# The Carbon at Risk measure to manage carbon removal risk and guide portfolio construction

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A physical-unit analogue of Value at Risk for forests, geological storage and mixed portfolios

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Rethinking Removals • Climate Resilient Solutions • Carbon Finance Labs • LEEP Institute, University of Exeter • Grantham Research Institute, LSE • CarbonPool • Kita

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LEEP INSTITUTE 10 YEARS

DRAGON CAPITAL

## 1. THE MARKET PROBLEM

### Carbon removals can under-deliver

Carbon dioxide removal is needed at very large scale, but projects differ sharply in cost, durability and risk. Forests burn; geological reservoirs can leak; institutional and technical conditions vary.

Markets still rely on labels such as 'permanent' versus 'non-permanent' or flat buffer rules. These heuristics do not state the probability, magnitude or timing of under-delivery.

The result can be over-collateralisation of low-risk projects, under-protection against high-risk projects, and residual climate risk shifted onto society.

PROJECT OR PORTFOLIO • CONFIDENCE LEVEL α • HORIZON T • TONNES OF $CO_2$

**How much storage could be lost in a bad-tail outcome - and how much must be buffered to make a promise safe?**

## 2. THE MEASURE

### Carbon at Risk in one line

$$\mathrm{CaR}_\alpha^T = Q^T - D_{1-\alpha}^T$$

$Q^T$ = contracted removals
$D^T[1-\alpha]$ = lower-tail quantile of realised storage at T

**DOWNSIDE RISK**
The shortfall that will not be exceeded with probability α.

**BUFFER**
Extra tonnes required to make a delivery obligation safe.

**ILLUSTRATIVE 95% EXAMPLE**
Q = 1,000 kg and $\mathrm{CaR}_{95}$ = 397 kg.
There is a 95% chance that at least 603 kg remains stored. A 397 kg buffer therefore makes a 603 kg obligation 95%-safe.

**Normalise by Q to report CaR as a percentage or kilograms per tonne contracted.**

## 3. PROOF-OF-CONCEPT RESULTS

### One scale, very different permanence risks

**>70%**
**California forest project 95% CaR at 200 years**
single project

**0.15%**
**well-regulated offshore storage 95% CaR at 200 years**
geological storage

**17%**
**poorly regulated onshore storage 95% CaR at 200 years**
geological storage

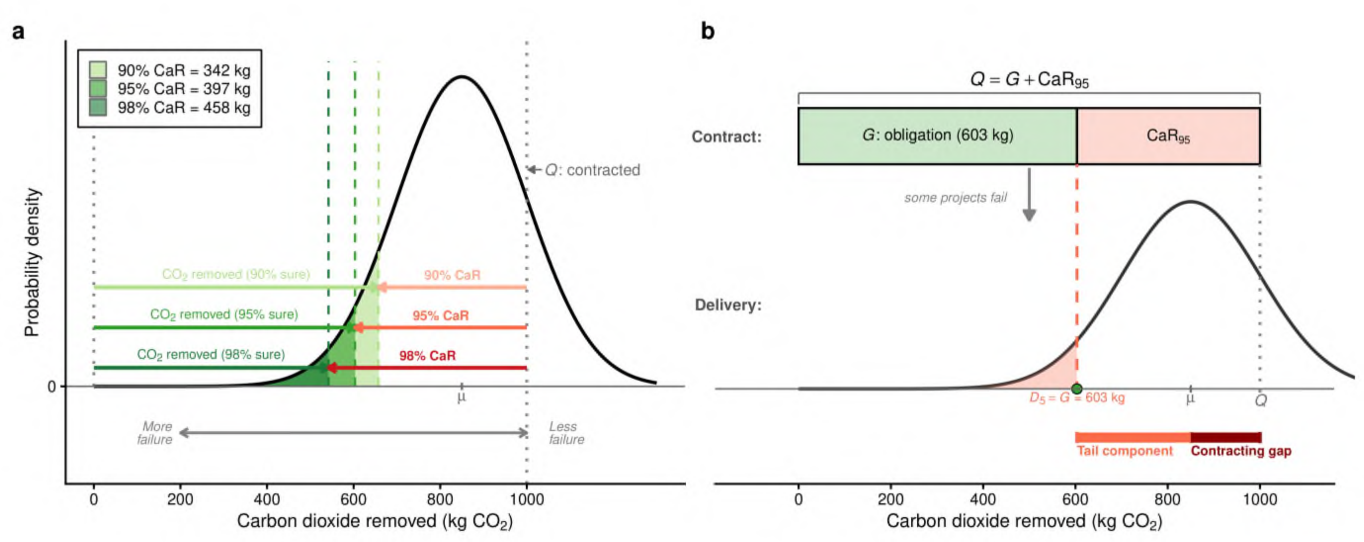
**7 pp**
**reduction in 100-year California CaR from pooling 100 projects when ρ = 0.10**
65% → 57.8%

**61 + 45**
**DACCS + forest projects in the cheapest stylised portfolio meeting a 30,000 t target**
95% confidence

**THE MEAN IS NOT ENOUGH**
Two portfolios can have the same expected storage but very different probabilities of large shortfalls. Risk magnitude and correlation - not qualitative labels - determine the cost-effective mix.

## FROM A DELIVERY DISTRIBUTION TO A BUFFER

### CaR turns the lower tail into an operational procurement rule




1. **CHOOSE THE RISK STANDARD**
Specify the assessment horizon T and confidence level α.

2. **ESTIMATE THE FULL DELIVERY DISTRIBUTION**
Use observations, simulations or both - including the lower tail.

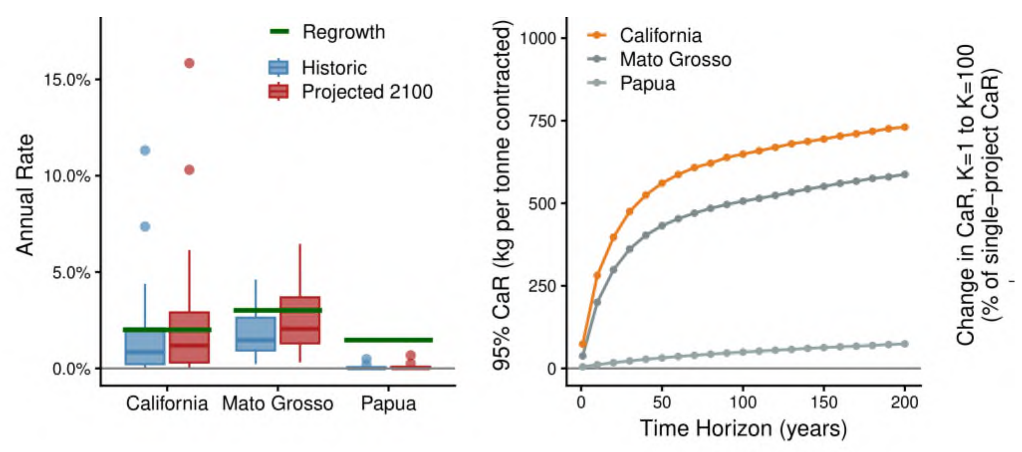
3. **READ THE LOWER-TAIL QUANTILE**
$D^T[1-\alpha]$ is the amount still stored in the adverse tail at horizon T.

4. **SIZE THE CONTRACT AND BUFFER**
Contract Q = G + CaR so the lower-tail delivery equals the obligation G.

**All contracted tonnes - including the buffer - enter the delivery distribution. No "buffer on the buffer" is required.**

## 4. FOREST CARBON

### Wildfire risk accumulates through time



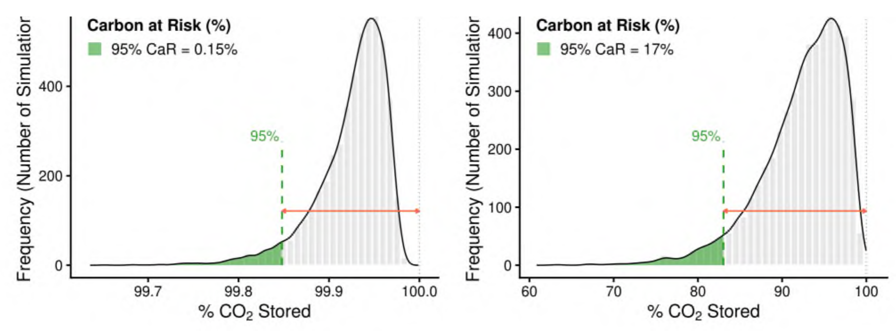

Monte Carlo simulations combine the 2002-2023 fire record, region-specific regrowth and a 0.5% annual climate-driven increase in burn rates.

**California: $\mathrm{CaR}_{95}$ ≈ 65% at 100 years and exceeds 70% at 200 years.**

Slow regrowth and a skewed fire tail matter. Fitting an extreme-value tail raises the 100-year estimate by about 23%.

## 5. GEOLOGICAL STORAGE

### "Permanent" is not a uniform risk class




**0.15%**
**well-regulated offshore**
200-year $\mathrm{CaR}_{95}$

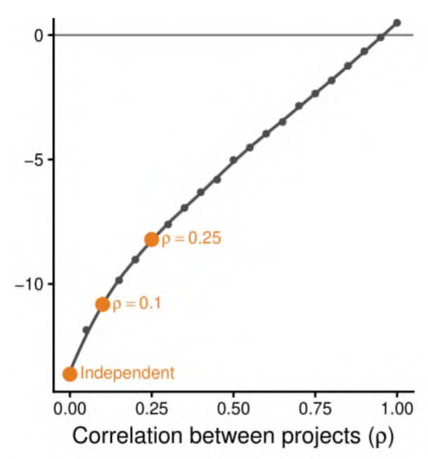
**17%**
**poorly regulated onshore**
200-year $\mathrm{CaR}_{95}$

Weak regulation degrades integrity through unplugged legacy wells and incomplete well inventories. At 1,000 years, $\mathrm{CaR}_{95}$ is 0.66% offshore but about 20% onshore.

**Site selection and regulation are first-order determinants of risk within the same technology.**

## 6. DIVERSIFICATION

### Correlation sets a floor to risk reduction




**WHAT DIVERSIFIES?**

Idiosyncratic project losses can diversify. Shared climatic, regulatory or policy drivers cannot.

**WHAT DOES NOT?**

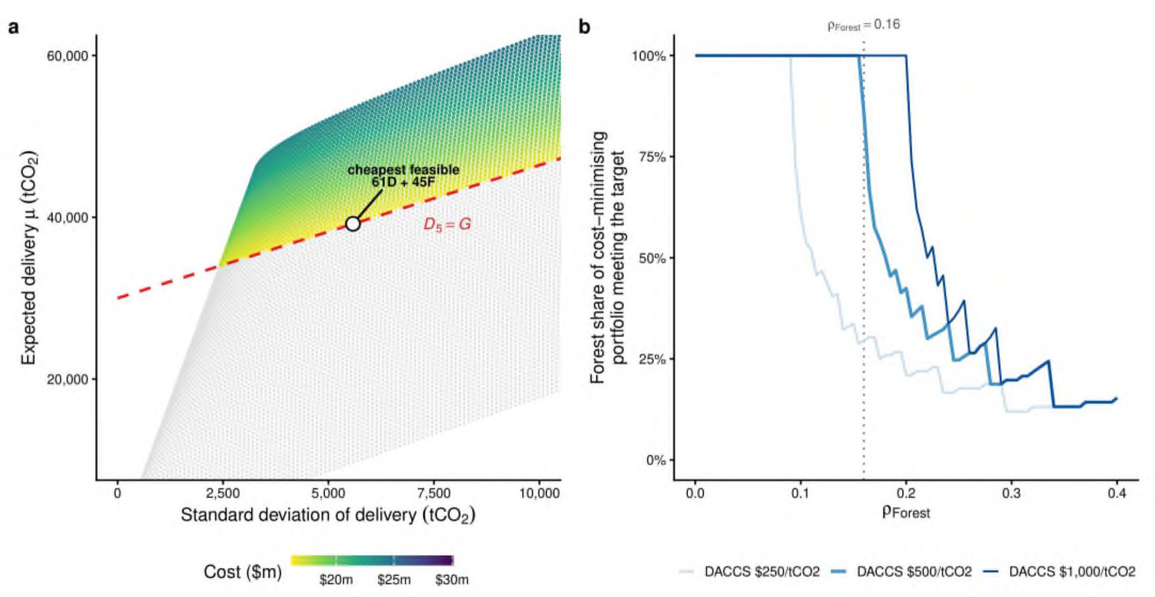
Diversification narrows the tail component of CaR, but leaves the contracting gap untouched.

**For 100 California projects, CaR falls only from about 65% to 57.8% when pairwise correlation is 0.10.**

**Most gains arrive by 20-50 projects. Spreading across regions and risk drivers matters more.**

## 7. PORTFOLIO DESIGN UNDER RISK

### Risk, cost and correlation jointly determine the cheapest mix




**STYLISED PROCUREMENT EXAMPLE**

Goal: at least 30,000 $tCO_2$ still stored after 200 years with 95% confidence.

Forest: $40/t, risky and climate-sensitive.
DACCS: $500/t, near-certain and regulation-sensitive.

**Cheapest feasible mix: 61 DACCS + 45 forest projects; $116.15m; $D_5$ = 30,016 $tCO_2$.**

Above forest correlation ρ ≈ 0.16, buying more forest stops purchasing enough tail protection and the optimum becomes mixed.

**A technology's portfolio value depends on what it is combined with.**

## 8. MARKET DESIGN AND USES

### What CaR changes in practice

1. **BUFFER AND CREDITING**
Size reserves to the measured tail rather than a conventional flat percentage.

2. **INSURANCE AND RESERVES**
Give actuaries a common basis for pricing reversal risk and holding capital.

3. **PROCUREMENT AND PORTFOLIOS**
Compare effective cost per tonne delivered and minimise cost subject to permanence.

4. **DISCLOSURE AND UPDATES**
State α, T, distributions and unmodelled risks; update estimates as data accumulate.

**PROOF OF CONCEPT: conditional on genuine removals entering storage; some delivery, additionality, tenure and technical risks remain outside the case studies.**

MEASURE THE TAIL • DISCLOSE THE ASSUMPTIONS • BUILD THE PORTFOLIO

LEEP INSTITUTE — Land, Environment, Economics and Policy Institute

UKRI Natural Environment Research Council

CaR tool

BIOADD Project

Dragon Capital Chair

Lee et al (2026) Carbon at Risk