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Keep cool in a changing climate: an integrated modelling procedure for costeffective mitigation of rising temperatures in rural landscapes

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Abstract
Rising temperatures may negatively impact rural landscapes in temperate climates due to reduced yields in agriculture and forestry, an increased risk of biodiversity loss, changes in the local climate and a decrease in recreational value. One promising way to mitigate increasing land surface temperatures (LST) in rural landscapes is to implement land-use and land-cover changes as adaptation measures that retain precipitation in soils, water bodies, and groundwater to allow vegetation to evaporate more water to reduce LST in summer. We develop an integrated modelling procedure to identify cost-effective spatially differentiated adaptation measures in agriculture and forestry to mitigate LST increases. We define cost-effective adaptation in a landscape as maximizing LST mitigation for given costs. The procedure combines the results of a model that predicts the spatially differentiated effects of adaptation measures on LST with the results of an economic model that estimates the respective spatially differentiated costs in an optimisation algorithm. We demonstrate how the procedure works by applying it to the Elbe-Elster-county in Germany. We find that a substantial share of results can only be explained by considering spatially differentiated costs and mitigation impacts and not average values showing the importance of taking into account costs and impacts of measures in a spatially differentiated manner. We also compare results from our integrated modelling procedure with a (purely natural science) approach that selects those adaptation measures first which perform best in terms of LST mitigation and find that our approach leads to a better heat mitigation effect by a factor of 3.5 – 4.8.

Keywords Climate change adaptation · Integrated assessment · Heat mitigation · Water stress · Climate water cycle · Landscape cooling · Nature-based solutions

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1 Introduction

Climate change adaptation measures with the aim to mitigate increasing temperatures typically focus on overheated settlements to reduce negative impacts of high temperatures on the population as a whole and, in particular, on vulnerable groups (e.g. Hunt and Watkiss 2011; Grafakos et al. 2019; Birkmann et al. 2021; Otto et al. 2021). However, in temperate climate zones increasing temperatures may also negatively impact rural landscapes. Higher temperatures increase soil moisture stress and accelerate microbial processes in soils, which trigger the leaching of nutrients and the degeneration of soils (Gelybó et al. 2018; Jansson and Hofmockel 2020). As a consequence, plants have less water and nutrients at their disposal for growth. This can result in reduced yields in agriculture (Challinor et al. 2014; Mahato 2014; Jägermeyr et al. 2021) and forestry (Fuhrer et al. 2006; Seidl et al. 2017; Venäläinen et al. 2022) posing challenges for the economic viability of the primary sector. Increasing temperatures may also cause range shifts of species leading to their endangerment (Bellard et al. 2012; Dasgupta 2021; Gerling et al. 2022), especially as fragmented landscapes prevent species from migration to new ranges (Vos et al. 2008). Moreover, rural landscapes often serve as recreational areas and their recreational value may decline if they become too hot in summer (Pröbstl-Haider et al. 2021). Finally, there is a systemic risk at the landscape level that an increase of the land–ocean temperature contrast, which is substantially influenced by vegetation through evapotranspiration, could cause the climate system (in Central Europe) to pass a tipping point and move from a wet to a dry state (Makarieva et al. 2022).

A promising way to reduce the land surface temperature (LST) is to improve the capabilities of rural landscapes to retain the existing precipitation by storing it in soils, water bodies and groundwater to make it available to vegetation for evapotranspiration (Procházka et al. 2019). Evapotranspiration by plants influences atmospheric moisture dynamics and contributes to landscape cooling by reducing the LST. One key option to improve these processes are changes in land-use and land-cover (henceforth referred to as climate change adaptation measures or simply adaptation measures). Examples of such measures include the enrichment of humus on agricultural land, the transformation of cropland to grassland, and the conversion from pine monocultures to near-natural mixed deciduous forests (Hildmann et al. 2022). Since the implementation of such adaptation measures is (often) costly and financial resources are scarce it is important to implement measures in a cost-effective way. Cost-effectiveness here means that measures are selected in such a way that the LST in a region is reduced most for given costs.

The purpose of this paper is to develop an integrated modelling procedure to identify cost-effective climate change adaptation measures in agriculture and forestry to mitigate the temperature increase in rural landscapes. The modelling procedure combines results from a model that predicts the impact of adaptation measures on LST and results from economic cost assessments that estimate the respective costs of these measures to mitigate LST increases. To identify the cost-effective allocation of adaptation measures, the integrated modelling framework uses an optimisation algorithm. The model is spatially differentiated, i.e. for each agricultural and forest plot, it quantifies the impact on the LST of potentially suitable climate change adaptation measures, estimates associated costs and puts LST mitigation effects and costs of the measures into relation. As a result, it specifies where to carry out which measures in the landscape to maximise the mitigation effect on the LST at the landscape level for given budgets. To demonstrate the superiority of our approach which integrates knowledge from economics and natural science, we contrast its results with those of a (purely natural science) approach that only considers the impact of climate change adaptation measures in terms of LST mitigation and ignores costs.

We demonstrate how the integrated modelling procedure works by applying it to the case study area of Elbe-Elster county in the federal state of Brandenburg, Germany, but would like to emphasize its general applicability to other rural landscapes in temperate climate zones. Elbe-Elster county is a suitable study region as the county is part of the highly climate-sensitive Lusatian region. The sensitivity is a result of the combination of low annual precipitation and sandy soils with little water retention capacity (Kühn et al. 2015; Gerwin et al. 2023). Weather data for the region have shown an increase of air temperatures over the last 30 years (Grünewald 2001; Pohle 2014, DWD Climate Data Center (CDC) 2020), and climate projections predict further temperature increases (Pfeifer et al. 2021). Alongside, rainfall patterns see a shift of precipitation from summer to winter (Zomer et al. 2022). This pattern shift highlights the importance of increasing the water retention capacity to counter the drying out of the landscape and, as a consequence, its overheating during the vegetation period.

Our work is at the intersection of three research areas. The first area is the economic literature on heat mitigation in urban areas. Often cost–benefit-analyses are applied to assess and investigate the economic feasibility of measures like the design of green urban water drainage systems (Johnson and Geisendorf 2019), urban green infrastructure such as green walls (Koch et al. 2020), pervious pavement systems (Wang et al. 2022), tree canopy cover (Bosch et al. 2021), and ecosystem-based approaches (Markanday et al. 2019) to mitigate adverse heat effects of climate change. In contrast, studies that investigate the cost-effectiveness of temperature mitigation measures are relatively scant. Notable exemptions are Zhang and Ayyub (2020) and Di Giuseppe et al. (2021) who respectively assess the cost-effectiveness of deploying cool and green roofs and dry mist systems as a water-based mitigation strategy against urban overheating.

The second research area is the development of integrated models to analyse the selection and spatial allocation of cost-effective land-use measures to obtain ecosystem services and biodiversity goals. A seminal paper is by Polaskya et al. (2008) who model the economic costs and conservation impacts of land-use patterns to derive spatially explicit, cost-effective land-use practises for species conservation. Further examples of the application of this research field of integrated modelling are Juutinen et al. (2020) who develop an integrated biophysical-economic modelling approach to analyse the costs and impacts of multiple peatland uses with multi-objective optimization to examine the trade-offs between biodiversity and ecosystem service goals and Gerling et al. (2022) who develop a climate-ecological-economic model to investigate the impact of climate change on the cost-effective spatial allocation and choice of measures to conserve a grassland indicator species.

The third area is the natural science literature on the impact of land-use and land-cover on the LST. The interaction of land-use respectively land-cover and LST has been the subject of research for many years (Liu and Weng 2008; Luyssaert et al. 2014; Jamei et al. 2022). However, other parameters also affect LST, such as elevation (Phan et al. 2018) or tree cover density (Greene and Kedron 2018). Similar to economic research, studies on temperature mitigation effects of greening measures focus mainly on heat islands in urban areas (Rahman et al. 2020; Gao et al. 2020; Shafiee et al. 2020). However, some studies also exist in the forest sector (e.g. Schwaab et al. 2020; Meeussen et al. (2021), and in the agricultural sector (Brunel-Saldias et al. 2018; Fischer et al. 2019).

We combine those three research strings as follows. We take up the challenge of cost-effective heat mitigation investigated in the context of urban heat islands but address it in the context of a rural landscape and the corresponding climate change adaptation measures. The development of our integrated modelling procedure is inspired by the typical structure of integrated models developed in the field of the spatial allocation of land-use measures to obtain ecosystem service and biodiversity goals cost-effectively. That research field—like our modelling approach—typically combines a cost assessment module and module(s) to assess the impact of land-use measures on ecosystem services in an optimisation framework (Polaskya et al. 2008). However, instead of biodiversity or ecosystem service goals typically investigated such as pollination, clean water or carbon sequestration, we focus on the goal of mitigating the impact of LST, which we estimate using a natural science modelling approach.

2 Overview of the integrated modelling procedure

The purpose of the integrated modelling procedure is to identify spatially differentiated, cost-effective climate change adaptation measures to mitigate the LST increase in rural landscapes. Figure 1 describes the structure of the procedure and how its different components are interrelated. Here, we provide an overview of the approach. For ease of communication, details of the approach are explained against the background of the case study application in Sections 3.2 to 3.5.

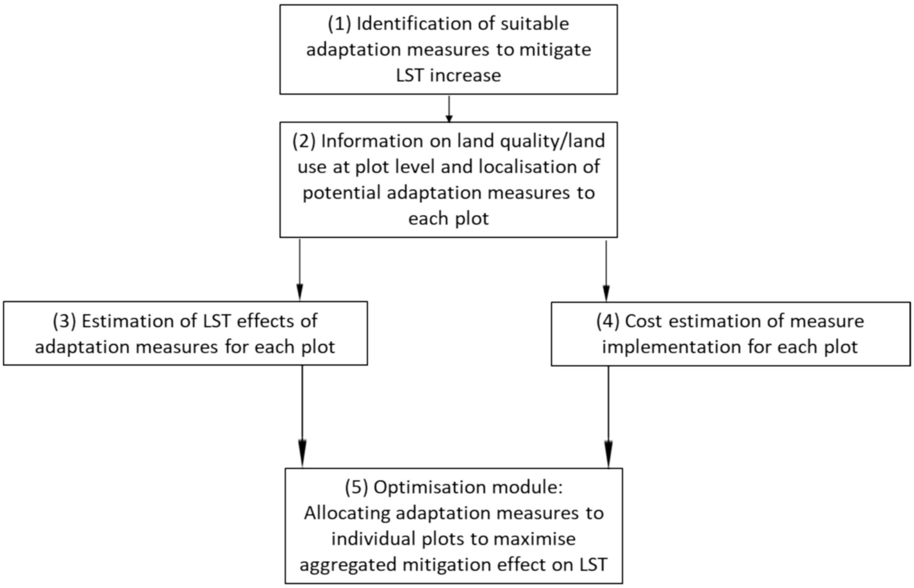

Fig. 1 Structure of integrated modelling procedure to identify cost-effective adaptation measures to mitigate LST increase

In a first step (Fig. 1, box 1), climate change adaptation measures, which are in principle suitable to mitigate LST increases in a specific region, need to be identified. In a second step (Fig. 1, box 2), information at the level of agricultural and forest plots[1] in the study region is gathered regarding the existing land use respectively land cover and land quality information (e.g. soil quality, land productivity, nutrition level). The precise information to be gathered depends on which information is needed for a specific region to estimate the plot-specific LST effects of adaptation measures and their costs. From the overall set of adaptation measures for each plot those are selected which are in principle suitable for this plot (e.g. agricultural measures are dropped for forests plots). This information feeds into an estimation of the impact of adaptation measures on LST (Fig. 1, box 3) in a spatially differentiated manner – i.e. for the individual agricultural and forest plots. For the estimation, a statistical model is applied to identify the influence of environmental variables such as tree cover density and soil water retention capacity on the LST, and to predict the effect of an individual measure on a plot (with the same time reference as for the costs, see chapter 3.3). In parallel (Fig. 1, box 4), the aggregated and discounted costs of implementing the selected adaptation measures on individual agricultural and forest plots for a certain period of time are estimated. Finally (Fig. 1, box 5), the cost data and the data on the impact of adaptation measures on LST are integrated in an optimisation procedure to identify cost-effective portfolios of measures and their spatial allocation. For that, the effect/cost ratios of all measures for all agricultural and forest plots are ranked according to their effect-cost-relation. On this ranking, an approximation algorithm is applied to identify where in the landscape which measures should be implemented for any given budget to maximise the reduction in the LST.

3 Case study application

3.1 Description of Elbe-Elster county

The Elbe-Elster-County is located in the south of the federal state of Brandenburg in Eastern Germany. It has a population of 100,902 people (Amt für Statistik Berlin-Brandenburg 2023) on an area of 1,899 km^2 with an annual GDP of 2,648 billion € (Euros) in 2020 (VGRDL 2022). About 1,900 employees worked in 2019 in forestry and agriculture contributing 80 million Euros (3%) to the local GDP (VGRDL 2022). 51% of the county are managed as agricultural land, and 36% are covered by forest (Amt für Statistik Berlin-Brandenburg 2022). With a relatively low average land productivity[2] (MLUK 2023a) cultivation

[1] We consider plots to be spatially contiguous linked areas of the same land use and management, e.g. forest stands with uniform tree cover or arable land cultivated with the same crop rotation. Each plot is adjacent to a plot of a different type. For our study region, plots were determined with the help of available spatial data (e.g. maps of forest stands, application data for agricultural subsidies).

[2] In Germany, the productivity of cropland and grassland is measured by the so called 'Ackerzahl' respectively 'Grünlandzahl' which contains information about soil quality, the local climate (average temperature and precipitation per annum), and other landscape elements (e.g. slope gradient) (Kaufmann-Boll et al. 2020). The Ackerzahl and Grünlandzahl range between 0 and 100 where higher scores represent a higher productivity. With an average Ackerzahl of 32 and Grünlandzahl of 35, the Elbe-Elster county has a relatively low productivity. In the following, the term soil quality index (SQI) is used for the Ackerzahl/Grünlandzahl. In addition, the German government authorities categorize forest areas into different nutrition levels ('Nährkraftstufe' in German). The nutrition level indicates the concentration of essential nutrients available

conditions for agriculture and forestry are less favourable compared to the rest of Germany (Kaufmann-Boll et al. 2020; Pfeifer et al. 2021). Grain farming dominates in the county, mainly with rye and silage corn for energy and fodder production for dairy livestock. About 23% of the agricultural land is grassland (Amt für Statistik Berlin-Brandenburg 2019). Opencast lignite mining played a crucial role to the local economy in past decades. As a result, the landscape transformed deeply with negative impacts on the water retention capacity of the local landscape (Gerwin et al. 2023) (Fig. 2).

Annual precipitation amounts to 556.8 mm/a (1971–2000, Pfeifer et al. 2021) (for comparison: Germany 922.8 mm/a) and shows a slight, statistically non-significant increase

to plants (typically N, P, K, S, Ca, Mg) in the upper soil layer. The R-Level represents soils rich in nutrients (highest level), the K-level soils strong in nutrients, the M-level soils middle in nutrients, and the A-level soils poor in in nutrients (LFB 2024).

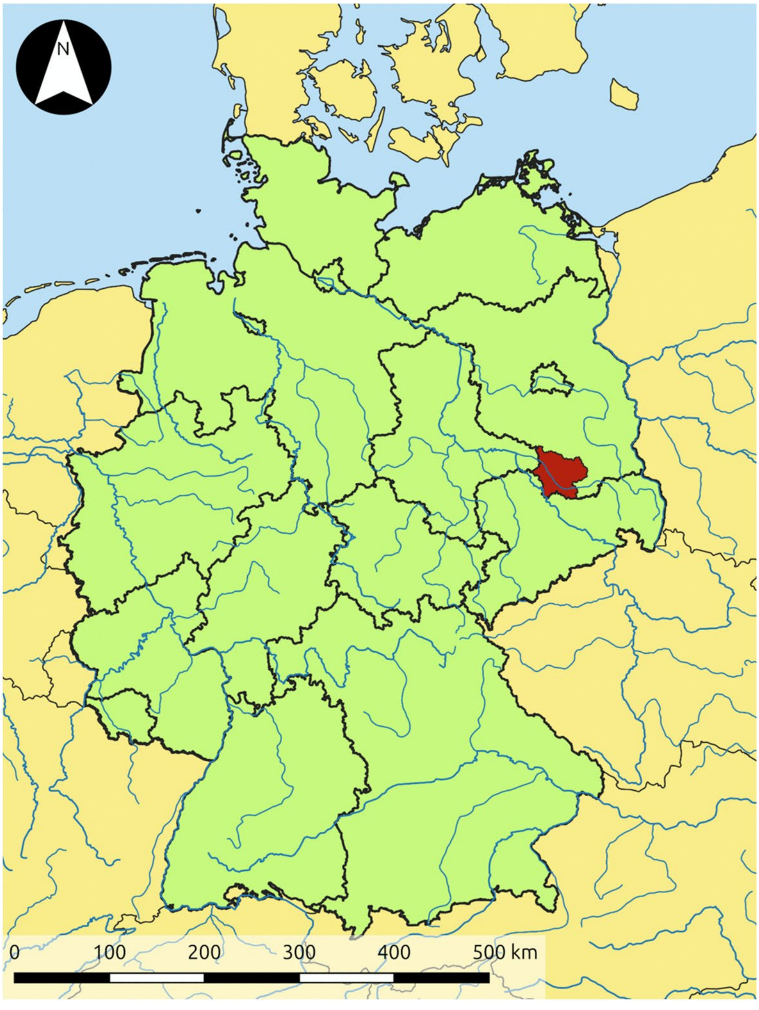

Fig. 2 Location of the study region Elbe-Elster county (red) within Germany (light green)

between the periods 1951–1980 and 1986–2015 (Pfeifer et al. 2021). However, there is also an increase of the mean annual temperature by an average of 0.9 K to 9.1 °C (similar to the German average of 9.3 °C) (Pfeifer et al. 2021). The overall result is a decrease in water availability in the region, particularly in the vegetation period. According to the classification of Zomer et al. (2022), the region is now considered dry sub-humid. Climate projections (Pfeifer et al. 2021) predict further rising temperatures and an extension of the vegetation period in the Elbe-Elster county. This may increase water demand of plants. Regarding annual amount, frequency and seasonal distribution of precipitation, climate projections indicate a more frequent occurrence of heavy precipitation events and a general shift of rainfall from summer into winter with no substantial changes in annual precipitation amounts. Overall, the impact of climate change is expected to reduce the water availability to plants during the vegetation period.

3.2 Identification of suitable measures for LST increase mitigation and localisation to plots

Table 1 lists six agricultural and two forestry adaptation measures we singled out for our analysis based on a comprehensive review of relevant scientific literature and suggestions from administrative decision makers and other stakeholders in the study region. For a detailed description of all investigated measures and how they influence surface temperatures see Hildmann et al. (2022).

From this overall set of adaptation measures those are selected for each plot, which are in principle suitable for it. For example, forest measures are only assigned to plots used for forestry. This localisation of measures is based on specific GIS algorithms that also determine certain plot-specific attributes such as the relative proportion of a plot that can be influenced by a measure. For example, as the measure 'landscape structure elements' is located exclusively along paths and ditches, the proportion of these elements varies among plots.

Table 1 List of agricultural and forest adaptation measures to mitigate LST increase in the Elbe-Elster county

Measures	Measure description
Agroforestry systems (alley cropping)	Combined cultivation of conventional arable crops and rows of perennial woody plants
Landscape structure elements	Planting hedgerows and field copses along ditches and trails
Conversion of cropland into permanent grassland	Establishment of evergreen, continuous grass cover
Organic fertilization	Application of organic matter (compost, manure, straw) to arable land
Cultivating deep-rooted crops	Cultivation of deep-rooted arable crops for better water supply
Afforestation of marginal cropland	Afforestation of marginal arable sites with deciduous trees
Reforestation	Reforestation of degraded forest with site-adapted tree species
Ecological forest conversion	Conversion from coniferous tree plantations to mixed or deciduous forest

3.3 Assessment of climate change adaptation measures on LST

The evaluation of the impact of climate change adaptation measures was based on their potential effect to mitigate LST increases. We only summarise our approach here and refer the interested reader to Appendix A.3 and Zimmermann et al. (2024) for details. In a first step, we developed a statistical model that quantifies the relationship between different environmental variables (called predictors hereafter) and a scaled LST (called LSTscale hereafter) as the dependent variable. We used 39 thermal images from the Landsat 8 satellite to derive LST during the main vegetation period (May to September) of the years 2013 to 2020 in the study region.

The predictors were identified based on knowledge in the literature of factors that influence the LST in rural landscapes (e.g. Bertoldi et al. 2010; Song et al. 2014; Alavipanah et al. 2015; Du et al. 2016; Kim et al. 2016; Das et al. 2020) and own previous work (Hildmann et al. 2019). They included, for example, land-use/land-cover class, tree cover density, imperviousness density and landscape structure metrics (Table A.3). To fit the model, we applied a Bayesian mixed-modelling framework using the statistical software R (R Core Team 2022) and the library brms (Bürkner 2021). The common geometry for both the predictors and the LSTscale was the raster data format with the LSTscale map resolution of 30 m × 30 m.

In the second step, the model was used to predict the LSTscale for predictor values, that can be expected before and after implementation of a climate change adaptation measure for each individual plot. The effect on the LST was then calculated as the difference in predicted LSTscale before and after a (hypothetical) measure implementation. In order to transfer the values in the raster cells to the agricultural and forest plots, respectively, we calculated mean values. For measures that do not cover the entire plot, area-weighted mean values were calculated instead of arithmetic mean values, whereby the weights were determined according to the plot-specific attributes (see chapter 3.2).

The LST values of each thermal image are rescaled with min–max feature scaling to the range [0, 1] before entering them into the model. This was done to account for the correlation between the absolute LST values and the air temperature without having to include additional predictors in the model. The scaling was necessary because the absolute LST values depend on the weather conditions at the time of the satellite overflight and are therefore not directly comparable. A spatially averaged effect of a measure can be scaled back to Kelvin to allow interpretation in the original unit. While most agricultural and forest measures achieve an average cooling effect of up to 1.5 K, the measure ‘afforestation of marginal cropland’ reduces the LST by 3.5 K on average. Other examples are the measure permanent grassland with an average LST reduction of 1.3 K and forest conversion with more than 1 K (Zimmermann et al. 2024). For comparison, Selim et al. (2023) determined an average cooling effect of 0.52 K through urban green spaces in the Mediterranean climate zone. In their UHI simulation analysis, Cortes et al. (2022) determined an average reduction in LST of 0.4 to 1.1 K through a combination of green roofs and urban vegetation in Mandaue City (Philippines).

3.4 Cost estimation of climate change adaptation measures

We followed the approach of identifying costs that occur when a measure to mitigate LST increase is implemented instead of a business-as-usual scenario (Sturm et al. 2018). With a business-as-usual scenario, we mean the existing land use on a plot in the study region which we assume to maximise the land users' profits. For the cost assessment of the adaptation measure, we distinguished between investment costs, management costs, and opportunity costs of land-use. Investment costs occur for some measures that require a one-time investment at the beginning of a measure (e.g. the implementation of 'agroforestry systems (alley cropping)' requires the plantation of tree seedlings on parts of the cropland). Management costs are ongoing costs of maintaining an implemented measure (e.g. the periodically recurring need of tree care in the case of 'alley cropping on cropland'), and opportunity costs are the difference between the profit from the existing land use and the profit from an adaptation measure. For example, the introduction of 'agroforestry systems' reduces the area for commercial crops as trees are now planted on parts of the cropland. This results in a decreased commercial crop yield and profit per hectare, which is not fully compensated by the profit generated from the sales of agroforestry products.

We considered spatially differentiated costs for (individual) agricultural and forest plots. Costs are based on current prices and depend on factors such as soil quality and other landscape features (e.g. slope gradient) (Kaufmann-Boll et al. 2020). We calculated the aggregated costs for the period of the next 30 years, and applied a discount rate which is common in economics to take into account that future costs and revenues are generally given less weight than present ones (see any textbook such as Boardman et al. (2018) for details). We chose 30 years as investigation period to match the time frame which is frequently used in climate research to determine climate trends and making decisions related to climate change (ClimateData Canada 2024; CCC 2024). A more detailed description of our cost calculation for adaptation measures listed in Table 1 provide Appendix A.1 and Hildmann et al. (2022).

3.5 Optimisation module and cost-effectiveness analysis

Based on data input on the spatially differentiated costs of adaptation measures and their effect on the LSTscale, we applied an optimisation algorithm to identify at which agricultural or forest plot to implement which measure to maximise the countywide LST increase mitigation effect for given budgets.[3] This optimisation problem corresponds to a higher dimensional knapsack problem which cannot be solved in polynomial time requiring an approximation algorithm (see Skiena 2020 for details). The approximation algorithm selects for a given budget the most cost-effective measure-plot combinations until the budget is spent. This corresponds to a heuristic greedy approach (see Sturm et al. 2018 for an example of how this approach can be applied to identify optimal land-use measures) which performs the following steps:

1) Select for all plots all possible measures and make a list of all possible measure-plot combinations including their costs and LSTscale impact (benefit). Sort this list by the ratio of LSTscale impact to cost (benefit/cost-ratio).

[3] The procedure allows generally only one adaptation measure per plot.

2) Select at each time step of the algorithm the most cost-effective measure-plot combination, i.e. the one with the highest benefit/cost ratio for this time step.
3) Check if the (additional) costs arising from this selection are within the overall available budget and if no measure is already allocated to the plot.
4) If both checks are positive (no plot allocated yet and additional costs do not exceed the budget), the measure is allocated to this plot and the measure-plot combination removed from the measure-plot list. The remaining budget is reduced by the costs corresponding to the implemented measure.
5) If either the plot is already occupied or the cost is too high for the remaining budget, the measure-plot combination is deleted from the list.
6) Repeat the procedure until the budget is exhausted or there is no measure-plot combination left.

This greedy approach does not guarantee that the optimal solution is found, but it does provide a good approximation of the optimum.

3.6 Results

We find that average LST increase mitigation effects and average costs vary substantially across climate change adaptation measures (see for details Table 2). In terms of the impact on LST, 'afforestation of marginal lands' has the largest effect, while 'cultivation of deep-rooted crops' has virtually no impact. In terms of cost, 'afforestation of marginal lands' is

Table 2 Average scaled LSTscale effects, average costs and average benefit/cost ratios of measures for all plots in study region

	Type of applied LULC measures to mitigate LST increase	Average LSTscale increase mitigation effect	Standard deviation LSTscale	Average cost per m2	Standard deviation cost	Benefit/cost ratio
Cropland						
	Agroforestry systems:					
	on cropland with soil quality index < 25	0.031	0.002	0.03 €	0.005 €	0.93
	on cropland with soil quality index ≥ 25	0.029	0.002	0.05 €	0.006 €	0.63
	Landscape structure elements:					
	on cropland with soil quality index < 25	0.018	0.016	0.11 €	0.005 €	0.16
	on cropland with soil quality index ≥ 25	0.016	0.017	0.14 €	0.008 €	0.11
	Conversion of cropland into permanent Grassland:					
	on cropland with soil quality index < 25	0.058	0.011	0.26 €	0.044 €	0.22
	on cropland with soil quality index ⩾ 25	0.052	0.011	0.51 €	0.049 €	0.10
	Organic fertilization:					
	on cropland with soil quality index < 25	0.020	0.002	0.12 €	0.000 €	0.17
	on cropland with soil quality index ⩾ 25	0.015	0.002	0.12 €	0.000 €	0.13
	Cultivating deep-rooted crops					
	on cropland with soil quality index < 25	0.005	0.004	0.64 €	0.036 €	0.01
	on cropland with soil quality index ⩾ 25	0.006	0.005	0.76 €	0.057 €	0.01
	Afforestation of marginal cropland					
	on cropland with soil quality index < 23	0.176	0.021	0.85 €	0.057 €	0.21
Grassland	Landscape structure elements	0.017	0.015	0.09 €	0.007 €	0.19
Forest	Reforestation:					
	on plots with nutrition level A	0.006	0.013	0.06 €	0.022 €	0.11
	on plots with nutrition level Z	0.008	0.016	0.08 €	0.026 €	0.11
	on plots with nutrition level Z+	0.015	0.027	0.08 €	0.015 €	0.18
	on plots with nutrition level M	0.016	0.023	0.10 €	0.030 €	0.17
	with onsite tree species	0.010	0.018	0.06 €	0.030 €	0.16
	Ecological forest conversion:					
	on plots with nutrition level A	0.013	0.026	0.06 €	0.028 €	0.22
	on plots with nutrition level Z	0.023	0.031	0.10 €	0.040 €	0.23
	on plots with nutrition level Z+	0.019	0.032	0.16 €	0.032 €	0.12
	on plots with nutrition level M	0.030	0.040	0.26 €	0.071 €	0.11

Values in table derived from combing results of calculations in box 3 and box 4 in Fig. 1

the most expensive adaptation measure and the introduction of ‘agroforestry systems’ is the least expensive. Comparing the average benefit/cost ratio of different adaptation measures provides a general assessment of the cost-effectiveness of the measures. On average, implementing ‘agroforestry systems’ on relatively low quality plots renders the highest benefit/cost ratio which can be explained by agroforestry systems having a medium LST effect while being comparatively cheap. By contrast, ‘cultivating deep-rooted crops’ has the lowest ratio. This is because the rotation from profit maximizing crops to deep-root cultivation has hardly any impact on LST while relatively high forgone profits make the change rather costly.

The standard deviations of LST increase mitigation effects and costs of the adaptation measures also substantially vary across measures and are quite high for some measures, which shows the importance of their spatial differentiation. In particular, forest related adaptation measures have comparatively large standard deviations for LST increase mitigation effects and costs. With respect to LSTscale, this large spread is explained by spatial variations in the predictor values among plots and differences in the proportion of plot area influenced by a measure (Zimmermann et al. 2024). For example, the predictor ‘tree cover density’ before implementation of the measure ‘ecological forest conversion’ varies between 0% (highly disturbed or recently cleared forest stands) and 100%. Regarding costs, one reason is that fencing which is required to avoid damage caused by game animals represents a substantial cost item for forest climate change adaptation measures. However, the amount of fencing costs varies greatly depending on the size and shape of the plot the forest measures are implemented on.

Table 3 shows the result for the cost-effective allocation of climate change adaptation measures across agricultural and forestry plots in the study region for a small budget (20 million €), a medium budget (40 million €) and large budget (80 million €) over the period of 30 years (for a visual presentation of the results see Fig. 3 in chapter 4). The small, medium and large budgets were selected to allow the analysis of the implementation of measures on a relatively small (47,911 hectares), medium (83,844 hectares), and large (126,859 hectares) share of the agricultural and forest area in the study region which amounts to 164,565 hectares.

Table 3 Results of cost-effective LST increase mitigation for a small, medium and large budget

			Budget of 20 Million €		Budget of 40 Million €		Budget of 80 Million €	
	Type of applied measures	Area measure is aplicable in hectare	Area measure applied to in hectare	% of area measure applied	Area measure applied to in hectare	% of area measures applied	Area measure applied to in hectare	% of area measure applied
Cropland								
	Agroforestry systems:							
	on cropland with soil quality index < 25	13,425	13,160	98%	13,220	98%	13,220	98%
	on cropland with soil quality index ≥ 25	57,168	28,155	49%	53,563	94%	53,611	94%
	Landscape structure elements:							
	on cropland with soil quality index < 25	13,368	44	0%	44	0%	44	0%
	on cropland with soil quality index ≥ 25	57,080	380	1%	480	1%	480	1%
Grassland	Landscape structure elements	29,046	520	2%	2,411	8%	15,072	52%
Forest*	Reforestation:							
	on plots with nutrition level A	2,635	75	3%	80	3%	185	7%
	on plots with nutrition level Z	22,000	982	4%	1,514	7%	3,104	14%
	on plots with nutrition level Z+	98	3	3%	6	6%	18	19%
	on plots with nutrition level M	8,991	913	10%	1,816	20%	6,179	69%
	with onsite tree species	4,425	254	6%	600	14%	2,481	56%
	Ecological forest conversion:							
	on plots with nutrition level A	5,565	584	11%	1,664	30%	3,135	56%
	on plots with nutrition level Z	39,531	2,683	7%	7,641	19%	25,392	64%
	on plots with nutrition level Z+	281	7	3%	25	9%	120	42%
	on plots with nutrition level M	15,132	150	1%	781	5%	3,811	25%

* Forest areas in the study region are categorized into four nutrition levels: A, Z, M, and Z+ (Z+ = between Z and M). The M-level represents soils middle in nutrients, and the A-level soils poor in nutrients (see for a detailed classification of nutrition levels footnote 2)

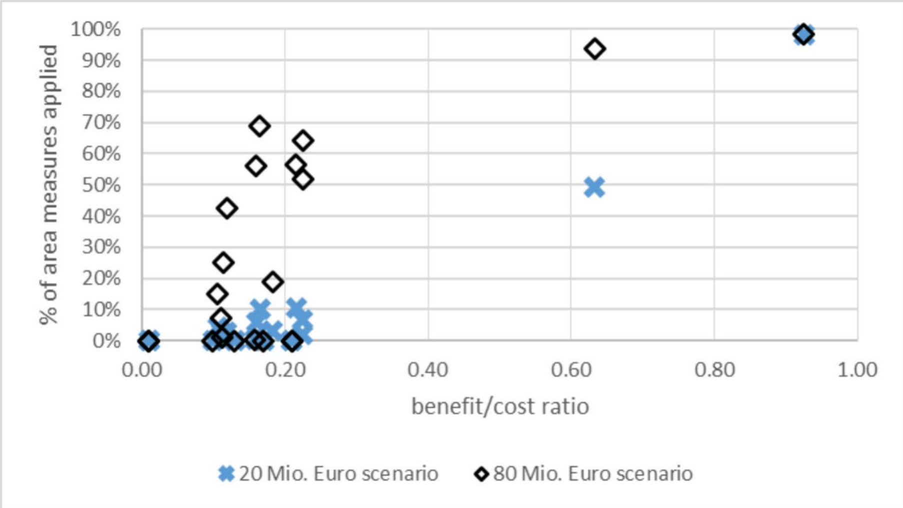

Fig. 3 Average benefit/cost ratio of measures versus percentage of area selected by cost-effective allocation for 20 and 80 million Euro budgets

For a small budget (20 million €), the cost-effective measure to mitigate LST increase is mainly the introduction of 'agroforestry systems' on cropland. This measure is implemented on almost all cropland plots with low productivity (soil quality index <25) and on almost half of the cropland plots with middle to high productivity (soil quality index ≥25). This result is reflected in the comparatively high average benefit/cost ratio of 0.93 and 0.63 respectively that exceeds those of other measures by far (Table 2) and can be explained by small opportunity costs for this measure, particularly on land with low productivity, while the LST increase mitigation effect is medium. The low opportunity costs result from the fact that only a small part of the cropland is planted with trees, while cropland continues to be cultivated on the remaining area. Unlike 'landscape structure elements', agroforestry strips additionally provide forest products (e.g. timber) that can be sold. Opportunity costs are somewhat higher for cropland with medium to high productivity, as more fertile land results in higher foregone crop yields. Furthermore, despite having a lower average benefit/cost ratio than the measures 'agroforestry systems' on cropland (Table 2), other measures are selected for some plots (Table 3) albeit having much lower average benefit–cost ratios than the measure 'agroforestry systems' on cropland (Table 2). This is an effect of the plot-specific spatial differentiation in benefit/cost ratios. In particular, 'reforestation' takes place on a few forest plots with middle to high nutrition levels (M levels), and 'ecological forest conversion' on a few forest plots with a low nutrition level (A level) and with low to medium nutrition level (Z level). Implementing these land-use measures is relatively inexpensive (with a comparatively high standard deviation indicating that there are some really low cost patches) while having a medium LST increase mitigation effect.

The results for the middle budget (40 million €) and large budget (80 million €) are largely in line with the findings for the small budget. The measure of 'agroforestry systems' is again implemented on almost the entire cropland area with low productivity and, additionally, on almost all cropland area with middle to high productivity. This share increase reflects the comparatively high benefit/cost ratio of ‘agroforestry systems’ for a large share of plots. In line with this, ‘reforestation’ takes place on bigger shares of forest plots with middle to high nutrition M-levels, and ‘conversion to ecological forest’ on bigger shares of forest plots with low nutrition A-levels and low to medium nutrition Z-levels. In addition, ‘landscape structure elements’ are implemented on about half of the grassland for a large budget. This is interesting, as the average benefit/cost ratio for ‘afforestation of marginal land’ and ‘conversion of cropland into grassland’ is slightly higher (0.21 and 0.22) than for ‘landscape structure elements’ (0.19) and one would expect the selection of some plots for those land-use measures. An explanation for the selection of ‘landscape structure elements’ is the substantial spatial differentiation of the LST mitigation impact, namely that on some grassland plots landscape structure elements have a particularly large LST increase mitigation effect. This happens when these elements cover a comparatively large part of the plot, e.g. due to a small plot size in combination with a high proportion of ditches or trails (as noted before, the localisation of measure ‘landscape structure elements’ was limited to these features). This results in high benefit/cost ratios of this measure on these grassland plots. Generally, the fact that for the two larger budgets in addition to the dominant measure ‘agroforestry systems’ on cropland a variety of measures is implemented (four measures on between 19 and 30% of their area for the 40 Mio. Euro budget and five measures on between 42 and 69% for the 80 Mio. Euro budget) shows that a plot-specific differentiation is important and taking average values of benefit/cost ratios would be misleading. Moreover, as only one measure can be implemented per plot and ‘agroforestry systems’ are already implemented on almost all cropland plots there is little room left for the implementation of other measures on this land-use type.

These relationships are illustrated in Fig. 3. The scatter plot contrasts the average benefit/cost ratio of a measure with the percentage of the area the measure is implemented for the 20 million (crosses) and the 80 million Euro budget (diamonds). The cross at the top right shows the measure 'Agroforestry systems on cropland' with low soil quality and in the middle the measure 'Agroforestry systems' on cropland with high soil quality, all other measures are represented by the crosses at the bottom left. For the diamonds, the two diamonds at the top also represent the measure 'Agroforestry systems' on cropland with low soil quality and 'Agroforestry systems' on cropland with high soil quality which are nearly fully implemented on the possible area for the large budget. The encircled diamonds at the middle left part of the figure show the measures which are only partially implemented ('Structure elements on grassland', 'reforestation and ecological forest conversation' on forest plots with different nutrition soil quality) for the large budget, for example as explained above due to substantial spatial variations in LST mitigation of the measure.

4 Efficiency advantage of cost-effectiveness approach over purely LST focused approach

In order to demonstrate the advantage of the cost-effectiveness approach in comparison to a (purely natural science) approach that selects adaptation measures with a higher effect on LST first, we repeated the optimisations for the three considered budgets applying such an approach. The structure of the optimisation problem corresponds to the cost-effectiveness approach and we applied the same heuristic greedy approach with slight modifications resulting in the following modified steps: 1) Sorting all possible measure-plot combinations based on their LST mitigation effect in a list, and 2) Selecting at each time step of the algorithm the measure-plot combination with the highest LST impact. Steps 3–7 are identical to the cost-effective approximation algorithm (chapter 3.5).

Compared to the cost-effectiveness approach, the selected adaptation measures differ substantially. Throughout all budgets, the optimisation based on LST-impacts mainly selects ‘afforestation on marginal land’. For medium and large budgets, the ‘conversion of cropland into grassland’ is also frequently chosen (see for details Table A.2 in the appendix). This selection was to be expected as these measures render the highest and second highest LST increase mitigation effects (Table 2). In contrast, the cost-effectiveness optimisation selects mainly the measures ‘agroforestry systems’, ‘reforestation’ and ‘ecological forest conversion’ as they have better benefit/cost ratios (Table 2). Optimisation based solely on LST-impacts also selects much less area than the cost-effectiveness approach. For the small, medium and large budgets it only allocates adaptation measures on 2,762 hectares, 5,918 hectares, and 13,137 hectares respectively versus 47,911 hectares, 83,844 hectares, 126,859 hectares under cost-effectiveness optimisation (Fig. 4 illustrates the differences in scope and spatial allocation of the different measures by LST optimisation and cost-effectiveness optimisation for different budgets). Again, this result is not surprising as high cost measures are selected which implies that the budget is exhausted with less measures than under the cost-effectiveness approach.

Depending on the available budget, the average LSTscale effect under optimisation based solely on LST-impacts ranges between 0.0833 and 0.1317 in the comparatively small area in which climate change adaptation measures with high LST increase mitigation effects are implemented. In the context of cost-effectiveness optimisation, the average LSTscale effect ranges for different budgets between 0.0297 and 0.0358. However, this effect occurs on the large area on which cost-effective climate change adaptation measures are applied (Table 4). To compare the effectiveness of both optimisation approaches, we relate the LST increase mitigation effects of both optimisations to the same reference area, i.e. the entire study area. When the average LSTscale effect in the entire study area is considered (last column in Table 4), the cost-effectiveness optimisation outperforms the optimisation based solely on LST-impacts by 3.5 to 4.8 times depending on the available budget.

5 Discussion

We developed a modelling framework that integrates knowledge from environmental science and economics to identify spatially differentiated cost-effective climate change adaptation measures in agriculture and forestry. To demonstrate how the modelling procedure works, we applied it to a case study, the Elbe-Elster county in Brandenburg, Germany, a highly climate-change sensitive region. To our knowledge, we are the first to develop an integrated modelling procedure to identify cost-effective climate change adaptation measures to mitigate LST increase in rural landscapes, while some work on cost-effective heat mitigation exists in an urban context (Zhang and Ayyub 2020; Di Giuseppe et al. 2021). The modelling procedure is transferable to other rural landscapes and can be used to identify cost-effective adaptation measure to mitigate LST increases.

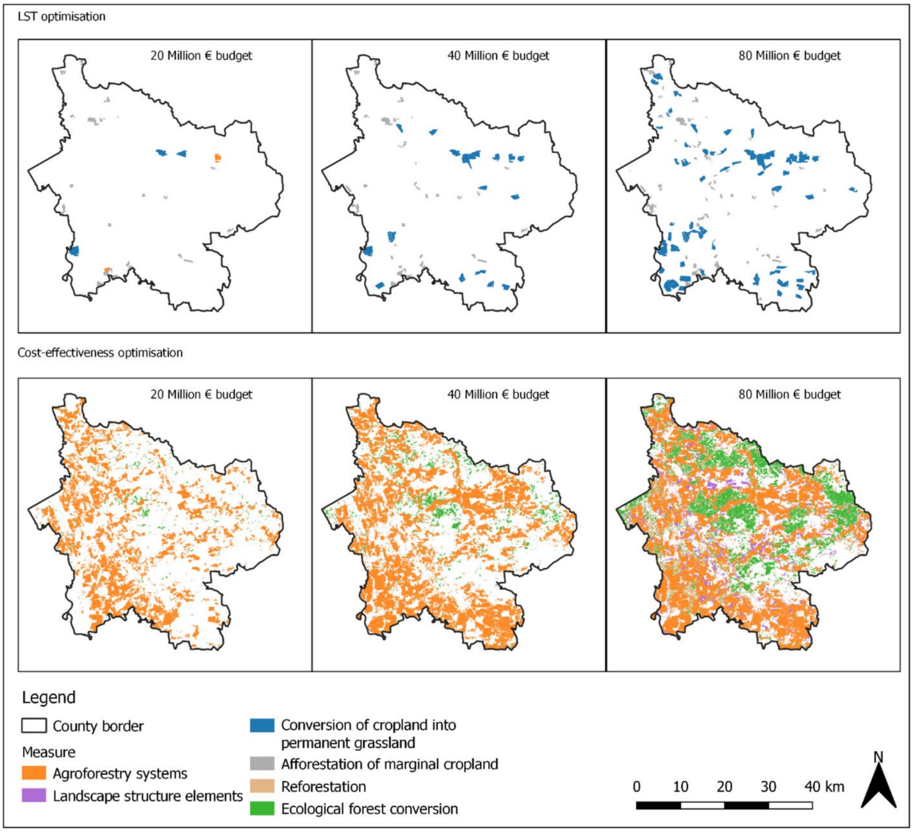

Fig. 4 Scope and spatial allocation of climate change adaptation measures by LST optimisation based solely on LST-impacts and cost-effectiveness optimisation for small, medium and large budgets

Table 4 Comparison of results of cost-effectiveness optimisation and optimisation based solely on LST-impacts

	Area measures applied to in hectare	Average LSTscale effect in area measures are applied to	Average LSTscale effect in entire study area (164,565 hectares)
20 Million € budget			
LST optimisation	2,762	0.1317	0.0023
Cost-effective optimisation	47,911	0.0358	0.0107
40 Million € budget			
LST optimisation	5,918	0.1022	0.0038
Cost-effective optimisation	83,844	0.0349	0.0182
80 Million € budget			
LST optimisation	13,137	0.0833	0.0068
Cost-effective optimisation	126,851	0.0297	0.0235

5.1 Importance of a spatially differentiated integrated approach

We demonstrate the value of our approach by comparing its results with a purely environmental science approach that ignores costs and selects those adaptation measures first which perform best in terms of LST mitigation. We find that our integrated approach increases the heat mitigation effect by a factor of 3.5–4.8 for a given budget. Given that public funding for climate change adaptation measures is scarce, this result provides a strong argument in favour of relying on integrated rather than disciplinary approaches when developing and implementing LST mitigation measures. While for researchers who are familiar with such integrated approaches this message may not be new, research on interdisciplinary work in climate change research (Schipper et al. 2021) suggests that such researchers are a minority and that knowledge of the benefits of integrated work is limited.

Even if one acknowledges the importance of integrated work, one may ask whether the laborious task of identifying plot-specific costs and LST impacts of mitigation measures is needed to identify cost-effective measures or if – alternatively – it is not sufficient to make decisions based on average values of costs and LST-impacts. Indeed, the results of our case study for a small budget (20 Mio. Euro for 30 years) seem to suggest this. The measure which dominates the solution is the measure with the highest average benefit/cost ratio, namely ‘agroforestry systems on cropland’. However, the results for medium and large budgets (40 respectively 80 Mio. Euro for 30 years) show the need for the spatial differentiation of costs and LST impacts. For these two larger budgets, in addition to the dominant measure ‘agroforestry systems on cropland’, a variety of measures is implemented (four measures on between 19 and 30% of their area for the 40 Mio. Euro budget and five measures on between 42 and 69% for the 80 Mio. Euro budget). This demonstrates that a plot-specific differentiation, which considers plot-specific variations in costs and LST impacts, is important and taking average values of benefit/cost ratios would be misleading.

Generalising the insights from our case study, we find that if one measure has a high benefit/cost ratio and small spatial variances in LST impacts and costs in comparison to other measures (as in our case ‘agroforestry systems on low quality cropland’ for a small budget), the benefits from spatial differentiation are small. However, with increasing similarity of benefit/cost ratios of measures and variances in costs and LST impacts (as in our case for different measures for the medium and high budget), the benefits of spatial differentiation increase as well.

5.2 Data limitations and uncertainty

Our approach is subject to limitations that may be addressed in further work. Our cost estimates do not include indirect costs due to limited data availability. For example, introducing ‘agroforestry systems’ increases shadowing on neighbouring fields, and less solar radiation may impact plant growth both negatively and positively which we ignored. Moreover, our cost assessment is a snapshot at a moment in time. However, prices do change. Both aspects introduce some uncertainty in our cost assessments. However, we believe this uncertainty to be minor and not to change our main insights.

The statistical modelling approach for predicting the effects of measures on LST is of course also subject to uncertainties, which span the entire process from data acquisition through model development and prediction (Zimmermann et al. 2024). For example, regarding satellite data, incorrect emissivities might be used in case of a change in ground cover, alternative modelling tools could lead to (somewhat) different, but equally valid predictions, and the prediction uses averaged predictor values which may differ from the specific situation in a plot (see Zimmermann et al. 2024 for details). Given the iterative modelling process and the many candidate models we examined (see for details Appendix A.3), we are optimistic that, despite the uncertainties, the general patterns of our results are robust.

5.3 Policy recommendations and further research

Adaptation measures to mitigate rising temperatures due to climate change have largely targeted overheated settlements (e.g. Birkmann et al. 2021; Otto et al. 2021). This is understandable given the direct health impacts of heat stress, particularly on vulnerable groups. However, rising temperatures can also negatively impact rural areas through soil degradation (Gelybó et al. 2018; Jansson and Hofmockel 2020), species endangerment due to climate-induced range shifts (Bellard et al. 2012; Dasgupta 2021), loss of recreational value (Pröbstl-Haider et al. 2021), and (in Central Europe) an increased risk of the climate system shifting from a wet to a dry state at the landscape scale (Makarieva et al. 2022).

If, for these reasons, LST mitigation in rural areas becomes a policy goal, we consider the value of our approach in providing a method for mitigating LST increases cost-effectively for given budgets for specific areas. As policy makers increasingly recognise that adaptation to climate change is important, adaptation policy objectives are increasingly emerging. For example, the climate change adaptation strategy of the federal state of Brandenburg (MLUK 2023b), where our case study area is located, identifies the adaptation of tourism and biodiversity conservation to climate change as goals, among others. These adaptation goals and their implementation are of importance beyond the state of Brandenburg.

With regard to tourism, our method is of general value for identifying measures that can cost-effectively mitigate increases in LST in areas with nature-based tourism involving activities such as walking, hiking and cycling. Studies have shown that the well-being and health, especially of the elderly and children, are affected by too high temperatures when engaging in such activities (Pröbstl-Haider et al. 2021). More generally, studies have shown that rising temperatures threaten the attractiveness of tourist destinations (Agulles et al. 2022). The importance of adaptation measures should therefore not be underestimated.

In terms of biodiversity conservation, studies expect climate change to be the most important driver of biodiversity loss by 2070 (Dasgupta 2021). A key strategy for conserving species under climate change is the establishment of climate refugia, commonly understood as areas that are relatively buffered from changing climatic conditions (Morelli et al. 2020). In these areas, mitigating increases in LST is a priority goal. Our method can be used to cost-effectively mitigate LST increases in areas selected as climate refugia for species threatened by climate change. We leave it to further research to apply our method to support the adaptation of tourism, biodiversity conservation and other areas to climate change.

Policy-making also needs to consider that adaptation measures based on land use and land cover change impact ecosystem services other than regulating the climate. For example, landscape structure elements such as hedgerows may provide important habitats for birds and other species (Kratschmer et al. 2024) and may act as carbon sinks and windbreakers (Drexler et al. 2021). Another example is ecological forest conversion, which generally improves the resilience of forests against climate change and thus supports the continuous provision of ecosystem services from forests including timber (Felton et al. 2024). Efficiency losses may occur, if the impacts on multiple ecosystem services are ignored in decision-making (Drechsler and Wätzold 2017). To avoid such losses, future research may investigate possible synergies and trade-offs of adaptation measures between the goal of mitigating the rise of LST and the provision of other ecosystem services and how to identify cost-effective measures that consider such synergies and trade-offs.

6 Conclusion

There is an increasing need to consider mitigation of climate change-driven LST increases in rural landscapes in temperate zones due to potentially negative impacts on land management and soils, biodiversity, the regional climate system and the recreational value of landscapes. We provide an integrated modelling procedure to identify spatially explicit changes in land use and land cover to cost-effectively mitigate LST increases. We demonstrate how the modelling procedure works by applying it to a case study, the county of Elbe-Elster in Brandenburg, Germany. Our results show the superiority of an approach that integrates knowledge from economics and environmental science over an approach that purely considers the impact of land use and land cover on LST and the need to consider spatially differentiated costs and impacts. We find that our integrated approach leads to a better heat mitigation effect by a factor of 3.5–4.8 compared to a purely natural science based approach. Our modelling procedure provides the basis for further studies on cost-effective adaptation measures with a specific aim in mind, such as maintaining the recreational value of a landscape or providing climate refugia for species. Such studies will become increasingly important given the increasing recognition of policy makers that climate change adaptation is essential.

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Author contributions Lutz Hecker carried out the cost calculations and led the article writing with substantial support from Frank Wätzold. Frank Wätzold and Christian Hildmann developed the idea of the integrated modelling procedure. Beate Zimmermann, Sarah Kruber and Christian Hildmann identified the climate change adaptation measures and assessed their impact on the LST. Astrid Sturm developed the optimisation algorithm and carried out the cost-effectiveness optimisation.

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