

AFFORESTATION FOR NET ZERO

- In order to achieve Net Zero CO₂ emitted by 2050, the UK government is considering planting trees to sequester carbon.
- The Natural Environment Valuation (NEV) suite of models ([7]) simulates ecosystem services, food production and biodiversity and can be used to help decision makers.
- The model has 6 inputs: prices offered per planted ha for 2 types of tree species, with 2 types of management (4 inputs in total), payment per ton of CO₂ captured and annual budget.
- The model outputs include: a) Categorical maps in 2030, 2040, 2050 indicating what tree is planted where; b) Biodiversity net gain for different groups of species; c) Time series of different important indicators for 150 years.

ECOLOGICAL MODELS EMULATION USING DGPs

- Gaussian Process (GP) surrogate models can be used to create replicas of the original model that are much faster with a quantification of uncertainty ([1]).
- Given a model input \mathbf{x} and a p -dimensional model output $\mathbf{Y}(\mathbf{x})$, the general approach ([2], [3]), consists in finding a reduced rank latent basis representation and a transform $g: \mathbb{R}^p \rightarrow \mathbb{R}^p$ s.t.:

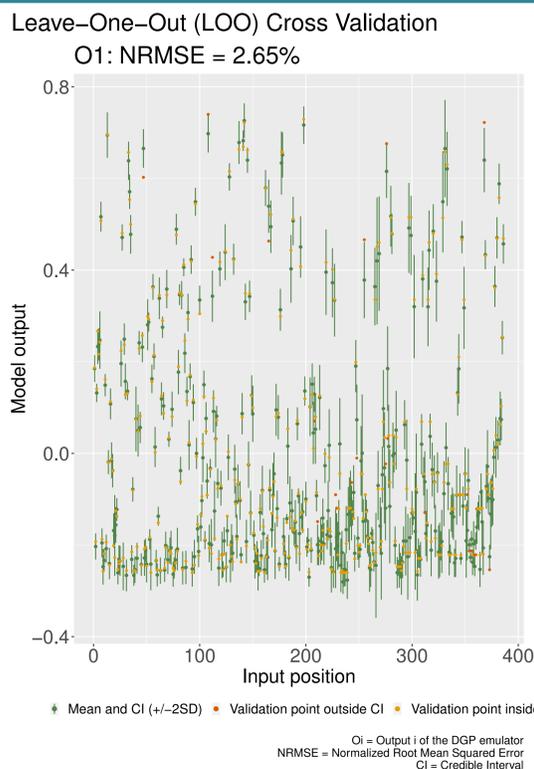
$$\mathbf{Y}(\mathbf{x}) \approx g(\boldsymbol{\mu} + \mathbf{K}\mathbf{W}(\mathbf{x})) \quad (1)$$

- \mathbf{K} is an orthonormal basis of size $N \times J$, $\boldsymbol{\mu}$ is a mean, and $\mathbf{W}(\mathbf{x})$ is a vector of basis multipliers of size J . g , $\boldsymbol{\mu}$ and \mathbf{K} are calibrated using an existing set (\mathbf{X}, \mathbf{y}) , of known true model responses for a series of n design points.
- The surrogate is a probabilistic model determining the conditional distribution $f(\mathbf{W}(\mathbf{x})|\mathbf{x}, \mathbf{X}, \mathbf{y})$ for all $\mathbf{x} \in \mathcal{X}$.
- We not only use GPs but also their extension adapted to non-stationary processes: Deep Gaussian Processes (DGPs) that are networks of GPs ([5], [4], [6]):

$$W_\ell(\mathbf{x}) \sim DGP(0, r_\ell(\mathbf{x}, \mathbf{x}'))$$

APPLICATION TO GREENHOUSE GAS REMOVAL

- The general structure from equation (1) was used to fit surrogates to the key outputs of the model.
- Biodiversity metrics could be emulated with \mathbf{K} and g equal to identity.
- The figure shows leave one out cross-validation (LOOCV) for a 2-layer DGP fitted to the increase in bee populations (y-axis) as the policies change.
- For time series, we can set g as identity and use Singular Value Decomposition (SVD) (see [2]) to derive \mathbf{K} and $\mathbf{W}(\mathbf{x})$.
- Emulating categorical maps with DGPs requires a new methodology that will be presented in an upcoming publication.



MODEL INVERSION

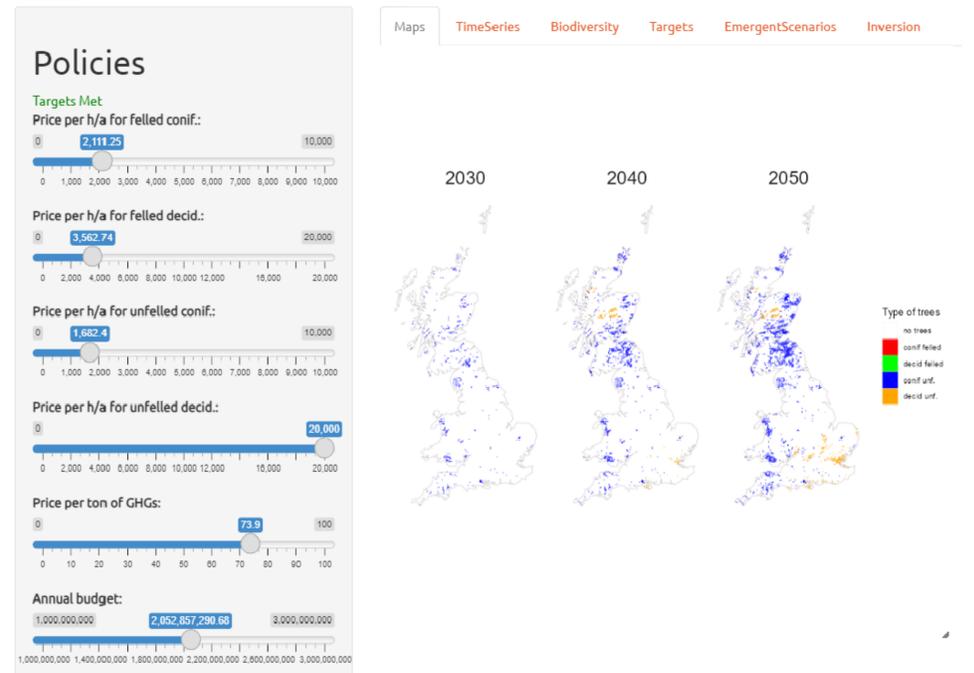
- We can 'invert the model', i.e. set targets on the outputs and obtain the space of possible inputs that is target-compatible.
- Assume an output $Y(\mathbf{x}) \in \mathbb{R}$ for which we want to meet a target \mathcal{T} .
- We want to rule out the $\mathbf{x} \in \mathcal{X}$ s.t. $\mathbb{P}(Y(\mathbf{x}) \geq \mathcal{T}) \leq \alpha$; $0 < \alpha < 0.5$.
- We define the Implausibility (as in [8]):

$$I(\mathbf{x}) = \frac{\mathcal{T} - E[Y(\mathbf{x})]}{\sqrt{\text{var}[Y(\mathbf{x})]}}$$

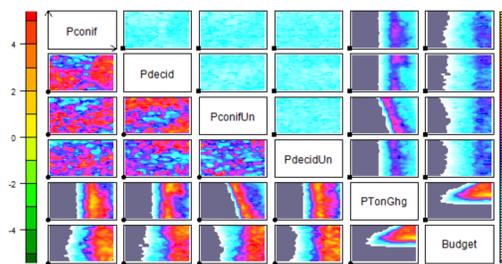
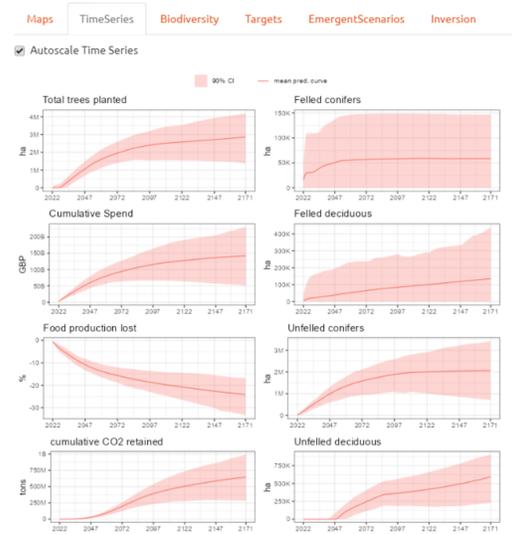
- We can show that:
- $$\mathbb{P}(Y(\mathbf{x}) \geq \mathcal{T}) \leq \alpha \Leftrightarrow \sqrt{\frac{1-\alpha}{\alpha}} \leq I(\mathbf{x}).$$
- This inequality can be used to exclude values of \mathbf{x} .

- This can be extended to targets on multiple outputs.

RESULTS: R SHINY APP DISPLAY



- Our surrogates are embedded into an R shiny app. The top figure shows an example of categorical map output.
- The right hand side figure shows another tab of the same app with the 8 time series.
- The uncertainty due to the emulation for the time series is displayed around the mean.



- To explore the target compatible space we can use multiple bivariate plots showing what percentage of policy space is retained given that 2 of the inputs are fixed within a small square (see [9]).

IMPACT OF THIS WORK AND CONCLUSION

- The work presented has the potential to transform the way decision by policy makers tackling climate change and ecosystem restoration are taken by giving direct access to the results of state-of-the-art ecological models in real time.
- This work will be extended further by developing tools to enhance the exploration of the target-compatible space, help make decisions at a more granular parcel level and by increasing the number of outputs, including fire hazard risk, flooding risk, recreation value...

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