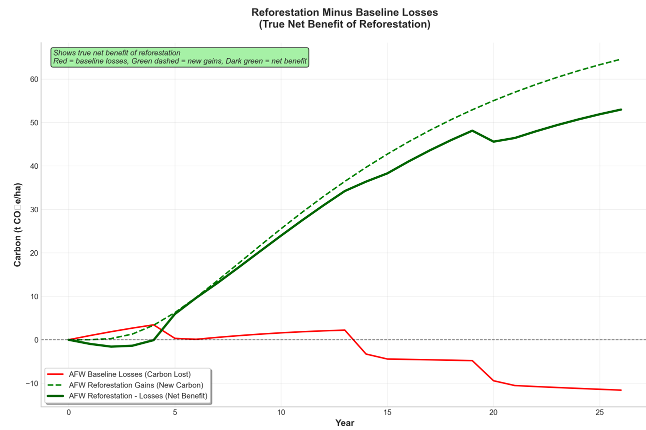


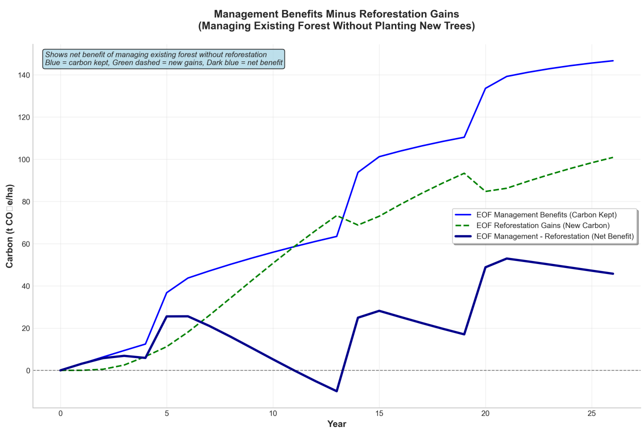
Figure 4: Net additional carbon sequestration from management interventions versus baseline scenarios.



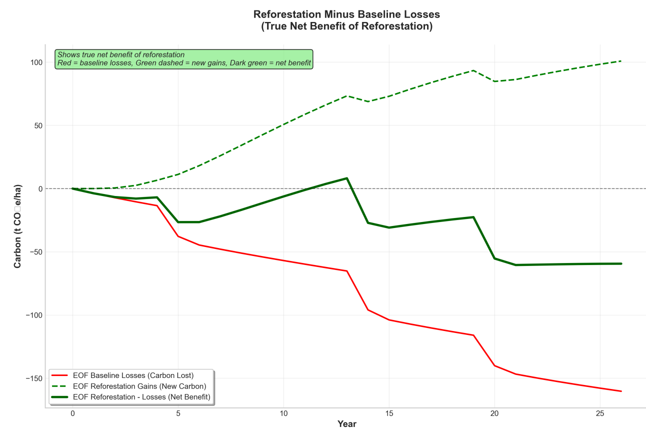
(a) AFW: Management vs Reforestation



(b) AFW: Reforestation Net Benefit

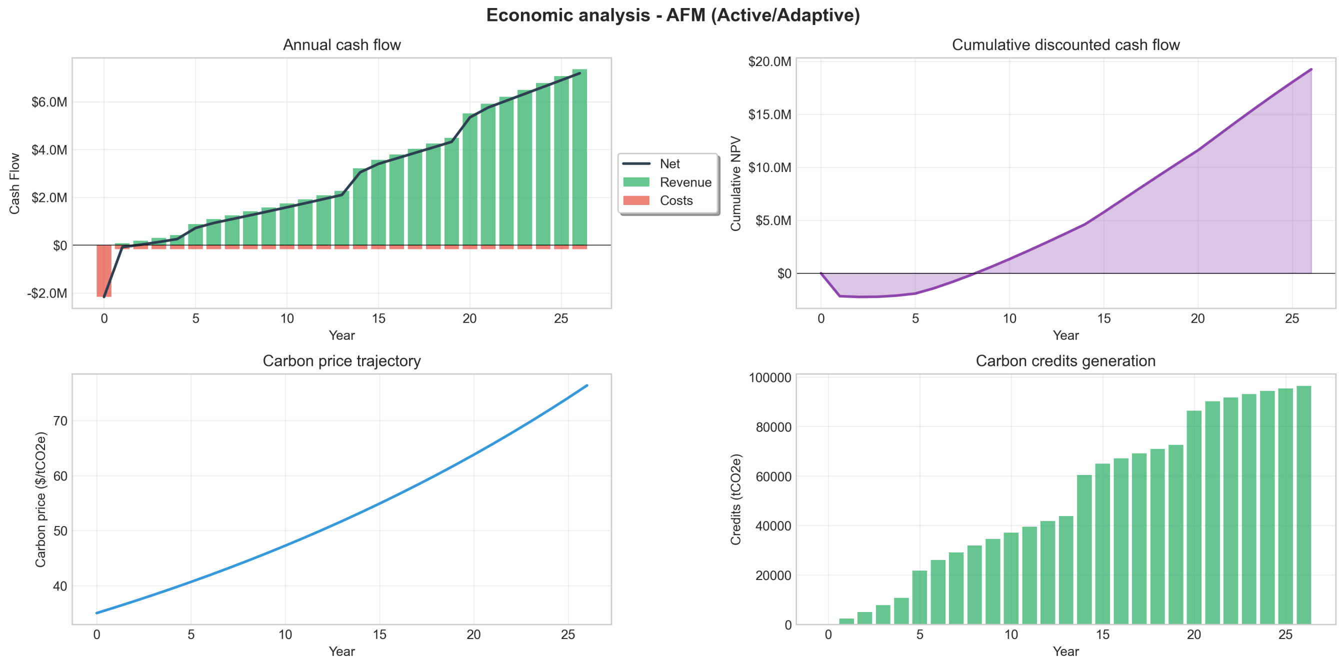


(c) ETOF Paris: Management vs Reforestation

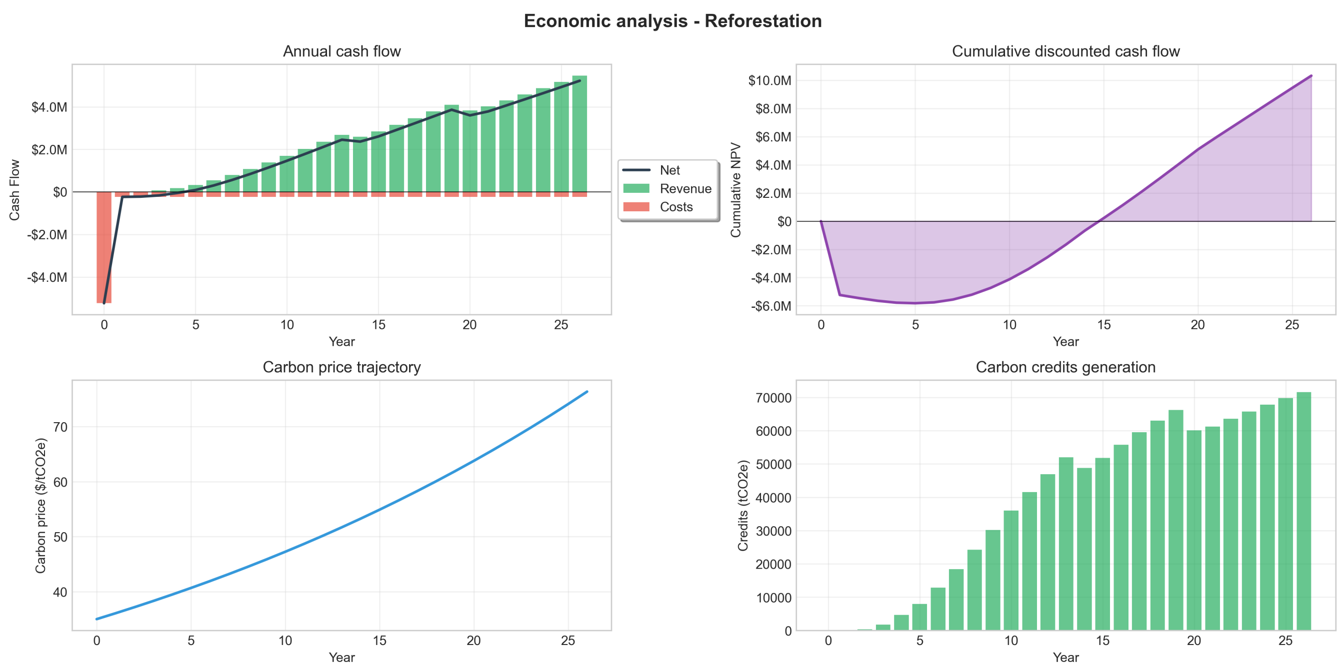


(d) ETOF Paris: Reforestation Net Benefit

Figure 5: Strategy comparison showing reforestation advantage in AFW versus management priority in ETOF Paris scenarios.



(a) Management Scenario Economics



(b) Reforestation Scenario Economics

Figure 6: NPV trajectories, cash flows, and break-even analysis for management versus reforestation strategies.

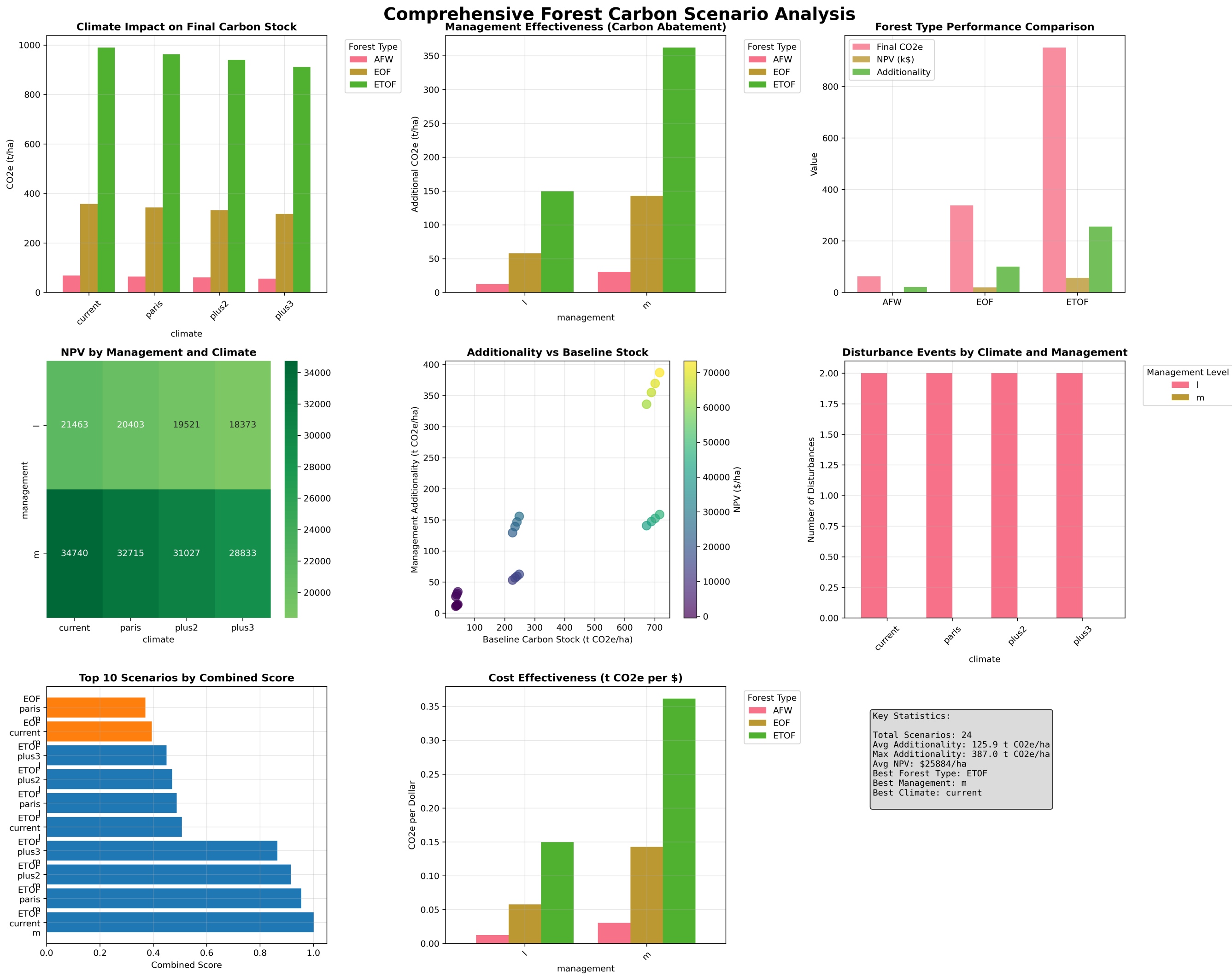
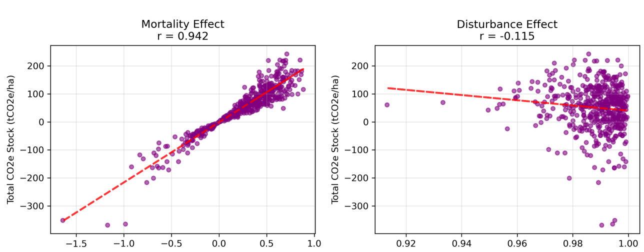
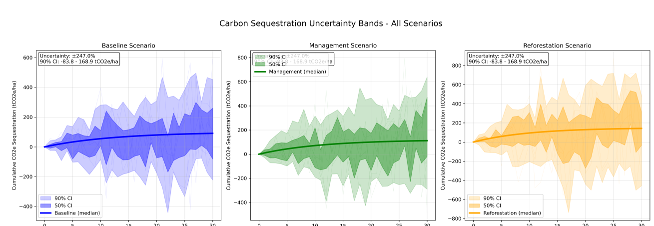


Figure 7: Comparative performance of forest types (AFW, EOF, ETOF) across climate and management scenarios.



(a) Parameter Sensitivity



(b) Uncertainty Bounds

Figure 8: Sensitivity analysis showing parameter influence on outputs and 90% confidence intervals across scenarios.

B Technical Specifications

This appendix provides the mathematical formulations underlying FCL's carbon accounting, climate response functions, economic calculations, and uncertainty analysis. These specifications support model transparency and enable independent verification of implementation.

B.1 Carbon Pool Dynamics

The model tracks carbon flows through a 10-pool system representing biomass, dead organic matter, soil, and wood products:

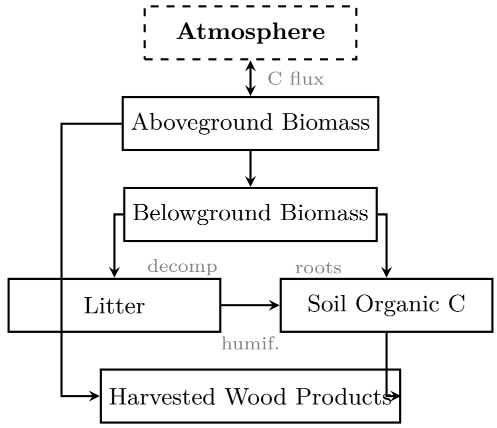


Figure 9: Hierarchical carbon pool structure in forest ecosystems.

The model implements a comprehensive 10-pool carbon accounting system:

$$\text{Total C} = C_{\text{AGB}} + C_{\text{BGB}} + C_{\text{litter}} + C_{\text{char}} + C_{\text{active\_soil}} + C_{\text{slow\_soil}} + C_{\text{HWP\_short}} + C_{\text{HWP\_medium}} + C_{\text{HWP\_long}} + C_{\text{slash}} \quad (8)$$

Pool definitions and decay rates:

- C_{AGB} = Above-ground biomass (from TYF, Section 2.2)
- C_{BGB} = Below-ground biomass (AGB$\times$ root:shoot ratio)
- C_{litter} = Forest floor litter (decay rate: 0.30 yr^{-1})
- C_{char} = Fire-produced charcoal (decay rate: 0.01 yr^{-1})
- $C_{\text{active\_soil}}$ = Active soil organic carbon (decay rate: 0.10 yr^{-1})
- $C_{\text{slow\_soil}}$ = Slow soil organic carbon (decay rate: 0.01 yr^{-1})
- C_{HWP} = Harvested wood products in three pools (2, 20, 50 year lifespans)
- C_{slash} = Harvest residue (decay rate: 0.20 yr^{-1})

Transfer equations:

$$\frac{dC_{\text{litter}}}{dt} = \text{mortality} \times C_{\text{AGB}} - d_{\text{litter}} \times C_{\text{litter}} \quad (9)$$

$$\frac{dC_{\text{char}}}{dt} = f_{\text{fire}} \times \text{severity} \times C_{\text{AGB}} - d_{\text{char}} \times C_{\text{char}} \quad (10)$$

$$\frac{dC_{\text{active\_soil}}}{dt} = f_{\text{transfer}} \times d_{\text{litter}} \times C_{\text{litter}} - d_{\text{active}} \times C_{\text{active\_soil}} \quad (11)$$

$$\frac{dC_{\text{slow\_soil}}}{dt} = d_{\text{active}} \times C_{\text{active\_soil}} - d_{\text{slow}} \times C_{\text{slow\_soil}} \quad (12)$$

where $f_{\text{fire}} = 0.1$ is the fraction of biomass converted to charcoal during fire events, and f_{transfer} is the humification factor (0.1-0.3) controlling litter-to-soil carbon transfer.

B.2 Mathematical Framework: Growth, Mortality, and Disturbance

The model implements a sequential annual simulation loop that applies growth, mortality, and disturbance effects in the following order:

B.2.1 Annual Simulation Sequence

For each year t, the model follows this sequence:

1. **Growth Application:** Calculate biomass increment using TYF equation (Section 2.2.1)
2. **Mortality Application:** Apply chronic mortality as multiplicative reduction
3. **Disturbance Application:** Apply stochastic disturbance events (if they occur)
4. **Carbon Pool Transfers:** Transfer dead biomass to litter and soil pools

B.2.2 Mortality Calculations

Chronic mortality is applied as a multiplicative reduction to existing biomass:

$$\text{AGB}_{\text{after mortality}} = \text{AGB}_{\text{before}} \times (1 - m) \tag{13}$$

where m is the annual mortality rate (0.75-1.75% for different forest types).

B.2.3 Disturbance Calculations

Disturbances are stochastic events with variable severity:

$$\text{AGB}_{\text{after disturbance}} = \text{AGB}_{\text{before}} \times (1 - s) \tag{14}$$

$$\text{Probability of disturbance} = p_{\text{baseline}} + \text{climate adjustments} \tag{15}$$

where s is disturbance severity (0.02-0.35) and p is annual disturbance probability (0.01-0.25).

B.2.4 Key Mathematical Properties

Multiplicative Effects: Both mortality and disturbance act as multiplicative reductions on current biomass, not additive:

$$\text{AGB}_{\text{final}} = \text{AGB}_{\text{initial}} \times (1 - m) \times (1 - s) \tag{16}$$

$$= \text{AGB}_{\text{initial}} \times (1 - m - s + ms) \tag{17}$$

Mass Balance: All biomass transfers maintain strict mass balance - carbon is never lost, only transferred between pools or to the atmosphere.

Expected Annual Mortality: The model calculates expected annual mortality as:

$$E[\text{Mortality}] = \text{AGB} \times m \times 0.75 \tag{18}$$

where 0.75 is the mean of the beta(2,2) distribution used for severity variability.

B.3 Climate Response Functions and Parameter Bounds

Forest Productivity Index adjustment:

$$\text{FPI}_{\text{adjusted}} = \text{FPI}_{\text{baseline}} \times (1.0 - \Delta T \times 0.10) \times \left(1.0 - \frac{\Delta P}{100} \times 0.08\right) \tag{19}$$

where ΔT is temperature increase (°C) and ΔP is rainfall reduction (mm).

FPI validation bounds:

- Global bounds: $0.4 \leq \text{FPI} \leq 1.2$ (forest survival limits)
- Typical operational range: $0.6 - 1.0$ (realistic productivity)
- Forest-specific minimums: AFW ≥ 0.5, EOF ≥ 0.6, ETOF ≥ 0.7

- Climate adjustment limits: ±30% maximum change from baseline

Climate-adjusted disturbance and mortality:

$$p_{\text{dist}} = p_{\text{baseline}} + (\Delta T \times 0.03) + \left(\frac{\Delta P}{100} \times 0.02\right) \tag{20}$$

$$s_{\text{dist}} = s_{\text{baseline}} + (\Delta T \times 0.02) + \left(\frac{\Delta P}{100} \times 0.012\right) \tag{21}$$

$$m = m_{\text{baseline}} + (\Delta T \times 0.012) + \left(\frac{\Delta P}{100} \times 0.008\right) \tag{22}$$

where p_{dist} = annual disturbance probability (bounds: 0.01-0.25), s_{dist} = disturbance severity (bounds: 0.02-0.35), and m = annual mortality rate (bounds: 0.005-0.080).

Management multiplier validation:

- Light management (l): 1.0-1.1 (minimal intervention)
- Moderate management (m): 1.1-1.2 (standard practices)
- Intensive management (i): 1.2-1.35 (high-intensity silviculture)
- Reforestation variants (ir, mr): 1.1-1.35 (with planting)
- Adaptive management (afm_m): 1.0-1.35 (climate-responsive)

B.4 Economic Parameters

Table 3: Economic parameters (2024 AUD) used in scenarios

Parameter	**Value**
Carbon price	\$35-70/tCO_2e
Establishment cost	\$1,500-3,000/ha
Management cost	\$25-100/ha/yr
Discount rate	5-7% real
Project period	25-100 years
Buffer pool	5-25%

Economic projections are informed by recent assessments of reforestation and management costs in Australian and global contexts (Austin et al., 2020; Busch et al., 2024; Jonson and Freudenberger, 2011).

B.5 Economic Calculations and Validation Status

Net Present Value:

$$\text{NPV} = -C_0 + \sum_{t=1}^{T} \frac{R_t - C_t}{(1+r)^t} + \frac{V_T}{(1+r)^T} \tag{23}$$

where C_0 = initial establishment cost, R_t = carbon credit revenue (year t), C_t = management costs (year t), V_T = terminal value, and r = real discount rate.

Carbon credit calculation (within crediting period):

$$\text{Credits}_t = \begin{cases} \max(0, \Delta C_t) \times (1-b) \times P_{\text{CO}_2}(t) & \text{if } t \leq T_{\text{crediting}} \\ 0 & \text{if } t > T_{\text{crediting}} \end{cases} \tag{24}$$

where ΔC_t = net carbon change (tCO_2e/ha), b = buffer withholding (default 0.20), $P_{\text{CO}_2}(t)$ = time-varying carbon price (\$/tCO_2e), and $T_{\text{crediting}}$ = crediting period (default 30 years).

Economic parameter validation:

- Carbon price: \$5-200/tCO_2e (market reality)
- Discount rate: 3-12% (project finance standards)

- Buffer: 5-30% (conservative crediting)
- Crediting period: 10-50 years (policy constraints)

Critical limitation: Economic calculations are theoretically sound and parameters are market-informed, but projections have NOT been validated against realized project outcomes, carbon credit revenues, or actual cost structures from completed forest carbon projects. NPV/IRR calculations should inform but not solely determine investment decisions until field validation establishes accuracy.

B.6 Uncertainty Quantification

Monte Carlo analysis samples parameters from defined distributions:

$$\text{Parameter}_i = \text{Base} \times (1 + \sigma \times \mathcal{N}(0, 1)) \tag{25}$$

Parameter distributions:

- Maximum biomass (M): Normal, CV = 15%
- Age at max growth (G): Normal, CV = 10%
- Growth multiplier (y): Normal, CV = 20%
- FPI multiplier: Normal, CV = 25%
- Mortality rates: Beta distribution, bounded by validation ranges
- Disturbance parameters: Gamma distribution for probability and severity

Output statistics: 1000 iterations per scenario provide 50% and 90% confidence intervals, parameter correlation matrices, and sensitivity rankings. Maximum biomass (M) and growth multiplier (y) explain 68% of output variance (Fig. 8).

C Calibration Data

This appendix documents the climate scenarios, management intensities, and validation datasets used to parameterize and test FCL v0.1.

C.1 Climate and Management Scenarios

Table 4: Climate scenario parameters

Scenario	ΔT (°C)	ΔP (%)	FPI ratio	Fire interval	Mortality increase
Current	0	0	1.00	20 yr	1.0×
Paris 1.5°C	+1.5	-5	0.85	15 yr	1.3×
Likely 2°C	+2.0	-10	0.80	12 yr	1.5×
High 3°C	+3.0	-15	0.70	8 yr	2.0×

Sources: Temperature scenarios aligned with IPCC projections (IPCC, 2023). FPI adjustments from Kesteven, J.L. (2004). Fire frequency and mortality increases based on Australian climate-fire relationships (Canadell et al., 2021; Furlaud et al., 2021; McColl-Gausden et al., 2022; Abram et al., 2021).

Table 5: Management intervention specifications

Intensity	y mult	Thin cycle	Burn cycle	Cost ($/ha/yr)	Carbon uplift
None	1.00	–	–	0	0%
Light	1.10	30 yr	10 yr	25	10%
Moderate	1.20	20 yr	7 yr	50	20%
Intensive	1.35	15 yr	5 yr	100	35%

Sources: Management costs from Austin et al. (2020), Busch et al. (2024), and Evans (2018). Carbon uplift estimates from Paul et al. (2018) and Paul and Roxburgh (2020). Thin/burn cycles based on Australian forest management guidelines.

C.2 Validation Plot Distribution

Table 6: TYF validation plot distribution by state and forest type

Source: Forrester et al. (2025) FullCAM national calibration dataset (9,300+ plots total; 2,790 held-out validation plots shown here). Additional data from Volkova et al. (2015).

State	**ETOF**	**EOF**	**AFW**	**Total**	**%**
Victoria	320	425	85	830	30%
NSW	285	510	125	920	33%
Queensland	180	265	95	540	19%
Tasmania	195	125	35	355	13%
Other	0	95	50	145	5%
Total	980	1,420	390	2,790	100%

Table 7: TYF validation plot age distribution (Forrester et al. 2025)

Age Class (years)	**Plots**	**%**	**Mean AGB** (t/ha)	**SD** (t/ha)
0-10	450	16%	25	18
11-30	780	28%	85	42
31-60	920	33%	165	65
61-100	480	17%	215	78
>100	160	6%	245	85

Source: Forrester et al. (2025) validation dataset. AGB values represent mean aboveground biomass for plots in each age class.

C.3 Parameter Sensitivity

Table 8: Sensitivity of 30-year carbon to ±20% parameter changes

Parameter	**Base** (tCO_2e/ha)	**-20%** change	**+20%** change
Max biomass (M)	195	-18%	+18%
Age at max growth (G)	195	-12%	+10%
Mortality rate	195	+8%	-7%
Climate (FPI)	195	-15%	+15%
Management (y)	195	-20%	+20%
Fire frequency	195	+5%	-4%

Note: Sensitivity analysis results from FCL model Monte Carlo simulations (1000 iterations). Base case assumes ETOF forest type under current climate with moderate management. Model uses validated TYF parameters (Forrester et al., 2025; Waterworth et al., 2007).

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