

Exploring Bioenergy's Role in Net-Zero Futures Using the IPCC AR6 Scenario Database

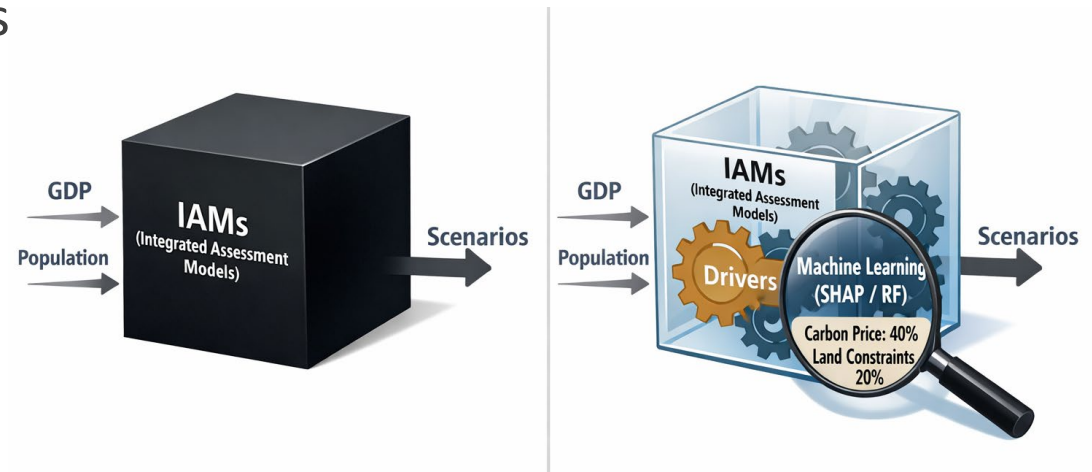


Bioenergy towards net-negative/neutral futures, 21 January 2025, Graz Austria

Dr. Alexandros Tsimpoukis, Mr. Michael Madianos, Dr. Panagiotis Fragkos

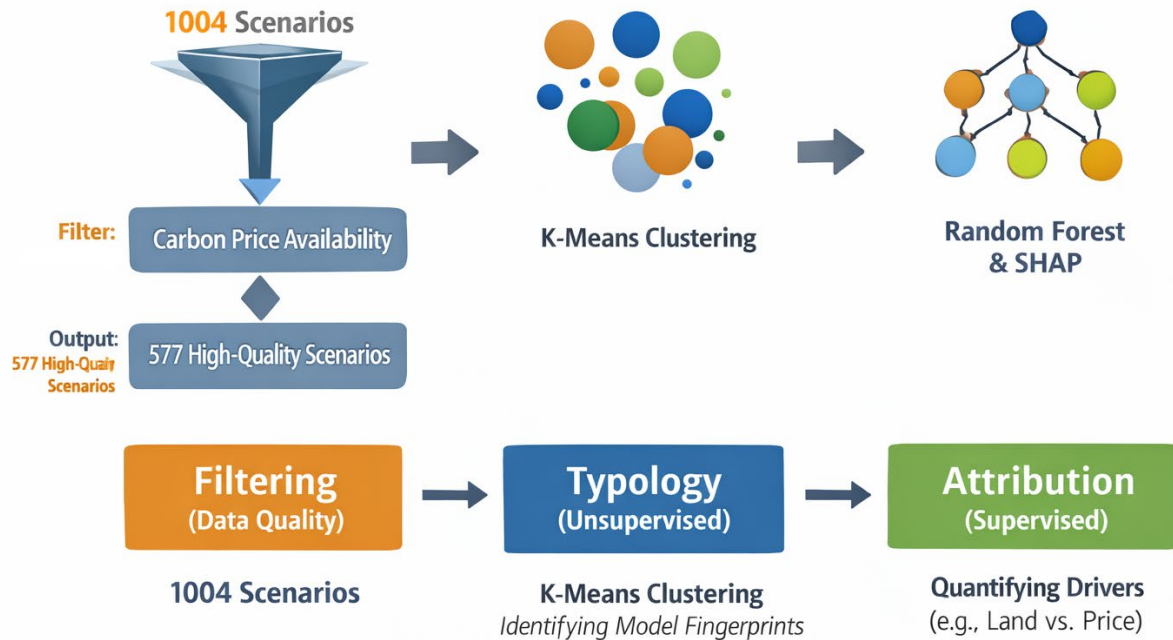
Introduction

- Bioenergy (BECCS) is critical for Net Zero, but projected deployment varies wildly across scenarios.
- We want to analyze the sectoral bioenergy use patterns and how bioenergy interacts with land-based carbon removal options in ambitious mitigation pathways.
- Using the IPCC AR6 Scenario Database, we evaluate synergies and correlations between bioenergy variables across hundreds of mitigation scenarios.
- Two result Sections:
 - Section 1: Analysis for biomass use by major sector and model identity
 - Section 2: Finding the drivers for BECCs and A/R



Methodology

Methodology Pipeline



- Geography: Global (World)
- Sectors: Energy (BECCS for Power) vs. Land (Afforestation).
- Clustering with k-means
- Find drivers - Apply **Random Forest regression** (and/or **Xgboost**) in the lateral (**model**) dimension for a **single** year (e.g., **2050**).
- To explain model predictions, we use the SHapley Additive exPlanations (SHAP) algorithm.

Preprocessing and selection of variables

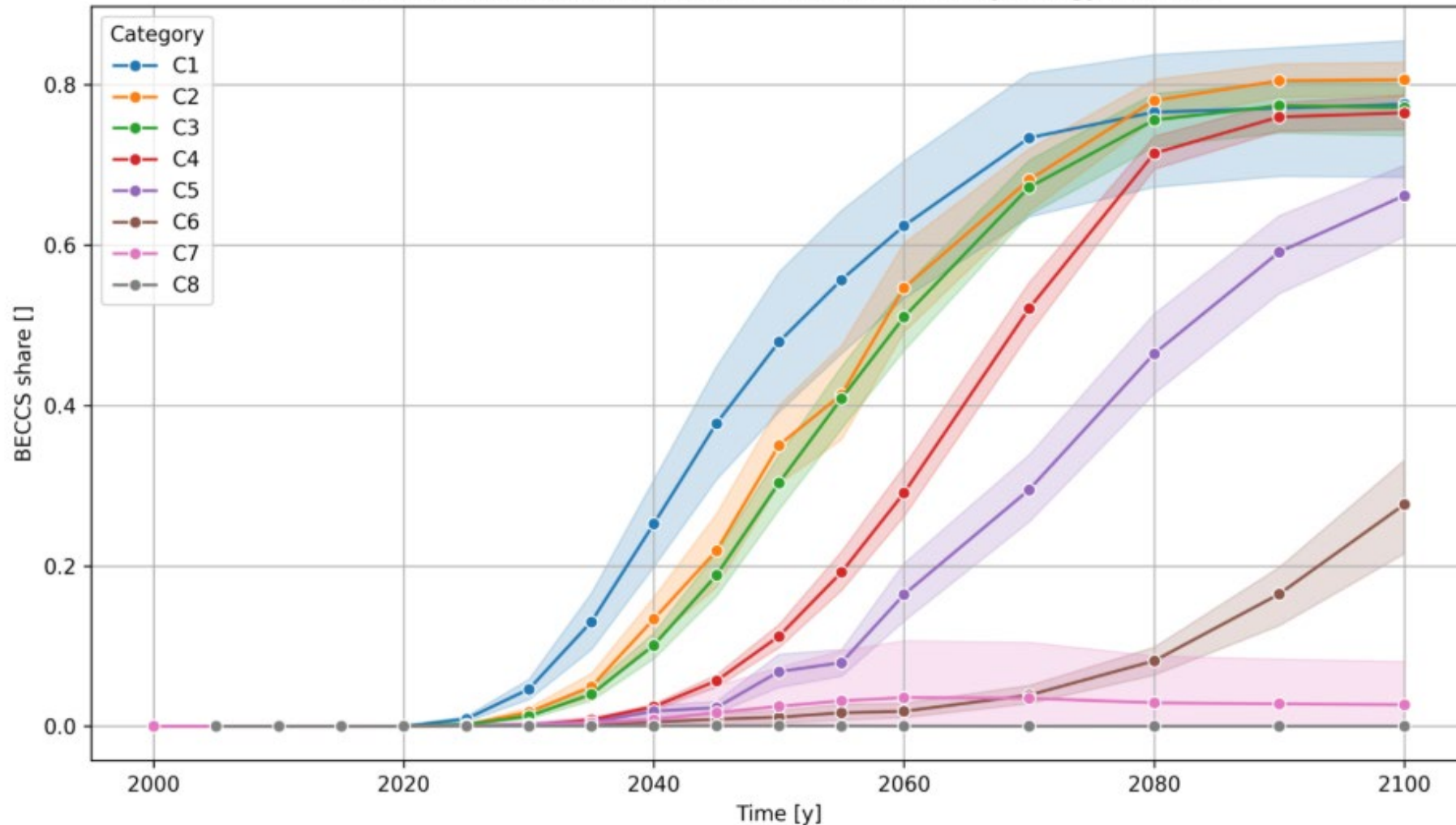
- Initial selected variables (features) and missing data (%) per variable

| Policy Drivers | Economic/Market Drivers | Land & Agriculture Drivers |
|--|---|---|
| Price Carbon (5%) | Price Primary Energy Biomass (44%) | Land Cover Cropland (19%) |
| Policy Cost Additional Total Energy System Cost (67%) | Price Primary Energy Coal (29%) | Land Cover Forest (18%) |
| | Price Primary Energy Gas (29%) | Yield Cereal |
| | Price Secondary Energy Electricity (31%) | Agricultural Demand Crops Food |
| | | Price Agriculture Corn Index |

- Selection of Scenario is critical!
 - Too many scenario categories identified in IPCC (C1-C8) -> less data to work with
 - Only three scenario categories (C1-C3) for **K-means clustering**
 - Final selection of scenario categories-> **(C1-C6) for RF**
- Example: Original Scenario Count: 1004 -> Final Scenario list -> Count: 577 for BECCs analysis

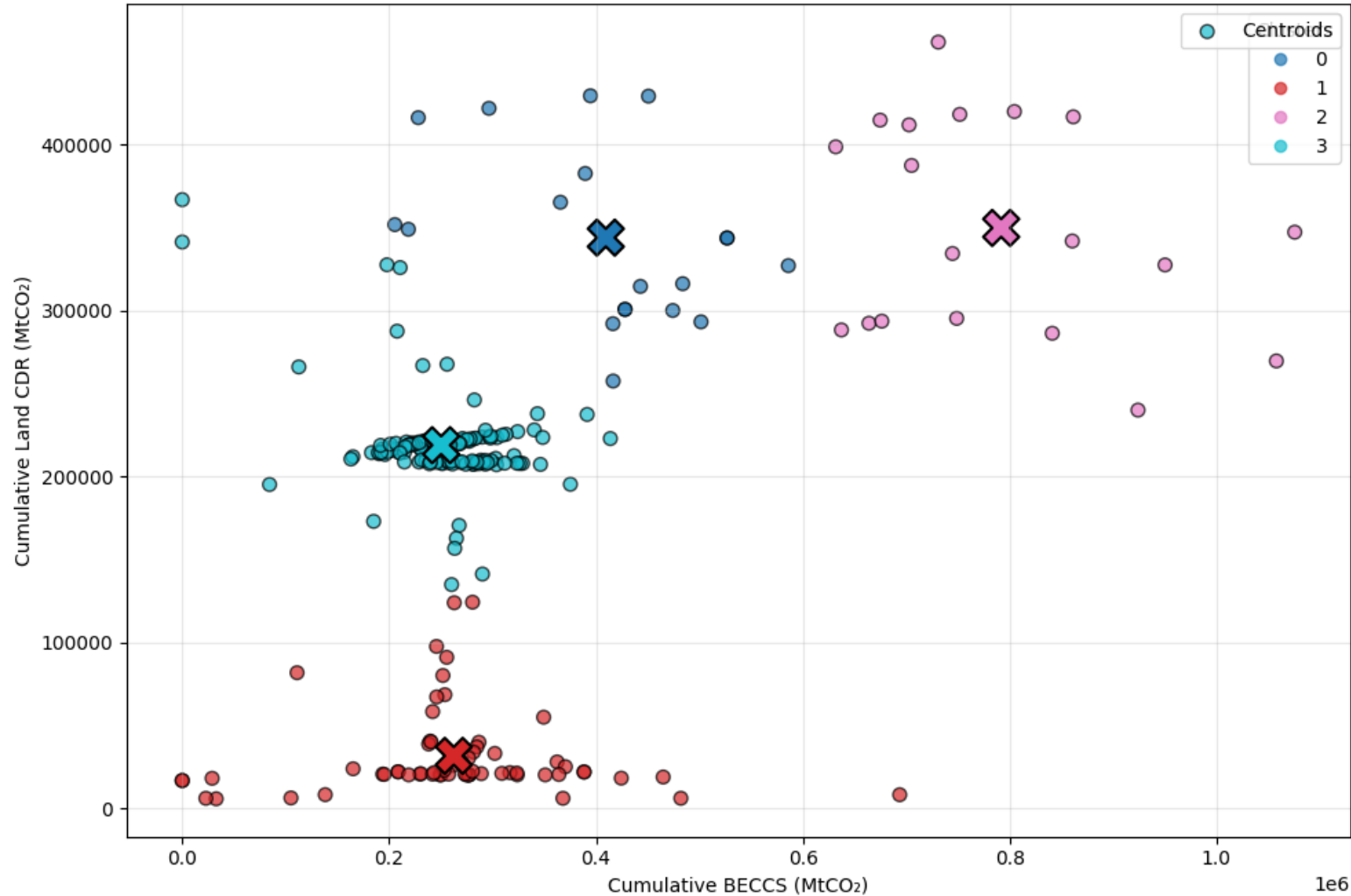
Results – BECCS share by scenario type

Share of BECCS use for All sectors over total Primary energy Biomass

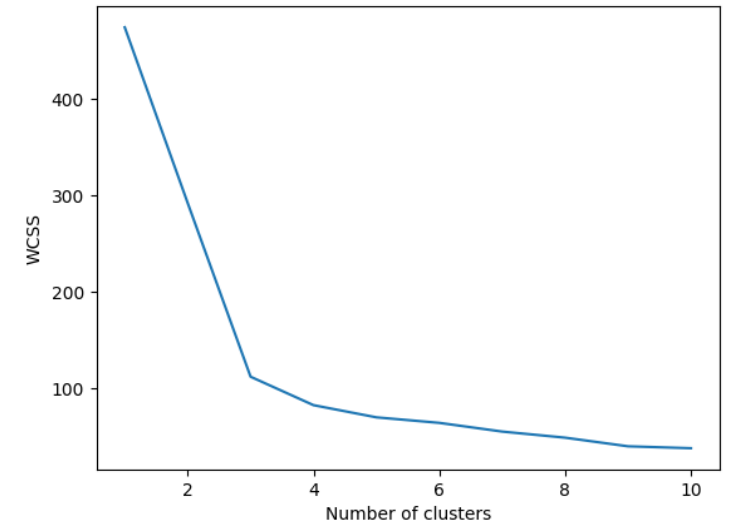


Results – Clusters

K-Means Clusters in Original Units



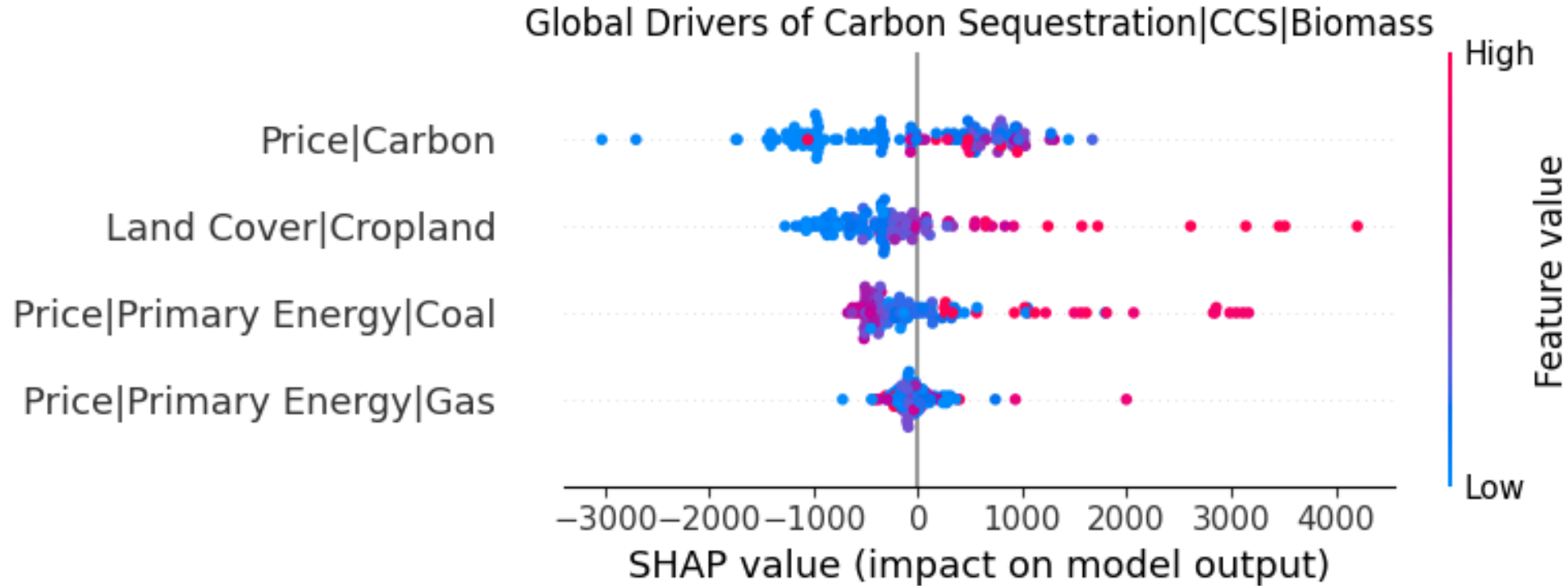
The Elbow Method



Results – The Four Archetypes

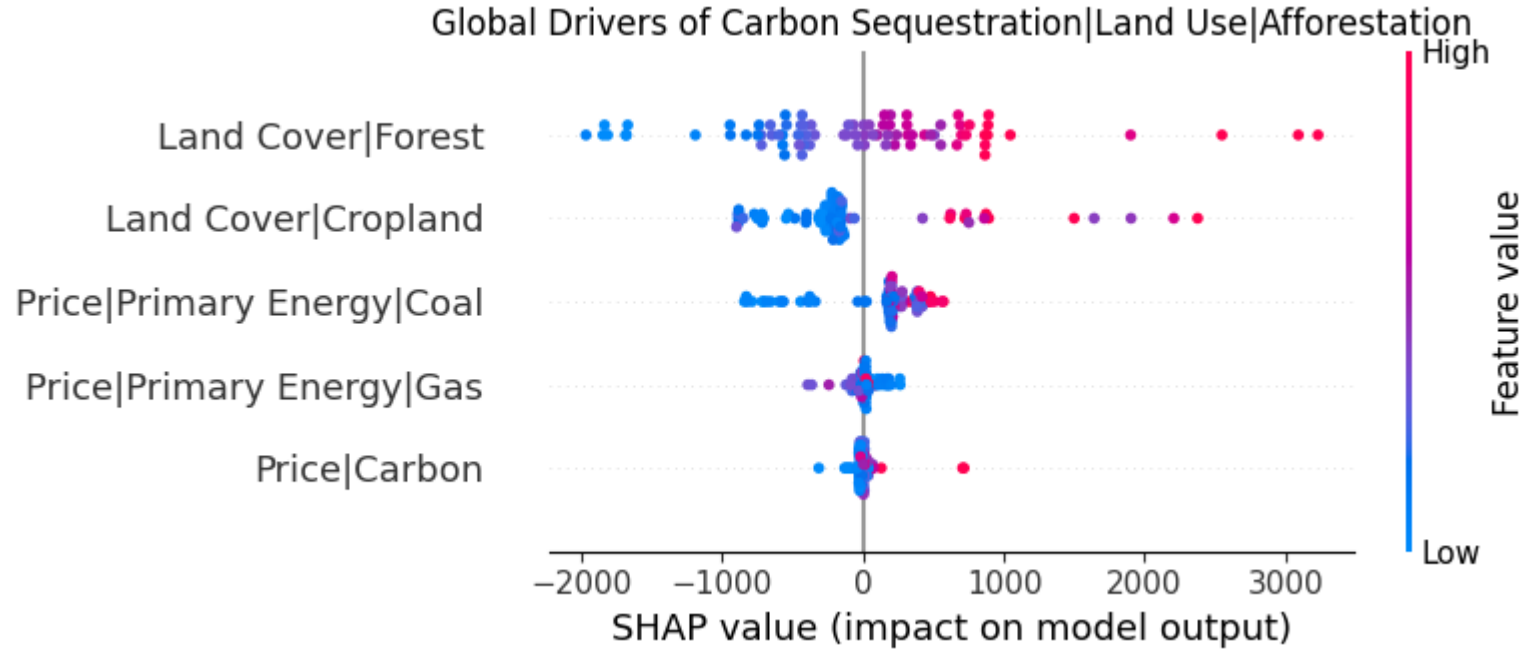
| Cluster | Scenarios | Narrative | Behaviour | Distribution by model |
|----------|-----------|----------------------------|---|---|
| 0 (Blue) | 19 | Land-focused mitigation | High Land CDR; Moderate BECCS. This group prioritizes land-based removal over extreme tech solutions. | IMAGE 3.2 → 6, REMIND 1.7 → 2 REMIND-MAgPIE 1.7–3.0 → 11 |
| 1 (Red) | 63 | Tech-driven / Land-sparing | Low Land CDR; Moderate BECCS. Distinctly avoids land-based measures in favor of technological removal. | REMIND-MAgPIE 2.1–4.2 → 55 REMIND-MAgPIE 2.1–4.3 → 6 C-ROADS→2 |
| 2 (Pink) | 19 | Extreme removal / outlier | Highest BECCS & Land CDR. Represents the most aggressive mitigation pathways. | IMAGE 3.2 → 13 REMIND-MAgPIE 1.7-3.0 → 6 |
| 3 (Cyan) | 136 | Balanced hybrid mitigation | Moderate BECCS & Land CDR. The most populated cluster representing "middle-of-the-road" strategies with balanced inputs. | MESSAGEix-GLOBIOM 1.1 → 78, WITCH 5.0 → 35, REMIND-MAgPIE 1.7–3.0 → 4, REMIND-MAgPIE 2.1-4.2 → 5, REMIND 1.7 (4), AIM/CGE (2), MESSAGE 1.0 (2), C-ROADS (3), IMAGE 3.2 (3) |

Results – BECCs analysis - 2050



| Variable | SHAP Impact (Mean val) | Importance |
|---------------------------|------------------------------|------------|
| Price Carbon | 773 Increases BECCS (+) | 24.5 |
| Land Cover Cropland | 627 Increases BECCS (+) | 50.1 |
| Price Primary Energy Coal | 598 Increases BECCS (+) | 18.7 |
| Price Primary Energy Gas | 165 Decreases BECCS (-) | 7.5 |

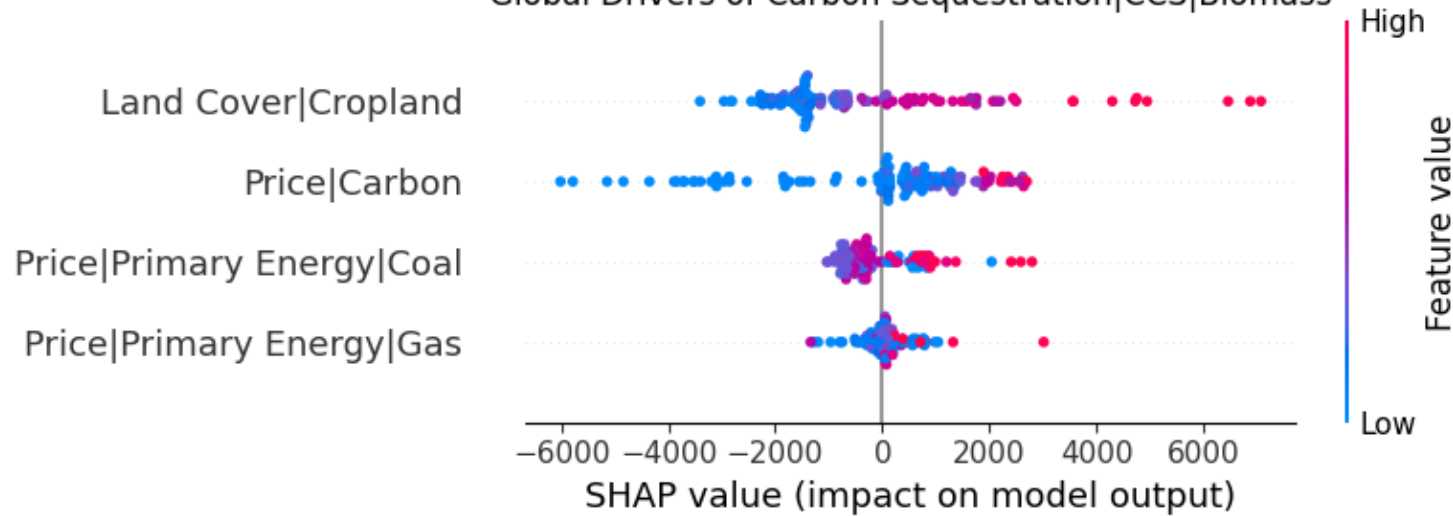
Results – A/R analysis - 2050



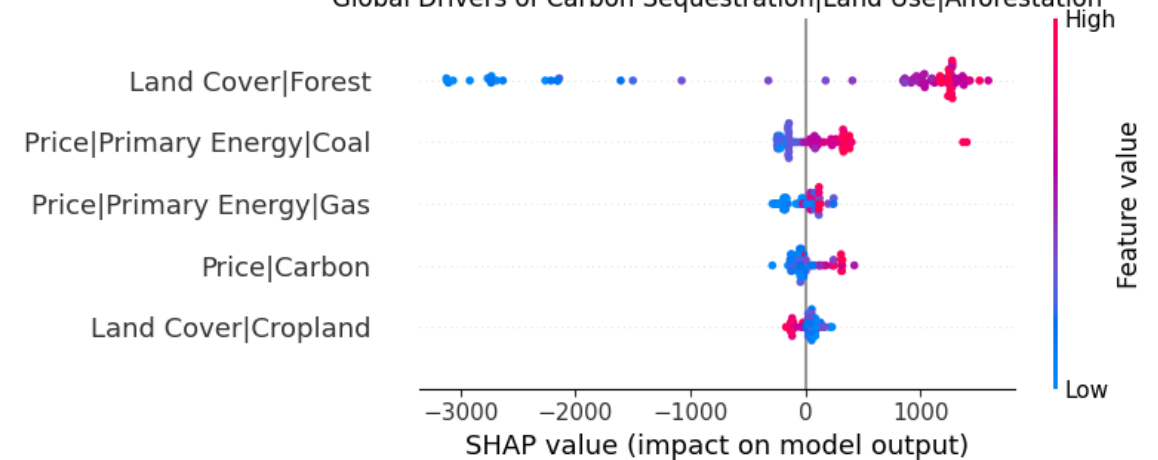
| Variable | SHAP Impact (Mean val) | Importance |
|---------------------------|--------------------------|------------|
| Land Cover Forest | 695 Increases (+) | 43.2 |
| Land Cover Cropland | 486 Increases (+) | 37.9 |
| Price Primary Energy Coal | 347 Increases (+) | 12.5 |
| Price Primary Energy Gas | 66 Decreases (-) | 3.6 |
| Price Carbon | 47 Increases (+) | 2.8 |

Results – Same remarks in 2100?

Global Drivers of Carbon Sequestration|CCS|Biomass



Global Drivers of Carbon Sequestration|Land Use|Afforestation



Conclusion and Next Steps

- Our analysis shows that BECCS is the preferred option to use biomass in ambitious mitigation scenarios due to its dual role (providing both energy and CO₂ removal).
- BECCs and A/R often compete in model logic (Cluster 0 vs 1). Achieving 'Net Negative' requires shifting to the 'Synergy' clusters (2 & 3), which requires explicit policy support for both sectors, not just a generic carbon price.
- Economic signals (Carbon Price) are the strongest lever for deployment, often overpowering land constraints in models.
- Many variables are missing so the analysis becomes more difficult and some more complex driving mechanisms cannot be found.
- Next Steps:
 - **Sectoral Fingerprints:** Move beyond global aggregates to create specific "Bioenergy Fingerprints" for Transport vs. Power sectors.
 - **Imputation:** Extend analysis using imputed data (Prütz et al.) to fill gaps in non-CO₂ and specific bioenergy feedstock variables.

For more information:

www.cdr-uptake.eu

And follow us on:

[linkedin.com/company/cdr-uptake](https://www.linkedin.com/company/cdr-uptake)



This project has received funding from the European Union's Horizon Europe programme under grant agreement No 101081521. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.



Thank you for your attention!

Questions?



For questions contact: alexandros.Tsimpoukis@ricardo.com,
michael.madianos@ricardo.com, panagiotis.fragkos@ricardo.com