Supplementary 3. Robust optimization models

A Baseline model

To establish a base of comparison with the robust optimization scenarios, we computed a baseline solution for the strategic forest planning problem, aiming to maximize forest profitability (NPV) and disregarding management impacts on biodiversity and storm risk.

$$MaxZ = \sum_{i \in P} \sum_{j \in M} AvgNpv_{ij} x_{ij} \tag{A1}$$

$$\sum_{j \in M} x_{ij} = 1 \qquad \forall i \tag{A2}$$

The objective function Eq. (A1) maximizes mean NPV across the climate change scenarios included in our analysis. Constraint Eq. (A2) limits the available area for forest management. For a description of model's parameters see Table A1.

B Model for wind risk mitigation

In the preference scenario B, we applied the robust optimization framework developed by Ben-Tal et al. (2009), specifically using a safe tractable approximation of ambiguous chance constraints, extending the approach employed in Augustynczik et al. (2018). We constructed a Bernstein approximation to establish the worst-case scenarios of forest profitability or biodiversity indicators (in the case of preference scenarios B and C). This approximation establishes a bound on the sum of uncertain variables using convex functions to compute the Bernstein uncertainty set, which is a more general case of the ball box uncertainty sets (e.g Gorissen et al. 2015). The Bernstein approximation offers a same level of protection of the latter uncertainty sets, but with a lower degree of conservativeness (Ben-Tal et al. 2009).

The model had the aim to maximize the worst-case Value-at-Risk (VaR) of forest profitability under storm risk, economic uncertainty and climate change. The worst-case VaR was introduced by Ghaoui et al. (2003) and calculates a bound on the worst-case forest profitability with only partial information on the distribution of uncertain data. Opposed to the conventional VaR metric, the worst-case VaR is a coherent risk measure (Matthies et al. 2019). The objective function in the optimization model was given by the sum of the mean NPV, reduced by the worst 5% NPV deviations in terms of storm damage and climate change (assuming a symmetric distribution of perturbations). Following the objective function introduced by Lempert and Collins (2007), we introduced in the objective function the additional parameter λ, which enables the control the weight of the best guess of the NPV and the worst-case scenarios. Therefore, decision-makers may select the degree of conservativeness in the solution. This functional form has the advantages of preserving ordering and it reduces to the min-max criterion (Lempert and Collins 2007).

$$MaxZ = \lambda\left(AvgNpv_{ij}x_{ij} + sAvgNpv_{ij}y_{ij} + psAvgNpv_{ij}z_{ij}\right) - (1-\lambda)t_{NPV} \tag{B1}$$

$$-t_{NPV} + \vartheta\sum_{i\in P}\sum_{j\in M}\begin{bmatrix}\ln(\cosh(\frac{NpvSd_{ij}x_{ij}}{\vartheta})) + \ln(\cosh(\frac{pNpvSd_{ij}y_{ij}}{\vartheta})) + \\ \ln(\cosh(\frac{psNpvSd_{ij}z_{ij}}{\vartheta}))\end{bmatrix} + \vartheta\ln(\frac{1}{\varepsilon}) \leq 0 \tag{B2}$$

$$\sum_{j\in M}\left(x_{ij} + y_{ij} + z_{ij}\right) = 1 \qquad \forall i \tag{B3}$$

The objective function Eq. (B1) maximizes the weighted sum of the mean NPV reduced by the worst-case deviations across all plots (t_{NPV}), with the weighting parameter λ set to 0.5. This weighting scheme reduces the model to the maximization of the VaR. Nevertheless, it can be modified to control the conservativeness of the solution, according to the decision-maker preferences. Constraint Eq. (B2) assigns the 5% worst-case deviations for forest profitability (ε = 0.05) based on a Bernstein approximation scheme (Ben-Tal et al. 2009) to variable t_{NPV} . Constraints Eq. (B3) limits the total managed area of the plot considering the area under management with no salvage logging (x_{ij}), full (y_{ij}) and partial salvage logging (z_{ij}).

C Balanced solution

We developed a third preference scenario, where managers aim to promote forest biodiversity under storm risk and climate change, while maintaining the economic feasibility of forest management. This is typical, for example, to the management of publicly owned forests with high conservation value, where external funding is undesirable to adopt conservation programs (see e.g. Augustynczik et al. 2019). We constructed here Compromise Programming (CP) model, following Yousefpour and Augustynczik (2019) and Knoke et al. (2020). The optimization model aimed to minimize the deviations in the worst-case species richness and TreM richness between the first and last period of the planning horizon, applying the same uncertainty sets of preference scenario B. The balanced solution aimed to minimize the deviations of all biodiversity indicators compared to their ideal value (maximum attainable change in richness in the worst-case scenarios) during the simulation period, normalizing these differences by their range (maximum – minimum attainable values in the worst-case scenarios). Hence, all indicators had a same weight in the objective function, so as not favor specific biodiversity indicators.

$$MinZ = \sqrt{{\beta_{bird}}^2 + {\beta_{bat}}^2 + {\beta_{insect}}^2 + {\beta_{trem}}^2} \tag{C1}$$

$$\beta_{bird} \geq \frac{\max\limits_{x,y,z} Bird_{VaR} - \left[\begin{array}{c} \lambda \sum\limits_{i \in P} \sum\limits_{j \in M} \left(AvgBird_{ij} x_{ij} + sAvgBird_{ij} y_{ij} + psAvgBird_{ij} z_{ij} \right) \\ -(1-\lambda) t_{bird} \end{array} \right]}{\max\limits_{x,y,z} Bird_{VaR} - \min\limits_{x,y,z} Bird_{VaR}} \tag{C2}$$

$$\beta_{bat} \geq \frac{\max\limits_{x,y,z} Bat_{VaR} - \left[\begin{array}{c} \lambda \sum\limits_{i \in P} \sum\limits_{j \in M} \left(AvgBat_{ij} x_{ij} + sAvgBat_{ij} y_{ij} + psAvgBat_{ij} z_{ij} \right) \\ -(1-\lambda) t_{bat} \end{array} \right]}{\max\limits_{x,y,z} Bat_{VaR} - \min\limits_{x,y,z} Bat_{VaR}} \tag{C3}$$

$$\beta_{insect} \geq \frac{\max\limits_{x,y,z} Insect_{VaR} - \left[\begin{array}{c} \lambda \sum\limits_{i \in P} \sum\limits_{j \in M} \left(AvgInsect_{ij} x_{ij} + sAvgInsect_{ij} y_{ij} + psAvgInsect_{ij} z_{ij} \right) \\ -(1-\lambda) t_{insect} \end{array} \right]}{\max\limits_{x,y,z} Insect_{VaR} - \min\limits_{x,y,z} Insect_{VaR}} \tag{C4}$$

$$\beta_{trem} \geq \frac{\max\limits_{x,y,z} TreM_{VaR} - \left[\begin{array}{c} \lambda \sum\limits_{i \in P} \sum\limits_{j \in M} \left(AvgTreM_{ij} x_{ij} + sAvgTreM_{ij} y_{ij} + psAvgTreM_{ij} z_{ij} \right) \\ -(1-\lambda) t_{trem} \end{array} \right]}{\max\limits_{x,y,z} TreM_{VaR} - \min\limits_{x,y,z} TreM_{VaR}} \tag{C5}$$

$$-t_{bird} + \vartheta_{bird} \sum_{i \in P} \sum_{j \in M} \left[\begin{array}{c} \ln(\cosh(\frac{BirdSd_{ij} x_{ij}}{\vartheta_{bird}})) + \ln(\cosh(\frac{pBirdSd_{ij} y_{ij}}{\vartheta_{bird}})) + \\ \ln(\cosh(\frac{psBirdSd_{ij} z_{ij}}{\vartheta_{bird}})) \end{array} \right] + \vartheta_{bird} \ln(\frac{1}{\varepsilon}) \leq 0 \tag{C6}$$

$$-t_{bat} + \vartheta_{bat} \left[\begin{array}{c} \ln(\cosh(\frac{BatSd_{ij} x_{ij}}{\vartheta_{bat}})) + \ln(\cosh(\frac{pBatSd_{ij} y_{ij}}{\vartheta_{bat}})) + \\ \ln(\cosh(\frac{psBatSd_{ij} z_{ij}}{\vartheta_{bat}})) \end{array} \right] + \vartheta_{bat} \ln(\frac{1}{\varepsilon}) \leq 0 \tag{C7}$$

$$-t_{insect} + \vartheta_{insect} \sum_{i \in P} \sum_{j \in M} \left[\begin{array}{c} \ln(\cosh(\frac{InsectSd_{ij} x_{ij}}{\vartheta_{insect}})) + \ln(\cosh(\frac{pInsectSd_{ij} y_{ij}}{\vartheta_{insect}})) + \\ \ln(\cosh(\frac{psInsectSd_{ij} z_{ij}}{\vartheta_{insect}})) \end{array} \right] + \vartheta_{insect} \ln(\frac{1}{\varepsilon}) \leq 0 \tag{C8}$$

$$-t_{trem}+\vartheta_{trem}\sum_{i\in P}\sum_{j\in M}\left[\begin{array}{c}\ln(\cosh(\frac{TreMSd_{ij}x_{ij}}{\vartheta_{trem}}))+\ln(\cosh(\frac{pTreMSd_{ij}y_{ij}}{\vartheta_{trem}}))+\\ \ln(\cosh(\frac{psTreMSd_{ij}z_{ij}}{\vartheta_{trem}}))\end{array}\right]+\vartheta_{trem}\ln(\frac{1}{\varepsilon})\leq 0 \quad \text{(C9)}$$

$$AvgNpv_{ij}x_{ij}+sAvgNpv_{ij}y_{ij}+psAvgNpv_{ij}z_{ij}-t_{NPV}\geq 0 \quad \text{(C10)}$$

$$-t_{NPV}+\vartheta\sum_{i\in P}\sum_{j\in M}\left[\begin{array}{c}\ln(\cosh(\frac{NpvSd_{ij}x_{ij}}{\vartheta}))+\ln(\cosh(\frac{pNpvSd_{ij}y_{ij}}{\vartheta}))+\\ \ln(\cosh(\frac{psNpvSd_{ij}z_{ij}}{\vartheta}))\end{array}\right]+\vartheta\ln(\frac{1}{\varepsilon})\leq 0 \quad \text{(C11)}$$

$$\sum_{j\in M}\left(x_{ij}+y_{ij}+z_{ij}\right)=1 \qquad \forall i \quad \text{(C12)}$$

The objective function (Eq. C1) minimizes the sum of deviations of the worst-case VaR of the species richness' change across all groups considered in the analysis (birds, bats and insects) and the richness of TreMs, all scaled by their ranges (maximum – minimum values) and applying the Euclidean norm. In this sense, the changes of all groups received a same weight in the objective function, avoiding favoring specific biodiversity indicators. Constraints Eq. (C2) – (C5) compute the worst-case richness changes under climate change and storm risk for birds, bats, insects and TreMs. Constraints Eq. (C6) – (C9) compute the worst-case deviations of richness changes during the simulation period, and assign its value to the variables t_{Bird}, t_{Bat}, t_{Insect} and t_{TreM}, respectively. Constraints Eq. (C10) and (C11) enforce that the VaR is greater or equal than 0, ensuring economic feasibility in the worst-case scenarios. Constraint Eq. (C12) limits the total managed area.

D Biodiversity maximization

For the biodiversity maximization solution, we aimed to maximize changes in species richness and TreM richness, however, disregarding the economic feasibility requirement. To this end, we applied the same model for biodiversity maximization (Eq. C1 – C12), but removing constraints Eq. (C10) and (C11).

We built all optimization models using the JuMP language (http://www.juliaopt.org/JuMP.jl) and solved them using the Ipopt solver (https://www.coin-or.org/Ipopt/).

Table S1. Description of the optimization model's variables and input data.

Variables	Description
x_{ij}	Area of plot i to be managed applying regime j
y_{ij}	Area of plot i to be managed applying regime j applying salvage logging
z_{ij}	Area of plot i to be managed applying regime j applying partial salvage logging
ϑ	Multiplicative variable in the Bernstein approximation for NPV
$\beta_{bird,bat,insect,trem}$	Deviation in the worst-case changes in bird richness
$\vartheta_{bird,bat,insect,trem}$	Multiplicative variable in the Bernstein approximation for biodiversity indicators
t_{NPV}	Worst-case NPV at the ε-confidence level
$t_{bird,bat,insect,trem}$	Worst-case of species and TreM richness at the ε-confidence level
Data	**Description**
λ	Weighting constant for mean value and worst-case
$AvgNpv_{ij}$	Average NPV of plot i under management j
$NPVSd_{ij}$	Deviation of the NPV of plot i under management j
$AvgBird_{ij}$	Average bird richness of plot i under management j
$BirdSd_{ij}$	Deviation of the bird richness in plot i under management j
$AvgBat_{ij}$	Average bat richness of plot i under management j
$BatSd_{ij}$	Deviation of the bat richness in plot i under management j
$AvgTreM_{ij}$	Average TreM richness of plot i under management j
$TreMSd_{ij}x_{ij}$	Deviation of the TreM richness in plot i under management j
$AvgInsect_{ij}$	Average insect richness of plot i under management j
$InsectSd_{ij}$	Deviation of the insect richness in plot i under management j
$sAvgNpv_{ij}$	Average NPV of plot i under management j with salvage logging
$sNPVSd_{ij}$	Deviation of the NPV of plot i under management j with salvage logging
$sAvgBird_{ij}$	Average bird richness of plot i under management j with salvage logging
$sBirdSd_{ij}$	Deviation of the bird richness in plot i under management j with salvage logging
$sAvgBat_{ij}$	Average bat richness of plot i under management j with salvage logging
$sBatSd_{ij}$	Deviation of the bat richness in plot i under management j with salvage logging

$sAvgTreM_{ij}$	Average TreM richness of plot i under management j with salvage logging
$sTreMSd_{ij}x_{ij}$	Deviation of the TreM richness in plot i under management j with salvage logging
$sAvgInsect_{ij}$	Average insect richness of plot i under management j with salvage logging
$sInsectSd_{ij}$	Deviation of the insect richness in plot i under management j with salvage logging
$psAvgNpv_{ij}$	Average NPV of plot i under management j with partial salvage logging
$psNPVSd_{ij}$	Deviation of the NPV of plot i under management j with partial salvage logging
$psAvgBird_{ij}$	Average bird richness of plot i under management j with salvage logging
$psBirdSd_{ij}$	Deviation of the bird richness in plot i under management j with partial salvage logging
$psAvgBat_{ij}$	Average bat richness of plot i under management j with partial salvage logging
$psBatSd_{ij}$	Deviation of the bat richness in plot i under management j with partial salvage logging
$psAvgTreM_{ij}$	Average TreM richness of plot i under management j with partial salvage logging
$psTreMSd_{ij}x_{ij}$	Deviation of the TreM richness in plot i under management j with partial salvage logging
$psAvgInsect_{ij}$	Average insect richness of plot i under management j with partial salvage logging
$psInsectSd_{ij}$	Deviation of the insect richness in plot i under management j with partial salvage logging
$\max_{x,y,z} Bird_{VaR}$	Maximum attainable VaR of bird richness change
$\max_{x,y,z} Bat_{VaR}$	Maximum attainable VaR of bat richness change
$\max_{x,y,z} Insect_{VaR}$	Maximum attainable VaR of insects richness change
$\max_{x,y,z} TreM_{VaR}$	Maximum attainable VaR of TreM richness change
$\min_{x,y,z} Bird_{VaR}$	Minimum attainable VaR of bird richness change
$\min_{x,y,z} Bat_{VaR}$	Minimum attainable VaR of bat richness change
$\min_{x,y,z} Insect_{VaR}$	Minimum attainable VaR of insects richness change
$\min_{x,y,z} TreM_{VaR}$	Minimum attainable VaR of TreM richness change
ε	Confidence level

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