frontiers | Frontiers in Climate

TYPE Original Research
PUBLISHED 16 January 2026
DOI 10.3389/fclim.2025.1715424

OPEN ACCESS

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RECEIVED 29 September 2025
REVISED 23 December 2025
ACCEPTED 30 December 2025
PUBLISHED 16 January 2026

CITATION
Winkler K, Witting M, Gulde F, Garschagen M, Pongratz J and Rounsevell M (2026) Spatiotemporal scenarios of socioeconomic futures in Germany.
Front. Clim. 7:1715424.
doi: 10.3389/fclim.2025.1715424

Spatiotemporal scenarios of socioeconomic futures in Germany

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Socioeconomic development influences both the drivers and consequences of climate change, but many scenario applications still rely on highly aggregated indicators such as GDP and population, which mask regional diversity. This study develops spatially explicit socioeconomic scenarios for Germany to support climate action and land-use planning with greater detail and contextual relevance. Using a mixed-methods framework, we integrate historical trend analysis, participatory scenario building, and quantitative projection to generate annual trajectories of key indicators at district level from 2020 to 2100. The indicators cover human, social, financial, and manufactured capital, including demographic dynamics, education, income, employment, inequality, and social cohesion. We analyse the dataset with correlation and clustering methods to explore interdependencies and to identify distinct regional development pathways. Results highlight persistent associations between income, education, and life expectancy, but also scenario-specific changes in the relations between inequality, employment, and urbanisation. Strong east–west disparities and urban–rural contrasts remain across all scenarios, while a sufficiency-oriented pathway demonstrates that wellbeing gains can occur without economic growth. By providing high-resolution, multidimensional socioeconomic scenarios, this study enhances integrated climate–land modelling and informs the design of regionally adaptive and socially equitable climate policies under multiple plausible futures.

KEYWORDS

national climate policy, regional planning and management, scenarios, shared socioeconomic pathways (SSPs), socioeconomic indicators

1 Introduction

Socioeconomic development influences both the causes and consequences of climate change by shaping greenhouse gas emissions, land use patterns, and energy consumption, as well as determining the capacity of societies to adapt to climate change impacts and recover from disruptions (O'Neill et al., 2020). To explore how alternative socioeconomic development pathways shape the challenges for climate change mitigation as well as adaptation, the Shared Socioeconomic Pathways (SSPs) have become a central framework in climate change research (O'Neill et al., 2017; Riahi et al., 2017). By integrating economic, demographic, technological, and institutional dimensions, the SSPs enable the analysis of plausible futures, typically until the year 2100, under varying climate and policy assumptions (van Vuuren et al., 2017).

Importantly, the SSP framework also provides global scenarios of land use, management, and emissions (Popp et al., 2017), which form the basis of many land use models by informing projections of land demand, land cover change, and competition among land-based sectors (e. g. Rabin et al., 2020). These indicators are integrated across diverse modelling frameworks, including integrated assessment models (IAMs; Moallemi et al., 2022), computable general equilibrium models (Palazzo et al., 2017), demographic and urban growth models (Jiang and O'Neill, 2017; Kc and Lutz, 2017; Terama et al., 2019), as well as agent-based approaches (Brown et al., 2022). In land system models in particular, the use of spatially explicit and context-sensitive socioeconomic data—such as regional employment structures, income distribution, or infrastructure development—is essential to simulate the complex interactions between land, climate, and society, while enabling assessments of the equity and effectiveness of mitigation and adaptation strategies (Riahi et al., 2017; Ohashi et al., 2019).

Despite their expanding relevance, most applications of SSPs in land use modelling remain confined to global or large regional scales and often rely on a narrow set of indicators, most notably GDP and population (Murakami and Yamagata, 2019; Wang and Sun, 2022). While such indicators provide comparability and broad applicability, this limited set tends to overlook important regional aspects and the diversity of development dynamics at sub-national levels (Pedde et al., 2025). In particular, many currently used SSP-implementations are insufficiently context-specific, often missing regional variation in institutional capacity, economic structure, and local policy environments. Although aspects such as inequality have been explicitly operationalised within the SSPs as quantifiable indicators, other critical dimensions—such as governance capacity, human capital, and regional social cohesion—remain under-represented or are downscaled in a manner that fails to capture their spatial heterogeneity (Absar and Preston, 2015; Merkle et al., 2023). Recent studies therefore call for more differentiated and spatially refined socioeconomic inputs, especially for national and sub-national land system assessments that are shaped by local infrastructures, actor behaviours, and heterogeneous economic structures (Harmáčková et al., 2022; Pedde et al., 2025).

Within this context, there is growing political and policy interest in Germany in carbon dioxide removal (CDR) and in exploring how its potential may unfold under different socioeconomic and climate futures. Germany represents a salient case given its high population density, diverse land-use configurations, and ambitious climate targets. The Federal Climate Change Act (2024) specifies the goal of reaching net-zero greenhouse gas emissions by 2045, alongside an enhanced land-use, land-use change and forestry (LULUCF) sink of 40 $MtCO_2$ per year by 2045. In addition, the federal government's long-term strategy on negative emissions emphasises land-based measures—such as afforestation, bioenergy with carbon capture and storage (BECCS), and so-called carbon farming—as central to achieving climate neutrality. The recent revision of the Carbon Storage Act (BMWK, 2024) further enables an opt-in framework for terrestrial CCS deployment, thereby facilitating the integration of BECCS pathways (Wettengel, 2025).

Existing SSP downscaling methods primarily translate broad, global or regional-scale scenario data into finer spatial resolutions for national or sub-national applications. Common downscaling approaches include linear downscaling, which distributes regional data to smaller units based on historical shares, and convergence downscaling, which assumes that indicators such as GDP per capita or emission intensities converge across regions over time (Gütschow et al., 2021). While these methods provide an essential bridge between global scenarios and regional assessments, they are often limited by their reliance on a narrow set of indicators and tend to overlook contextual variables such as local governance, institutional capacity, and societal acceptance. Moreover, downscaled SSP data frequently lack spatial and thematic complexity required to reflect regional economic disparities and the social dimensions vital for land-based climate policies. These limitations hinder the robustness of climate and land-use model outputs when used for detailed policy planning and integrated assessment, particularly concerning the spatially heterogeneous deployment of CDR measures (Lutz et al., 2019; Gütschow et al., 2021; Reimann et al., 2021).

To address this gap, we present a novel set of spatially explicit socioeconomic change indicators specifically tailored for modelling future land system dynamics in Germany. Our approach transcends conventional demographic and economic metrics by integrating indicators related to financial, social, human, and manufacturing capital—dimensions widely recognised as critical for understanding land use decision-making but often under-represented in existing scenario frameworks. Employing a mixed-methods approach that combines quantitative trend analysis with participatory scenario development involving stakeholders and domain experts, we develop a coherent, open-access dataset designed to support land system modelling, climate policy assessment, and spatial planning across various exploratory trajectories. By enhancing both the granularity and policy relevance of socioeconomic assumptions, this dataset enables the construction of more robust, equity-oriented, and context-sensitive scenarios for land-based climate action, including but not limited to carbon dioxide removal (CDR).

This study addresses the following research questions: (1) How do relationships between key socioeconomic indicators evolve under different scenario assumptions? (2) What spatiotemporal patterns emerge across Germany under alternative SSP-aligned trajectories?

To answer these questions, socioeconomic indicators are selected and processed at the NUTS-3 level, with forward projections made in annual time-steps aligned with narrative-driven assumptions. Regional dynamics are examined using spatiotemporal correlation and clustering techniques. The results illuminate cross-indicator interdependencies and reveal distinctive regional development trajectories, capturing urban–rural contrasts, East–West divisions, and scenario-specific shifts. The discussion explores the implications of these scenarios for the German land system, climate mitigation and adaptation modelling and offers policy-relevant insights into regional inequality, social cohesion, and sustainable development strategies.

By providing a robust, spatially explicit, and temporally detailed set of socioeconomic indicators, this study advances integrated climate-land research and facilitates evidence-based policymaking at the nexus of climate change, society, and land systems. While the scenarios are primarily oriented towards land-based climate action—particularly CDR—they are flexible and sufficiently comprehensive to support broader land-use modelling and related sectoral analyses.

2 Materials and methods

We developed a structured mixed-methods approach (see Figure 1), which integrates downscaled national SSP narratives, a spatial database of socioeconomic indicators, and quantitative scenario analysis to derive regionally differentiated projections of socioeconomic change at the NUTS-3 level as classified by Eurostat (see Supplementary Material 1.1 and Supplementary Figure 1 for more detail).

The methodology consists of three main components: (1) preparing the indicator dataset based on historical and spatial data; (2) projecting future indicator trends informed by co-developed narratives and contextual benchmarks; and (3) analysing socioeconomic trajectories using correlation analysis and clustering techniques, accompanied with an uncertainty assessment.

2.1 Data input and processing

The foundation of this work is a set of six narrative storylines for Germany based on the Shared Socioeconomic Pathways (SSPs) outlined in Gulde et al. (2025). These include six pathways—SSP1a (Green growth), SSP1b (Degrowth), SSP2 (Middle of the road), SSP3 (Regional rivalry), SSP4 (Inequality), and SSP5 (Fossil-fuelled development)— that are embedded within the global SSP framework. The narratives, downscaled to the national context of Germany, where developed through a stakeholder-driven co-creation process and are summarised in Table 1. Translating SSPs to the NUTS-3 level inevitably involves interpretation and simplification. For example, national-level notions of 'regional rivalry' or 'inequality' must be operationalised as assumptions about spatial divergence, convergence, and policy heterogeneity among German districts. Our approach therefore combines downscaled national SSP narratives (Gulde et al., 2025) with Germany-specific expertise, but we acknowledge that this 'localisation' changes both the granularity and the emphasis of the original global SSPs. The qualitative assumptions embedded in these national narratives form the backbone of a fine-scaled indicator selection and the basis for scenario-specific projections.

As a first step, we identified and processed socioeconomic indicators relevant for the land system in Germany in accordance with the national SSP narratives. Indicator selection was guided by three main criteria: (1) thematic alignment with the storylines; (2) data availability at NUTS-3 resolution over multiple years; and (3) applicability to the agent-based land use model CRAFTY (Brown et al., 2022) through allocation to different forms of capital (human, social, financial, and manufactured). Indicators such as population density, employment, income, and built-up area form the basis for these capital representations.

Spatial and temporal resolution were key to ensuring that the dataset would support valid trend extrapolation and that it would integrate with spatially explicit land system models. To enable a complete set of indicators at NUTS-3 level, the few missing entries in the source data were filled by using two-dimensional linear interpolation over space and time. All indicators were harmonised and pre-processed to ensure regional consistency, and derived metrics—e.g. employment rate from unemployment data, or social cohesion index interpolated to the NUTS-3 level—were included to fill key thematic gaps. Table 2 provides an overview of the selected indicators, including definitions, temporal coverage, and data sources. A more detailed description of each indicator, capital attribution and pre-processing steps applied is given in Supplementary Table 1.

2.2 Indicator projection

The indicator projections were based on an analysis of historical data to establish baseline development trends and a contextual analysis that included a review of existing literature and available quantitative

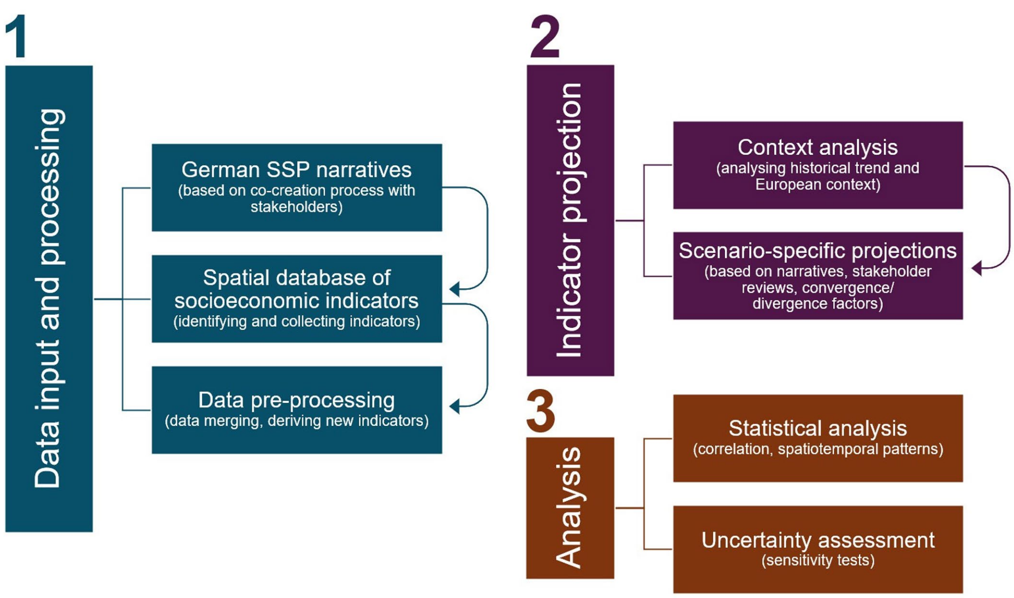

FIGURE 1
Schematic overview of the methodological approach.

TABLE 1 Summarised narrative of six SSP-based scenarios (based on Gulde et al., 2025).

Scenario	Description
SSP1a – Green growth	With strong government backing and sustainability standards, Germany becomes a leader in green economics. Traditional industries such as automotive and steel decarbonise successfully, while new markets thrive through innovation, research, and an equitable education system. Society values sustainability highly, with trust in democracy, strong welfare structures, and active civic participation. Consumption remains high but shifts towards environmentally friendly goods, while agriculture and forestry adapt early to sustainable practices.
SSP1b – Degrowth	This path reflects a deliberate move away from growth, with well-being, ecological restoration, and social justice at its core. Bottom-up initiatives face resistance at first but eventually reshape society through equity-oriented policies, redistribution, and support for unpaid care work. Sufficiency-focused lifestyles and strict regulation drastically reduce consumption and strengthen the common good while prioritising opportunities for the Global South. Local and circular economies expand, traditional industries rapidly decarbonise, and unsustainable sectors are phased out, reducing dependence on global trade.
SSP2 – Middle of the road	Germany largely continues on its current trajectory, facing mounting demographic challenges, labour shortages, and rising inequalities. Policy decisions favour maintaining established structures, and technological advances concentrate on traditional industries, while education and digitalisation lag. Social cohesion weakens under growing polarisation, hampering effective reforms. Sustainability awareness grows but remains limited by resource-intensive lifestyles, bureaucratic inefficiencies, and slow progress in the energy transition.
SSP3 – Regional rivalry	Rising insecurity and inadequate political responses fuel distrust in democracy and growing nationalist sentiment. Protectionist policies restrict trade, leading to economic stagnation, declining prosperity, and worsening inequalities. Industry is re-shored to Germany, fossil fuels are reactivated, and investment priorities shift to defence and security. Consumption, services, and migration decline, while employment increasingly shifts towards agriculture, forestry, and industry in a fragmented, inward-looking society.
SSP4 – Inequality	Rapid technological progress and automation create new markets, boosting Germany's global competitiveness in sectors like robotics, renewables, and IT. However, economic elites and lobby groups increasingly dominate politics, weakening democracy and curbing public investment in education and infrastructure. Structural change brings job losses in traditional industries, eroding the middle class, widening inequalities, and driving rural depopulation. Advanced technologies reshape agriculture, meat becomes a luxury item, and Germany strengthens its position in globalised markets at the expense of the Global South.
SSP5 – Fossil-fuelled development	Initially hindered by energy and demographic pressures, Germany restores growth by abandoning environmental standards and investing heavily in fossil fuels. Subsidies, alongside a strong STEM focus in education, drive industrial innovation, while environmental awareness fades. Traditional industries benefit from deregulation, lifestyles remain resource-intensive, and consumption rises sharply, including demand for meat and luxury goods. Despite persisting inequalities, growing prosperity, robust institutions, and social spending sustain social stability and trust in democracy.

projections for key indicators such as life expectancy (Eurostat, 2021b), population (Eurostat, 2021a; Statistisches Bundesamt, 2022; BBSR, 2024), and education (KMK, 2024). These sources provided initial assumptions on future indicator dynamics (e.g., based on recent trends), which were subsequently aligned with the assumptions of the six SSP narrative variants.

These analyses served as starting point for a stakeholder-based semi-automated process for quantifying the indicator projection. It combines historical data from the previous step (1), scenario mean trajectories (2), spatial differentiation (3) and upper/lower bounds (4) (further explained in the Supplementary Material 1.3). The stakeholder engagement consisted of a workshop in June 2023 with participants from fields including economics, regional statistics, demography, and spatial planning, to review and refine key trend assumptions (see Gulde et al., 2025). Additionally, group interviews were held in November and December 2023 to validate scenario-specific assumptions and discuss plausible bounds for inter-regional convergence or divergence trends (further explained in the Supplementary Material 1.2). Participants represented public agencies, research institutions, and NGOs (see Supplementary Material 1 from Gulde et al., 2025). For the years 2040, 2060, 2080 and 2100, values were explicitly set by experts and stakeholders based on historical trend extrapolation and published projections within specified upper and lower bounds. These national-level trajectories reflect the different SSP logics. For example, SSP1a assumes higher income growth than SSP1b, consistent with a green-growth narrative, whereas SSP1b assumes stronger improvements in social indicators (e.g., inequality reduction, social cohesion) despite declining income levels, in line with a sufficiency-oriented pathway. To represent spatial differentiation, we then combined historical spatial deviation with the scenario-specific convergence/divergence factors that determine how regional disparities evolve over time. Higher convergence factors imply stronger regional cohesion policies and faster narrowing of gaps between leading and lagging regions; higher divergence factors imply weaker cohesion and increasing disparities. These parameters translate narrative assumptions about regional policy, governance, and cohesion into quantitative rules for adjusting regional trajectories around the national mean. Scenario-specific national trajectories for each indicator in 20-year steps (2040–2100) are given in Supplementary Figure 2 and convergence/divergence parameters are listed in Supplementary Table 2.

The projections were visualised and saved for each SSP, indicator, and year, including spatiotemporal trends illustrated in maps for selected years (see Supplementary Figures 3a–d). Additionally, the data is provided as a set of normalised and composite capital indices (Human, Financial, Social, Manufactured), which facilitates integrated analysis and modelling. Therefore, projected data were merged with geospatial shape files of the NUTS-3 regions and a 1×1 km base grid.

This comprehensive indicator projection framework thus synthesised historical trends, stakeholder expertise, narrative alignment, and spatial differentiation to generate robust, scenario-aligned regional projections of key socioeconomic indicators from 2020 to 2100. This approach explicitly accounted for both temporal mean changes and evolving spatial heterogeneity, enabling detailed

TABLE 2 Selected socioeconomic indicators: definitions, units, and sources.

Indicator name *short name*	Definition	Unit	Reference period	References
Population density *POP*	Population density	persons/km^2	2019–2100	Eurostat (2021a)
Life expectancy *LIF*	Projected life expectancy at birth	years	2019–2100	Eurostat (2021b)
Secondary education *EDU*	Share of school leavers with at least upper secondary education	%	1995–2022	Statistische Ämter des Bundes und der Länder (2023h)
Household income *INC*	Annual income of private households	1,000 €	1995–2022	Statistische Ämter des Bundes und der Länder (2023c)
Employment rate *EMP*	Employment rate derived from unemployment rate of civilian workforce	%	2001–2022	Statistische Ämter des Bundes und der Länder (2023a)
Crimes per person *CRI*	Reported crimes per person and year	1000/ person	2014–2021	Bundeskriminalamt (BKA) (2023) and Statistische Ämter des Bundes und der Länder (2023g)
Social cohesion *COH*	Index of social cohesion normalised from survey data on social relationships, attachment/ identification and community spirit	-	2017/2020	Arant et al. (2017) and Brand et al. (2020)
Income inequality *INE*	GINI index of income inequality (derived from income groups in tax declarations)		1998–2004/2007–2019	Statistische Ämter des Bundes und der Länder (2023e, 2023f)
Share of urban and traffic area *BUI*	Share of urban and traffic area on the total land area	%	2016–2022	Statistische Ämter des Bundes und der Länder (2023d)
Gross value added (manufacturing) *GVA*	Gross value added of the manufacturing sector	%	2000–2020	Statistische Ämter des Bundes und der Länder (2023b)

Except from social cohesion (NUTS-2 and grouped regions), the spatial level of all indicators was NUTS-3.

assessment of future socioeconomic trajectories across diverse scenario contexts.

2.3 Statistical analysis

Subsequently, we analysed the dataset to explore interdependencies among the socioeconomic indicators within and across German regions and to identify patterns in regional development using correlation analysis and clustering techniques. The robustness of the statistical analysis was assessed by using a set of sensitivity tests in order to identify methodological uncertainties.

2.3.1 Spatiotemporal correlation analysis

Separate spatiotemporal correlation matrices were calculated for each SSP scenario. Each observation in this analysis corresponds to a unique pair of region and year at the NUTS-3 level, thereby capturing not only static spatial relations but also temporal dynamics and changes over time across regions. Several steps are taken to create and analyse spatiotemporal interdependencies:

For each SSP, harmonised indicator datasets spanning all years and regions were pooled into a single panel of (region × year) observations. As a prerequisite, we ensured that the indicator panels were complete at NUTS-3 level. Pearson correlation coefficients were then calculated between all pairs of indicators across this full spatiotemporal dataset within each scenario. The resulting correlation matrices should be interpreted as time-averaged, scenario-specific summaries of linear associations that integrate both spatial and temporal variation, rather than as evidence that correlation structures remain constant over the entire 2020–2100 period. A detailed description of the procedure is provided in Supplementary Material 1.4.

To visualise and interpret the patterns, heat maps of correlation matrices were generated for each scenario using diverging colour scales centred at zero to highlight positive and negative associations. Furthermore, differences between correlation matrices of contrasting SSPs were computed and plotted (see Supplementary Figures 6a,b), illuminating how scenario assumptions may modify the coupling of key indicators such as income, inequality, and employment across regions and time.

Overall, this spatiotemporal correlation analysis offers a rigorous and transparent framework to disentangle complex interrelations among socioeconomic indicators influenced by both spatial heterogeneity and temporal evolution within alternative future scenarios.

2.3.2 Spatiotemporal clustering of socioeconomic trajectories

The time-series clustering analysis on scenario-specific trajectories was conducted for 10 core socioeconomic indicators using annual data from all SSPs at NUTS-3 level: population, life expectancy, secondary education, household income, employment, crime, social cohesion, inequality, built-up area, and gross value added in manufacturing.

For robust cross-scenario comparison, the optimal number of clusters was determined globally by concatenating the time series of all regions and scenarios into a single dataset. We employed k-means clustering adapted for multivariate time series, utilising the *TimeSeriesKMeans* implementation from the Python *tslearn* library combined with *TimeSeriesScalerMeanVariance* for standardisation. Prior to clustering, all time series were standardised to zero mean and unit variance per indicator, which prevented bias from differences in scale across variables and ensured comparability. Cluster validation was based on the silhouette score, which quantifies how well each time series fits within its assigned cluster relative to neighbouring clusters (Rousseeuw, 1987). The silhouette analysis was performed over cluster numbers ranging from 5 to 30 on a random subset of samples (up to 500) to reduce computational burden. This approach identified 24 as the optimal global cluster count, sufficiently capturing the diversity of socioeconomic trajectories across all SSPs and regions. The clustering algorithm used the Euclidean distance metric, which compares the overall shape of the multivariate temporal trajectories. Resulting cluster assignments were mapped back to each scenario and region, thus grouping German NUTS-3 regions by similarity of their projected multidimensional socioeconomic development pathways. To further explore similarity among clusters, the indicator-wise temporal trends of the cluster centroids (expressed as slopes of scaled indicator trajectories) were subjected to hierarchical clustering using Ward's method. Based on the similarity of the temporal trends of each NUTS-3 region, a reorganisation of the 24 clusters was carried out leading to a final set of seven larger cluster groups (see Supplementary Material 1.5, Supplementary Figure 7, and Supplementary Table 3 for more detail).

In summary, the spatiotemporal clustering combined advanced multivariate time-series methods, rigorous cluster validation, and hierarchical aggregation to reveal dominant regional development typologies across multiple socioeconomic dimensions and future scenarios. This enabled nuanced analysis of heterogeneous regional trajectories under differing SSP assumptions, providing spatially explicit and interpretable clusters as a basis for further interpretation and policy-relevant insights.

2.3.3 Uncertainty assessment

To assess the robustness of the spatiotemporal clustering based on the projected socioeconomic indicators, we applied four different sensitivity tests, all based on the Adjusted Rand Index (ARI) (Hubert and Arabie, 1985). ARI measures the agreement between two partitions of the same set of objects; a value of 1 denotes identical partitions, whereas values close to 0 indicate similarity no better than random. The sensitivity tests were to estimate the effects of (1) the number of clusters, (2) each of the selected indicators (leave-one-indicator), (3) errors or noise in the dataset (Monte-Carlo perturbation), and (4) the parameter range (see Supplementary Material 1.6 for more detail). These tests evaluate whether the clustering structure is robust to reasonable changes in modelling choices, indicator selection, and input noise.

3 Results

In this section we describe patterns emerging from the exploratory conditional SSP-aligned scenarios, which represent consistent plausible future trajectories for Germany.

3.1 Correlation patterns among socioeconomic indicators

To lay the groundwork for understanding the interplay of socioeconomic processes in Germany, we first examined the spatiotemporal correlations among ten key indicators across all NUTS-3 regions and years for each scenario. The resulting Pearson correlation matrices (Figure 2) reveal several robust relationships that persist across most scenarios, as well as notable scenario-specific deviations.

A consistently strong positive correlation was observed between household income and life expectancy ($r > 0.6$) in all scenarios except SSP1b (Degrowth), underscoring the enduring link between economic prosperity and health outcomes. The employment rate also exhibited a positive association with life expectancy, reinforcing the importance of labour market participation for societal well-being. Conversely, crime rates were generally negatively correlated with employment ($r \approx -0.6$ to -0.8), income ($r \approx -0.3$ to -0.7), and life expectancy ($r \approx -0.2$ to -0.7), suggesting that regions with greater economic and health advantages tend to experience lower crime levels.

However, the scenario context is clearly important. In SSP1b, for example, the expected positive correlation between education and life expectancy is absent, and the negative correlation between income and crime weakens. These patterns reflect fundamental shifts in values and policies inherent to alternative development pathways, particularly those that move beyond conventional growth paradigms. SSP5 (Fossil-fuelled development) stands out as the only scenario in which the typical negative association between inequality and employment or social cohesion disappears—potentially indicating altered social dynamics in rapid-growth settings. In contrast, across all scenarios, population density is positively correlated with inequality, crime, and built-up area, illustrating the complex and multifaceted impacts of urbanisation.

Comparative analysis of the matrices shows that while the overall structure of indicator associations is relatively stable, the strength—and occasionally the direction—of specific correlations shifts depending on the underlying assumptions of each scenario. For instance, the correlation between income and inequality weakens in SSP3 (Regional rivalry), reflecting the fragmented development and slower economic growth characteristic of that scenario. Meanwhile, the positive association between employment and built-up area is strongest in SSP5, indicating intensified urban expansion linked to high economic activity.

These correlation patterns provide an important empirical base for the following analysis of regional trajectories, suggesting which socioeconomic processes may reinforce or counteract one another under different scenarios.

3.2 Spatiotemporal dynamics and regional cluster trajectories

Building on these correlations, the cluster analysis of the socioeconomic indicators across Germany resulted in seven distinct clusters, each characterised by a unique trajectory shaped by spatial context and scenario-specific drivers (Figure 3; Table 3). Interestingly, the six scenarios can be grouped into two broader sets based on shared socioeconomic dynamics across all indicators: SSP1a, SSP1b, and SSP5

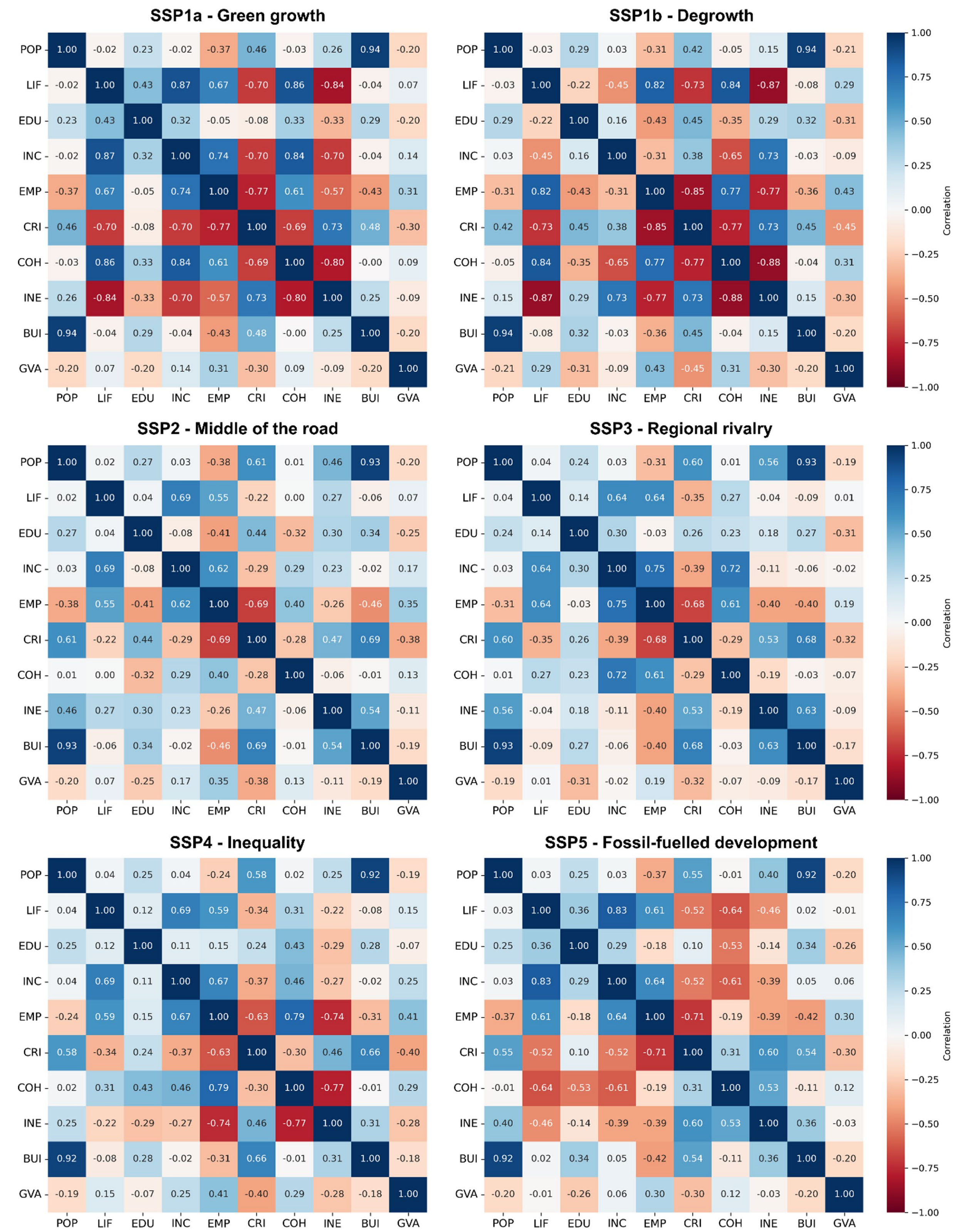

FIGURE 2
Spatiotemporal correlation matrices between 10 socioeconomic indicators (short names according to Table 2) across six different scenarios. These matrices reveal regional development typologies (see section "Material and methods").

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form one cluster group, while SSP2, SSP3, and SSP4 constitute the other.

A prominent feature across all scenarios is the interplay between urban and rural regions: In SSP1a, SSP1b, and SSP5, we observe a shift of population from urban centres to rural areas (see Figure 4B), driven either by active policy, lifestyle changes, or saturation of urban infrastructure. By contrast, SSP2, SSP3, and SSP4 are characterised by intensified urbanisation pressures (see Figure 4B): SSP3 and SSP4 reflect weaker regional planning frameworks and strong urban pull factors, while SSP2 shows simultaneous population decline in both rural and urban areas, with disparities instead becoming more visible in manufacturing output and employment trajectories.

The east–west divide in Germany remains a persistent feature across scenarios, particularly with respect to financial indicators such as income and employment. This divide is most pronounced in SSP2 and SSP4, where temporal income trends reveal that western regions continue to outpace the east over time (see Figure 4B). Patterns of inequality in SSP3 and SSP5 further amplify these disparities (see Figure 4B), as they reflect a combination of fragmented development and uneven economic opportunities. Spatial fragmentation also varies across scenarios: while western Germany displays a high degree of heterogeneity in socioeconomic outcomes, eastern Germany exhibits greater uniformity, particularly under SSP1a, SSP1b, and SSP2—scenarios that assume greater cohesion and stabilisation policies.

A close examination of the clusters reveals differentiating characteristics. In Cluster 1 (SSP1a/b), major urban regions show an overall positive trend: declines in population density, crime, and inequality are accompanied by gains in life expectancy, employment, and social cohesion. Notably, subtle differences emerge between SSP1a and SSP1b: while cities in SSP1a experience slight reductions in income and secondary education attainment, SSP1b cities register increases—highlighting the nuanced effects of divergent socioeconomic pathways.

Cluster 2 (SSP5) exemplifies the urban–rural divide most strongly. Urban areas in this group benefit from rising education levels and economic output, particularly in manufacturing, while simultaneously experiencing a decline in population density. In contrast, rural areas—though seeing an increase in population density—suffer rising inequality and a decline in industrial output. The Ruhrgebiet, a former industrial hub, typifies the structural challenges faced by

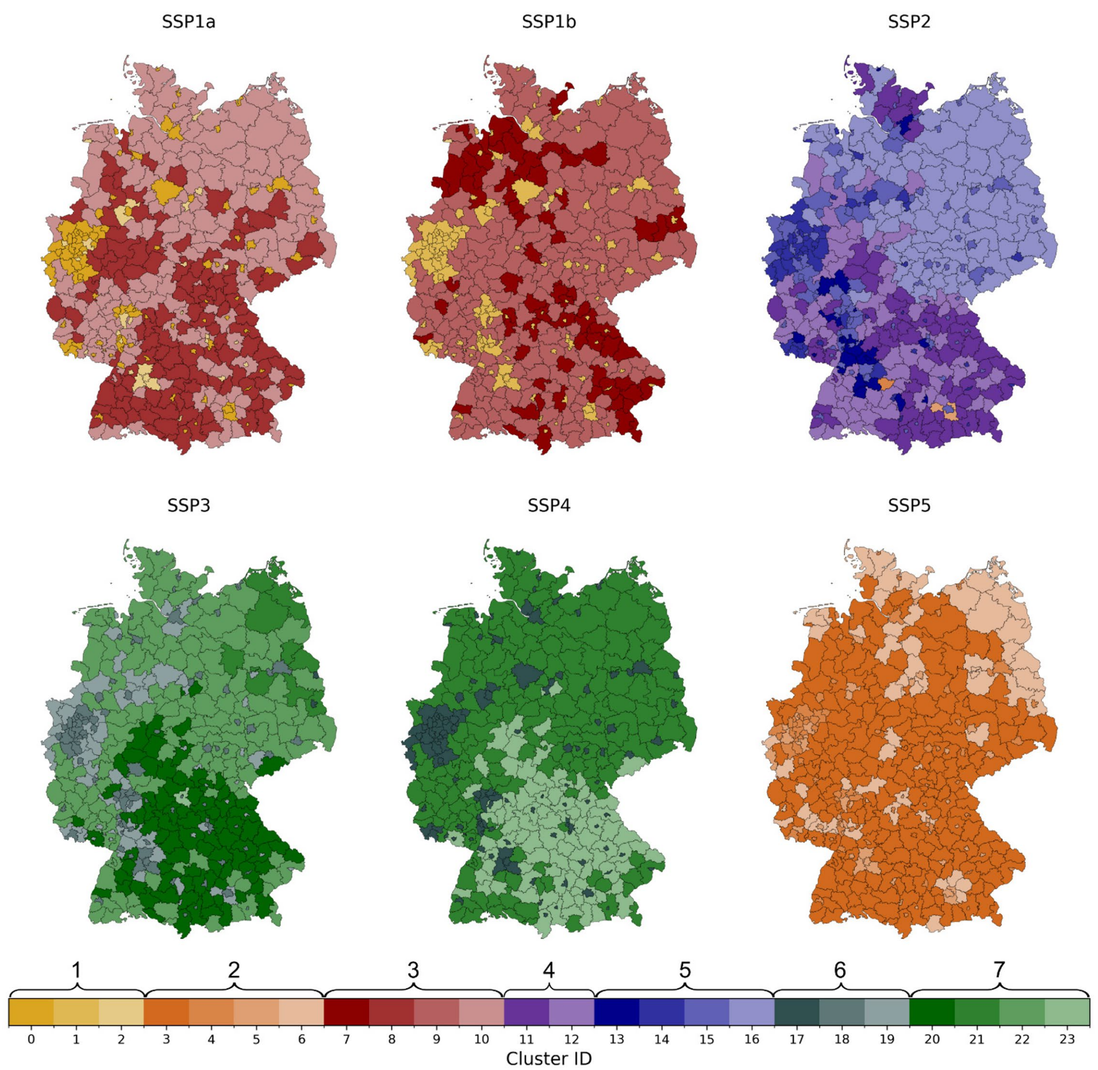

FIGURE 3
Grouped clusters from sub-clusters with similar spatiotemporal trends (see Material and methods) from 2020 to 2100 of socioeconomic indicators across different scenarios. Groups and cluster IDs are ordered by similarity with adjacent cluster numbers being more similar than distant numbers.

TABLE 3 Clusters and their linear trend (slope) as average annual percentage change (%) of each socioeconomic indicator, as derived from time series k-means clustering.

Scenario	Cluster ID	Sub-cluster ID	Population density (POP)	Life expectancy (LIF)	Secondary education (EDU)	Household income (INC)	Employment rate (EMP)	Crime per person (CRI)	Social cohesion (COH)	Income inequality (INE)	Share of urban and traffic area (BUI)	Gross value added (manufacturing) (GVA)
SSP1a, SSP1b	1	0	−3.8	4.2	−3.2	−3.8	4	−4	4.2	−4.1	−4.2	3.5
		1	−4.1	4.1	4.1	4.2	4.2	−4.2	4.1	−4.1	−4.2	4.2
		2	−3.8	4.1	4.1	3.7	4.1	−4.2	4.1	−4.1	−4.2	−3.8
SSP2, SSP5	2	3	4.1	4.1	4.1	4.1	3.6	−4.1	−3.9	−3.6	4.2	−4.2
		4	−3.7	4	4.1	4.1	4.1	−4.1	−4	−3.5	3.4	−4.1
		5	−3.9	4.1	4.2	4.1	4	−4.2	−3.9	−3.8	3.1	4.1
		6	4	4.1	4.1	4.1	3.4	−4.1	−3.9	−3.7	4.2	4
SSP1a, SSP1b	3	7	4.2	4.2	2.1	−4	3.8	−3.8	4.2	−4.1	4.2	2.7
		8	4	4.2	−3.8	−4	3.9	−3.8	4.2	−4.1	4.1	3.1
		9	4.1	4.1	4.2	4.1	4	−4.1	4.1	−4	4.3	−4
		10	3.7	4.1	4.1	4.1	4.1	−4.1	4.1	−4	4.3	4
SSP2	4	11	−4.2	4	−3.1	4.1	3.9	−0.4	−4.2	3.7	−4.3	−4.1
		12	−3.8	4	−1.5	4.1	3.9	0.7	−4.2	3.8	−4.1	4
SSP2	5	13	−3.7	4	−2.9	4.2	3	2.8	−4.2	3.7	3.8	4.2
		14	−3.9	4.1	3.9	4.2	1.3	4.1	−4.2	3.7	4.1	4
		15	−3.6	4.1	2.9	4	0.4	3.9	−4.2	3.7	4.1	−4.1
		16	−3.9	4.1	3.3	2.5	−2.8	3.3	−4.2	3.9	−4.2	−2.6
SSP3, SSP4	6	17	−0.6	−4.1	−3.9	−3	−4.2	4.1	−4.2	4	4.2	−4.2
		18	3.8	−4	−3.8	−3.6	−3.4	3.7	−2.3	1.2	4.3	1.5
		19	−3.8	−4.1	−3.6	−3.7	−3.1	2.7	−2.3	0.3	3.4	2.8
SSP3, SSP4	7	20	−3.9	−4.2	−4.1	−3.7	−2.7	−1.7	−2.2	0.1	−4	4
		21	−3.8	−4.1	−3.7	−3.8	−3.3	2.8	−2.3	1	−4.1	2.8
		22	−3.6	−4.1	−4	−3.6	−4.2	3.6	−4.2	3.9	−4.2	−4.2

Cells with red shading indicate negative values, cells with blue shading indicate positive values.

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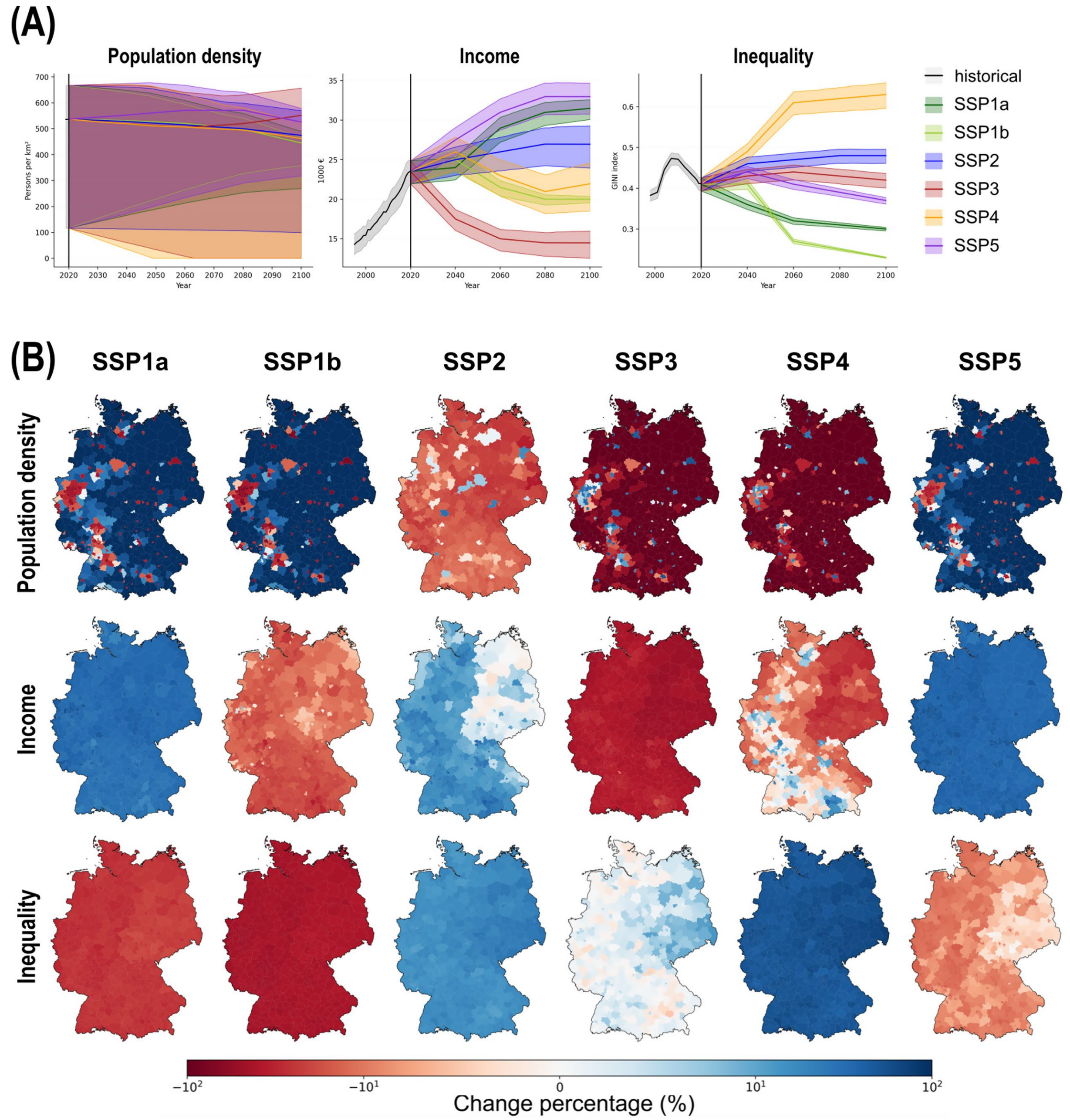

FIGURE 4
Future projections of selected socioeconomic indicators: **(A)** Mean (line) and standard deviation (shaded area) of selected socioeconomic indicators across NUTS-3 regions in Germany for different scenarios from 2020 to 2100 (see Supplementary Figure 4 for all indicators). **(B)** Maps of temporal trends of selected indicators for different scenarios as change percentage from 2020 to 2100 (see Supplementary Figures 5a,b for all indicators).

post-industrial regions under even high-growth scenarios: while economic activity may rise nationally, certain regions struggle to regain lost manufacturing capacity or reduce socioeconomic disparities.

Clusters 3 through 7 reflect a diversity of regional transitions—ranging from rural or peripheral regeneration (Cluster 3, mainly in SSP1a and SSP1b), to mixed urban–rural regions with moderate growth (Cluster 4, SSP2), and finally to regions under increasing socioeconomic pressure (Clusters 6 and 7, SSP3 and SSP4). For instance, Cluster 3 highlights areas in northern Germany that show a "catch-up" effect under progressive scenarios, marked by rising income, improved education, declining inequality, and higher life expectancy.

These trajectories align strongly with the earlier correlation findings. For example, the positive correlation between manufacturing and employment plays out clearly in SSP1b, where certain urban and rural regions experience industrial revival. Conversely, the weakening link between income and inequality under SSP3 underscores the persistence of regional disparities, even in areas where income growth occurs.

The sensitivity tests for assessing the robustness of these regional trajectories showed that the seven-cluster configuration is highly stable. Varying the number of clusters yields Adjusted Rand Index (ARI) values of 0.91–0.98; leave-one-indicator tests give ARI scores of 0.75–0.95, with the lowest values for the built-up and gross value added (manufacturing) indicators; the Monte-Carlo perturbation (5% Gaussian noise, 30 replicates) produces a mean ARI of 0.87 ± 0.03 and the perturbation of the parameter ranges gives a mean ARI of 0.90 ± 0.01 (see Supplementary Figure 8 and Supplementary Table 4). This indicates that the regional trajectories described above are insensitive to reasonable variations in the number of clusters, to the omission of any individual socioeconomic indicator, to modest stochastic perturbations of the input data and changes in the parameter ranges. All ARI values are well above the random-partition baseline, confirming that the spatial patterns reported in Figures 3, 4 and Table 3 can be interpreted as genuine features of the underlying socioeconomic dynamics rather than data artefacts or modelling choices.

In sum, the dynamics uncovered through time-series clustering reveal that relationships between socioeconomic indicators—such as manufacturing, employment, education, and social cohesion—are highly scenario- and region-dependent. While industrial growth can be correlated to both economic and social benefits in some scenarios, persistent divides and declining cohesion in other scenarios point to the need for tailored, context-sensitive policy interventions and long-term regional planning strategies.

4 Discussion

The study provides a spatially explicit and temporally detailed set of exploratory socioeconomic indicator trajectories, aiming to represent SSPs more multifaceted in modelling. The following section discusses the added value of this approach for research, its implications for climate policy, and existing limitations.

4.1 Added value for land system modelling

The high spatial resolution and multidimensional socioeconomic coverage of the dataset mark a substantial methodological advance beyond traditional SSP quantifications and offers significant potential for advancing climate change research. By capturing regional differences in economic, demographic, and social dynamics, such integration enables more realistic assessments of land use, mitigation, and adaptation strategies (Verburg et al., 2016). For example, shrinking regions—particularly in eastern Germany and rural peripheries—may be less able to sustain infrastructure and are thus more exposed to climate risks, while growing urban centres could see reduced adaptive capacity as inequality and housing pressures intensify.

The clustering analysis revealed such spatial heterogeneities in Germany's socioeconomic trajectories. In SSP1a and SSP1b, major urban regions exhibit the potential to combine economic dynamism with socially progressive outcomes—improving life expectancy, employment, and social cohesion while concurrently reducing crime and inequality. This aligns with well-known findings from the OECD Regional Outlook 2023, which shows that metropolitan regions across the OECD outperform others economically by around 32% GDP per capita on average, while peripheral regions continue to face depopulation, ageing, and weaker infrastructure (OECD, 2023). SSP5, on the other hand, illustrates trade-offs of rapid economic growth, where urban areas benefit from agglomeration and knowledge spillovers, achieving high socioeconomic performance at the cost of declining social cohesion and rising inequality. The persistent performance gap is particularly evident in rural areas and eastern Germany, where industrial output and human capital accumulation lag behind, reinforcing the broader east–west divide common across Europe (Diermeier et al., 2024). These outcomes reaffirm the central role of education and employment as levers for resilience (Maruseva and Kroll, 2024), while persistent industrial decline in regions such as the Ruhrgebiet underscores the importance of tailored labour market and industrial policies (Hüther et al., 2019).

Furthermore, differences in correlation patterns across scenarios reveal how alternative socioeconomic pathways may alter structural relationships between indicators. This is clearly illustrated by the contrasting SSP1b scenario. Unlike growth-oriented pathways, SSP1b explores a degrowth-oriented system in which wellbeing improves independently of economic expansion. This decoupling between social and economic indicators is novel and challenges conventional assumptions that higher income or employment automatically translate into greater equality, health gains, or environmental sustainability. Evidence from other contexts supports this reorientation: despite rising GDP, many nations continue to face social deficits while simultaneously overstepping ecological limits (Fanning et al., 2022). Moreover, conventional SSP-based mitigation pathways often fail to capture scenarios that reconcile stringent climate targets with material sufficiency, thereby neglecting degrowth-oriented strategies that may be key to achieving 1.5 °C ambitions (Keyßer and Lenzen, 2021).

These findings highlight the need for more flexible and adaptive modelling approaches, which are capable of recognising both spatial heterogeneities and scenario-sensitive interdependencies among socioeconomic indicators and representing their dynamic trajectories. Land-use change models are well suited for this purpose, as they simulate how land managers and societal actors respond to spatiotemporally shifting conditions, incentives, and constraints. Previous applications in Europe demonstrate that adding socioeconomic detail can surface emergent behaviours and pathways that would remain hidden in purely biophysical models (Blanco et al., 2017; Brown et al., 2019, 2022). In this sense, the regional scenarios developed here broaden the foundation for land-use modelling: they allow researchers to test how divergent socioeconomic trajectories—such as varying degrees of urbanisation, inequality, or labour market transitions—could alter land system outcomes. As such, these tools will be particularly valuable in informing the feasibility and distribution of land-based climate mitigation strategies, including carbon dioxide removal, across heterogeneous regional contexts.

4.2 Implications for climate policy

Advancing integrated human–environment modelling frameworks underpinned by robust socioeconomic data is essential for designing adaptive, equitable, and effective climate policies that reconcile economic development, social cohesion, and environmental sustainability at both regional and national scales.

The high spatial resolution and detailed integration of socioeconomic parameters presented here provide a basis for planning mitigation and adaptation strategies and to derive central policy implications. This includes analysing how socioeconomic developments can shape regional structures, such as the identification of the persistent performance gap between leading and lagging regions, a pattern that resonates with our SSP2 findings. In contrast, SSP1b offers a contrasting trajectory: its decoupled development model reduces dependency on GDP growth and emphasises equity, wellbeing, and environmental integrity. This highlights that alternative growth paradigms can play a role in shaping inclusive sustainability transitions. Similarly, persistent regional differences and inequalities in scenarios, for example between East and West Germany (e.g. in SSP2 and SSP4), highlight the regions that could benefit most from targeted policies, including training programs, innovation promotion or structural regional support.

This enriched indicator framework enables the development of finer-scale, policy-relevant scenarios that are attuned to sub-national climate and land use planning challenges. Looking ahead, embedding this enhanced socioeconomic detail into land system modelling frameworks opens up powerful avenues for exploring the complex interplays between land-use decisions, socioeconomic trajectories, and climate drivers under deep uncertainty.

4.3 Validity, interpretation, and limitations

Particularly in light of these policy implications, it is important to interpret the results of this study with care. The projections provide a rich, multidimensional depiction of plausible futures. However, given the long time horizon to 2100 and the central role of assumptions, we strongly recommend using the scenarios in ensemble or comparative mode (across SSPs), rather than treating any single pathway as a best estimate or planning target. For policymakers, the utility lies less in the literal outcomes of individual trajectories than in exploring how different development logics affect resilience, inequality, and land-use planning.

Embedding national scenarios in the global SSP framework ensures compatibility and comparability with global assessments, as the global framework provides the conceptual design for key scenario elements (e.g. economic trajectories). Downscaling global SSPs to the national level has both benefits and limitations. On the benefit side, it allows the integration of detailed, region-specific information. Locally salient factors such as municipal governance quality, place-based identities (e.g. social cohesion) or inequalities are not explicitly present in the global SSPs and therefore enter only through stakeholder expertise. At the same time, adapting globally designed SSP narratives to the NUTS-3 scale in a single country introduces constraints. Some SSP dimensions (e.g. geopolitical fragmentation) have no direct analogue at district level and are represented only indirectly via assumptions on economic divergence, policy priorities, or infrastructure investment. This 're-scaling' should therefore be seen as a translation of SSP logics into a German land-use context, not as a strict downscaling of global quantitative SSP projections.

The scenario outcomes are sensitive to the assumed national mean trajectories and to the convergence/divergence parameters that govern regional disparities. Alternative but still plausible parametrisations—for example, assuming stronger regional cohesion and faster convergence in SSP3, or a slower expansion of secondary and tertiary education in SSP1a—would shift the quantitative results and could change the cluster membership of some NUTS-3 regions. The robustness checks reported above, based on the Adjusted Rand Index (ARI), show that dominant spatial patterns—including east–west divides and urban–rural stratification—are relatively stable under indicator omission, parameter variation, and stochastic noise (ARI > 0.75 across tests). This robustness, however, should not be misread as a validation of specific parameter values. Instead, our numerical settings should be understood as one coherent, expert-elicited interpretation of the SSP narratives within a wider space of plausible futures. Future work could systematically explore this parameter space by varying national trajectories and convergence/divergence assumptions, thereby generating ensembles of regionalised SSP implementations and quantifying the resulting scenario uncertainty.

A further limitation concerns the interpretation of correlation patterns. The reported correlations are scenario-specific and time-averaged, and should be read as broad summaries of associations under each scenario rather than as stable relationships over the entire century. Structural breaks and time-varying relationships over the 21st century are likely. Analysing such dynamics more explicitly in exploratory scenarios (e.g., via rolling or regime-specific correlations) represents an important avenue for future work. Uncertainty also increases with the length of the time horizon, and this affects not only the projections themselves but also the expert judgements that underpin them. The emphasis of the scenarios in general, and of the expert judgements in particular, is therefore on plausibility and internal coherence, rather than on forecasts for specific indicators. This makes the scenarios well suited for scientific applications such as modelling relative differences across pathways.

It is also critical to recognise that the relationships identified—such as between income and life expectancy, or urbanisation and inequality—reflect statistical associations rather than causal links. These patterns likely emerge from shared underlying conditions (e.g., access to healthcare, education, or social infrastructure), which vary regionally and are only partially captured in our indicators. For instance, the weakening of income–inequality correlations in SSP3 does not indicate that growth reduces inequality, but rather that under fragmented governance, economic gains may not translate into broader social equity. Future work should integrate causal-inference or behavioural modelling approaches to disentangle drivers from outcomes.

Finally, data constraints at the NUTS-3 level limit our ability to represent institutional capacity, civic trust, or cultural attitudes—factors that may decisively shape land-use outcomes, especially for climate interventions such as carbon farming or afforestation. Future iterations should therefore place greater emphasis on integrating qualitative or participatory inputs to better reflect local agency and context.

In sum, while we acknowledge substantial uncertainties in assumptions, parameters, and data, the scenarios offer a valuable comparative lens. They enable planners to anticipate regional disparities, stress-test policy options, and design interventions that are resilient to multiple plausible futures—not because those futures can be predicted, but because their implications can be systematically explored.

5 Outlook and future directions

Future research can build on these scenarios by embedding them into dynamic land-use models, particularly agent-based approaches such as CRAFTY (Brown et al., 2022). Such models are designed to capture how heterogeneous land managers respond to shifting socioeconomic conditions and policy incentives. Linking our projections with agent-based modelling would allow exploration of emergent dynamics across regions, testing how divergent socioeconomic pathways influence land-based mitigation, adaptation, and the distributional outcomes of climate policies. In this way, the scenarios move from being primarily descriptive to serving as decision-support tools that bridge socioeconomic diversity with land-system and climate challenges.

Data availability statement

The datasets presented in this study can be found in online repositories. The spatially explicit, annual socioeconomic indicator projections for Germany generated for this study can be found and downloaded in the repository zenodo, under the following doi: https://doi.org/10.5281/zenodo.17213707.

Author contributions

KW: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. MW: Conceptualization, Formal analysis, Methodology, Writing – review & editing. FG: Conceptualization, Formal analysis, Methodology, Writing – Review & editing. MG: Conceptualization, Funding acquisition, Writing – review & editing. JP: Conceptualization, Funding acquisition, Project administration, Writing – review & editing. MR: Conceptualization, Funding acquisition, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. The SSP downscaling process, scenario development and development of a national dataset on socioeconomic indicators was part of the STEPSEC project, funded by the German Federal Ministry of Education and Research.

Acknowledgments

We would like to thank all participants of the stakeholder workshops and interviews for contributing to the development of the national land use-specific SSP narratives. In this context, we would also like to thank PROSPEX for moderating the stakeholder workshops. We also would like thank Bumsuk Seo for setting up a first database for modelling socioeconomic indicators in Germany.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2025.1715424/full#supplementary-material

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