

Three Decades of Progress: Spatiotemporal Patterns and Trend Forecasting in the Global Bladder Cancer Quality of Care Index

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Abstract

Object: This study evaluates spatiotemporal trends of the bladder cancer Quality of Care Index (QCI), identifies its key determinants, and projects future trends at global, regional, and national levels.

Methods: Based on Global Burden of Disease (GBD) data from 1990 to 2021, we constructed a QCI (scaled 0–100) using principal component analysis. Holt-Winters and Random Forest models were employed to forecast trends and quantify the nonlinear effects of age, gender, and year. A Random Forest model with SHAP quantified nonlinear effects of age, gender, and year.

Result: The global QCI for bladder cancer increased by 21.0% between 1990 and 2021, strongly correlating with the sociodemographic index ($r = 0.90$, $p < 0.001$). A five-fold gap existed in 2021 between high-income North America (QCI 99.20) and Central Sub-Saharan Africa (18.51). Age was the primary determinant, with the QCI showing an inverted U-shape trend peaking at ages 35–39. Projections indicate global QCI growth will plateau around 2038.

Conclusion: Although bladder cancer care has significantly improved, future advancements are expected to stagnate. This necessitates a strategic shift toward achieving equitable and sustainable care, particularly for elderly populations and underserved regions.

Keywords: Quality of care index; Bladder cancer; GBD database; machine learning

1 Introduction

Bladder cancer is one of the most common malignant tumors of the urinary system worldwide. Its persistently high incidence and mortality present a significant public health

challenge^[1]. Tobacco exposure is a well-recognized risk factor for bladder cancer, contributing to more than 50% of new cases globally each year. The global variation in tobacco control measures is closely linked to the regional disparities in bladder cancer burden and healthcare access^[2]. Thus, analyzing the quality of care for bladder cancer on a global scale is of great significance for improving the management of tobacco-associated diseases and reducing their global health burden. The management of bladder cancer has seen recent progress across its multimodal landscape, encompassing diagnostics, robot-assisted surgery, and systemic therapies ranging from chemotherapy to immune checkpoint inhibitors^[3]. However, substantial disparities still exist in the global accessibility and application of these medical resources, which directly contributes to inequalities in survival outcomes across countries and regions^[4]. High-income countries usually have more comprehensive early screening systems, faster diagnosis, and more advanced treatment options. In contrast, low- and middle-income countries face limited medical resources, shortages of specialists, and delays in patient access to care. Therefore, it is crucial to objectively and quantitatively assess the quality of bladder cancer care worldwide and to identify inequalities. Such efforts are essential for optimizing the allocation of global health resources and developing targeted intervention strategies.

Traditional indicators such as mortality or morbidity rates cannot fully capture the Quality of Care across the continuum from prevention and diagnosis to treatment and rehabilitation. The Quality of Care Index (QCI), developed from Global Burden of Disease (GBD) data, offers a more comprehensive assessment tool for this purpose. The QCI is an innovative, integrated evaluation tool^[5] that uses principal component analysis (PCA) to synthesize multidimensional metrics, including incidence, prevalence, mortality, and disability-adjusted life years (DALYs).

It generates a standardized score ranging from 0 to 100, with higher scores indicating better quality of care. This index allows standardized comparisons of quality of care across time, regions, and populations. This index allows for standardized comparisons of quality of care across time, regions, and populations. It has been widely applied in the quality assessments of various cancers and chronic diseases^[5,6], demonstrating robust evaluation capabilities. However, systematic analysis of the QCI in bladder cancer, particularly long-term, cross-regional, and cross-national studies, remains limited. In addition, there is a notable lack of machine learning-based exploration of key drivers and trend forecasting^[7].

Based on this, this study aims to use the latest GBD 2021 data to conduct the first systematic analysis of the evolution of the QCI for bladder cancer at global, regional, and national levels from 1990 to 2021. The study seeks to reveal inequalities in care quality and their underlying mechanisms, providing evidence-based guidance for resource-constrained regions. This will support the development of targeted policies, optimize healthcare resource allocation, and ultimately narrow global health disparities, improving survival and quality of life for bladder cancer patients.

2. Materials and Methods

2.1 Data Source

We extracted annual estimates of the GBD for bladder cancer from 1990 to 2021, along with estimates for 21 GBD regions and 204 countries and territories, using the online GBD 2021 data query tool (<https://vizhub.healthdata.org/gbd-results/>). We strictly followed the Guidelines for Health Assessment Reports statement^[8].

2.2 Research Variables

In this study, bladder cancer is defined as a malignant tumor of the bladder, classified under the International Classification of Diseases, Tenth Revision (ICD-10) code C67. We extracted the following key indicators from the GBD 2021 database: incidence rate, mortality, prevalence rate, years of life lost (YLLs), years lived with disability (YLDs), and DALYs. Age-standardized rates are adjusted for age structure using a standard population (per 100,000) to eliminate the impact of differences in age composition across populations and ensure comparability of data over time and across regions. DALYs serve as a comprehensive metric for total health loss, combining YLLs due to premature death and YLDs due to impairment. The sociodemographic index (SDI) is a composite measure of per capita income, average years of schooling, and total fertility rate, ranging from 0 to 1. Based on this index, the GBD study categorizes countries and regions into five tiers: low (<0.45), lower-middle (<0.61), middle (<0.69), high-middle (<0.80), and high (≥ 0.80).

2.3 Statistical Analysis

To evaluate bladder cancer care, we constructed four derived indicators: the mortality-to-incidence ratio (MIR), prevalence-to-incidence ratio (PIR), DALYs-to-prevalence ratio (DPR), and YLLs-to-YLDs ratio (YLR). These were integrated into a QCI using PCA. While traditional methods use only the first principal component (PC1)^[9], this can lead to information loss. We therefore applied a modified approach^[10], combining the first and second principal components, weighted by their respective variance contributions, to comprehensively capture the underlying quality of care. To ensure that the generated PCA scores are standardized and intuitively comparable on a 0–100 scale, a linear transformation was applied. The final

QCI calculation is as follows:

$$QCI(x) = \frac{PCA_{score}(x) - \min(PCA_{score})}{\max(PCA_{score}) - \min(PCA_{score})}$$

Where: $QCI(x)$ is the final QCI score for a specific observation unit x (e.g., a particular country, year, or age group). $PCA_{score}(x)$ is the composite score calculated for that observation unit after weighting via PCA. Through this method, the QCI score has a clear interpretation: a score of 0 represents the lowest quality of care across the entire spatiotemporal scope, while a score of 100 represents the highest.

To forecast future QCI, we first projected six core indicators using Holt-Winters triple exponential smoothing. These projections were then integrated via principal component analysis, using the first principal component (PC1) to represent the dominant trend. Finally, forecasted PC1 values were corrected and linearly scaled to the historical 0–100 QCI range, ensuring seamless integration of past and future data. We constructed a random forest regression model to quantify the nonlinear effects of age, gender, and year on QCI. Model performance was evaluated using key metrics (e.g., coefficient of determination, root mean square error) and visual diagnostics, including predicted versus actual plots and residual analysis to detect systematic biases. Finally, the SHAP framework was applied to interpret the model, quantifying each variable's contribution to the QCI predictions.

3. Results

3.1 Global QCI Age Patterns and Gender Differences: A Comparative Analysis of 1990 and 2021

In both 1990 and 2021, the global bladder cancer QCI demonstrated a consistent nonlinear inverted U-shaped distribution with age. The QCI peaked in the 35–39 age group in both years

(1990: 99.27; 2021: 99.12), with a sharp drop after age 75. For the oldest cohort (95+), the QCI was near zero in 1990 (0.77) and remained very low in 2021 (4.74). Significant gender differences were also observed. Across most age groups in both 1990 and 2021, men had higher QCI scores than women. In 1990, this gap was most pronounced in younger adults, though the trend reversed in the oldest cohorts (≥ 80 years), where women showed slightly higher QCI. By 2021, men maintained a QCI advantage across nearly all age groups. The disparity was most extreme in the 95+ age group, where the female QCI dropped to 0.00 while the male QCI was 8.32, possibly reflecting data instability at extreme ages (Fig 1).

3.2 Spatial-Temporal Distribution Characteristics of the QCI Across Global, Regional, and SDI Stratifications from 1990 to 2021

From 1990 to 2021, the global quality of bladder cancer care steadily improved, with the overall QCI rising 21.0% from 63.63 to 76.97. A strong positive correlation was found between QCI and the SDI across 21 global regions ($r = 0.90$, $P < 0.001$) (Fig 2), highlighting significant disparities. In 2021, high-SDI regions like High-Income North America (99.22) led, while low-SDI regions lagged substantially. Growth rates varied significantly. Low-SDI regions showed immense gains from low baselines (e.g., Central Sub-Saharan Africa saw a 20-fold increase), whereas high-SDI regions saw minimal growth (e.g., High-Income North America increased by only 3.8%), indicating a plateau phase in care quality. Regional-level correlation analysis revealed that three derived indicators (YLR, DPR, MIR) were strongly inter-correlated (all Pearson $r > 0.96$) and all were strongly negatively correlated with the PIR (all $r < -0.96$). This structure was confirmed by PCA, where the PC1 explained 98.7% of the variance (Supplementary Fig 1).

3.3 Geographic Distribution of Bladder Cancer QCI 204 Countries and Regions

Worldwide, 1990–2021

Analysis of 204 countries and regions revealed substantial QCI disparities in 2021, from a high of 99.1 in the United States to a low of 15.4 in the Central African Republic, underscoring severe global inequality. At the national level, QCI was also strongly correlated with SDI ($r = 0.87$, $P < 0.001$) (Fig 3). However, economic development was not the sole determinant; for instance, Japan and South Korea had lower QCI scores than some European countries with similar SDI levels. From 1990 to 2021, the absolute inequality in QCI remained stable, while the relative inequality declined significantly (Concentration Index: 0.21 to 0.16) (Supplementary Fig 2). To confirm the underlying drivers of QCI, PCA and correlation analyses were repeated at the national level. The results mirrored the regional findings: the indicators YLR, DPR, and MIR were strongly positively inter-correlated (all $r \geq 0.96$) and all were extremely negatively correlated with PIR (all $r \leq -0.96$). The almost perfect mirror-image relationship between MIR and PIR ($r = -0.99$) was particularly notable (Supplementary Fig 3).

3.4 Machine Learning-Based Attribution Analysis of Factors Influencing QCI

A random forest regression model was developed to assess the drivers of QCI, demonstrating excellent predictive performance ($R^2 > 0.99$) and generalization capability (Fig 4a). Interpretation using the SHAP method identified age as the strongest determinant, followed by year and gender. Age exhibited a clear nonlinear inverted U-shaped effect, with middle-aged cohorts (30–60 years) positively influencing QCI and the oldest cohorts (≥ 82.5 years) having a strong negative impact. The year variable confirmed a clear temporal improvement in care quality over the three decades. Gender showed a consistent effect, with being male associated

with positive contributions to QCI and being female associated with negative contributions (Fig 4b, c). For example, in a representative case (a 72.5-year-old male in 2009), the SHAP waterfall plot showed that Year (SHAP = +1.41) and Gender (SHAP = +1.05) contributed positively to QCI, while Age (SHAP = -0.67) partially offset these effects (Fig 4d).

3.5 Future Trend Predictions for QCI in Global and SDI Regions Based on Time Series

Models

Time-series forecasting projects that the rapid growth of the global QCI will decelerate, reaching a projected peak around 2038. Subsequently, the index is expected to enter a plateau phase and exhibit a marginal decline by 2050. While males are forecasted to maintain a higher absolute QCI, their peak will occur slightly earlier than for females (2038 vs. 2039). Projections for all SDI regions also show only modest future growth, suggesting that global improvements in care quality are projected to saturate (Supplementary Fig 4).

4 Discussion

This study provides a systematic assessment of the spatiotemporal evolution, determinants, and future trends of the global QCI for bladder cancer from 1990 to 2021. Our findings show that the global quality of bladder cancer care has improved markedly over the past three decades, yet substantial disparities persist across different socioeconomic development levels, forming a pronounced gradient between high-SDI and low-SDI regions. Beyond geographic and economic inequalities, the QCI displays a systematic population distribution, following a nonlinear inverted U-shaped relationship with age, peaking in middle age and declining sharply in older groups. Men consistently demonstrated higher care quality than women across most stratifications. Machine learning analysis further confirmed age as the strongest determinant of

QCI, followed by year and gender. Projections suggest that the period of rapid global growth in care quality may have ended, with the QCI likely entering a plateau phase. These findings highlight the urgency of addressing structural limitations within existing care systems.

This study found the bladder cancer QCI exhibits an inverted U-shaped pattern, peaking at ages 35–39 and declining markedly after 70. This highlights systemic inequalities where elderly patients often receive inadequate care. This sharp decline is not an inevitable consequence of aging but reflects systemic challenges in managing elderly patient heterogeneity^[11]. A core driver is the under-treatment of older patients; despite a higher prevalence of muscle-invasive bladder carcinoma (MIBC), many do not receive curative therapy^[12,13]. For instance, a study of over 40,000 MIBC patients^[14] reported cystectomy rates dropping from 55% for those under 70 to 21% for those aged 79 and older. Concurrently, comorbidities and physiological frailty^[15,16] lead clinicians to recommend intensive treatments cautiously, fearing toxicities may outweigh benefits. This decision-making bias is rooted in evidence gaps, as pivotal trials often excluded elderly or comorbid patients^[17,18]. Consequently, elderly patients have unequal access to quality care. However, chronological age should not be the primary determinant for treatment. Modern geriatric oncology^[19] prioritizes tools that differentiate physiological from biological age, and the International Society of Geriatric Oncology recommends comprehensive geriatric assessments to guide individualized treatment^[20]. The QCI decline is a global warning that medical systems have not adapted to population aging. Future efforts must focus on inclusive trials, integrating geriatric assessments into clinical pathways, and developing tailored protocols for the elderly to bridge this age-based care gap.

This study found that in most regions and age groups, the QCI for male bladder cancer was higher than that for female ones. Previous studies have reported that the incidence of bladder cancer in men is three to four times higher than in women, and that male patients generally have a significantly better prognosis than female patients^[21,22]. A study involving 47,229 patients with MIBC reported that female patients had a higher 90-day mortality and reduced overall survival after radical cystectomy^[23]. Therefore, this persistent disparity in care quality is unlikely to be explained by a single factor, but rather reflects the combined influence of multiple contributors, including systemic delays in diagnostic pathways and differences in treatment outcomes. Women presenting with initial hematuria are more likely to be diagnosed with urinary tract infections^[24], and only 8% of women are referred to urologists^[25]. Gender disparities also exist in hematuria referral guidelines^[26], with the American Urological Association guidelines placing greater emphasis on male hematuria^[27]. Additionally, a cross-sectional study found lower cystoscopy rates among women compared to men^[28], leading to later clinical staging at diagnosis. Beyond these staging disparities, female bladder cancer patients also face a higher cancer-specific mortality rate than males^[29,30]. Research has confirmed female gender as an independent predictor of cancer-specific mortality (HR = 1.17, P = 0.004)^[31]. Thus, the gender disparities in care quality observed in this study are not the result of isolated failures but reflect systemic biases and barriers embedded throughout the healthcare pathway. Bridging this gap requires comprehensive reforms across multiple levels from revising hematuria assessment guidelines and enhancing primary care physicians' vigilance toward female patients' symptoms to ensuring that women receive standardized specialist evaluation and treatment.

The predictive results of this study suggest that, after a prolonged period of sustained improvement, the global bladder cancer QCI may enter a plateau phase, with some high-SDI regions even experiencing a slight decline. This trend indicates that improvements in bladder cancer care quality are limited and do not follow a linear or unlimited trajectory. The observed “quality ceiling” phenomenon may be explained by multiple factors. First, in high-income countries, the cancer diagnosis and treatment systems are relatively mature. As a result, the potential for quality improvement through conventional methods is diminishing, and further progress may rely more on substantial technological innovations or new treatment strategies, rather than solely optimizing existing models^[32]. Second, demographic shifts have led to a rising proportion of elderly patients in the general population, whose care quality levels are significantly lower than those of younger patients^[7]. Consequently, population aging emerges as a key factor contributing to the decline in overall quality indicators. Third, the sustainability of healthcare systems is facing increasing pressures. Soaring cancer treatment costs, strained medical resources^[33], professional burnout^[34], and disruptions to oncology pathways caused by public health emergencies (such as COVID-19)^[35] may all contribute to stagnation or even slight declines in care quality. In this context, future efforts should not solely focus on continuous improvements in care quality. Instead, the emphasis should shift toward maintaining and optimizing the high standards already achieved under conditions of limited resources and rapid demographic changes. Novel care models, including digital health management^[36], AI-assisted decision-making^[37], and personalized pathways based on precision medicine^[38], hold promise for overcoming this “quality ceiling”. These approaches aim to enhance patient outcomes while preserving the stability of care delivery.

This study has several limitations. First, it relies on GBD 2021 data, where a significant portion of information for regions with low SDI is based on model estimates and data interpolation, which may introduce uncertainty regarding accuracy. Differences in cancer registration completeness and diagnostic coding standardization across countries and regions could also introduce systematic biases that are difficult to fully correct. Additionally, the QCI, as a composite metric, is constructed based on statistical assumptions, making it more suitable for measuring relative performance than absolute quality. Second, the study lacks critical individual-level clinical data, such as tumor staging, treatment regimens, and comorbidity information, limiting the ability to analyze the specific mechanisms underlying observed disparities. This confines the conclusions to the ecological level and precludes causal inference. Finally, our predictive model does not fully capture all uncertainties. While the high predictive power of the machine learning model reflects inherent structural associations between QCI and factors such as age and year, the results should be interpreted as contribution decomposition rather than causal attribution.

5 Conclusion

This study comprehensively analyzed the evolution of global bladder cancer care quality from 1990 to 2021. While overall standards have improved, structural inequalities driven by age, gender, and sociodemographic factors remain pronounced. Projections suggest that future improvements are nearing saturation, with high-income regions potentially facing stagnation or even decline. The key challenge ahead is to sustain existing achievements under resource constraints and population aging. Targeted interventions for vulnerable populations will be essential to reduce inequalities and promote a more equitable and sustainable global care

landscape. This study on the global quality of care for bladder cancer also provides a valuable reference for the assessment and optimization of healthcare quality for other tobacco-associated diseases worldwide, especially in low-SDI regions with inadequate tobacco control

Clinical trial number

Not applicable.

Ethical approval

This study represents a secondary analysis of publicly available databases containing anonymized data without personally identifiable information. Therefore, institutional review board approval and patient informed consent were not required.

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Conflicts of Interest

All authors declare that there are no conflicts of interest.

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Author Contributions

Guangyi Zhu: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing-Original Draft. Jieming: Validation, Investigation, Resources, Data Curation, Writing-Review & Editing. Kun Yang: Methodology, Software, Validation, Formal analysis, Visualization. Tianyu Zhang: Investigation, Resources, Data Curation, Supervision. Mingjun Shi: Conceptualization, Resources, Writing-Review & Editing, Supervision, Project administration. Yinong Niu: Conceptualization, Resources, Writing-Review & Editing, Supervision, Funding acquisition.

Data Availability

All data used in this study are publicly available and were obtained from the Global Burden of Disease (GBD) Results Tool, a resource managed by the Institute for Health Metrics and Evaluation (IHME). The specific datasets supporting the conclusions of this article can be accessed by querying for bladder cancer indicators from 1990 to 2021 at the following URL: <https://vizhub.healthdata.org/gbd-results/>. No new data were generated in this study.

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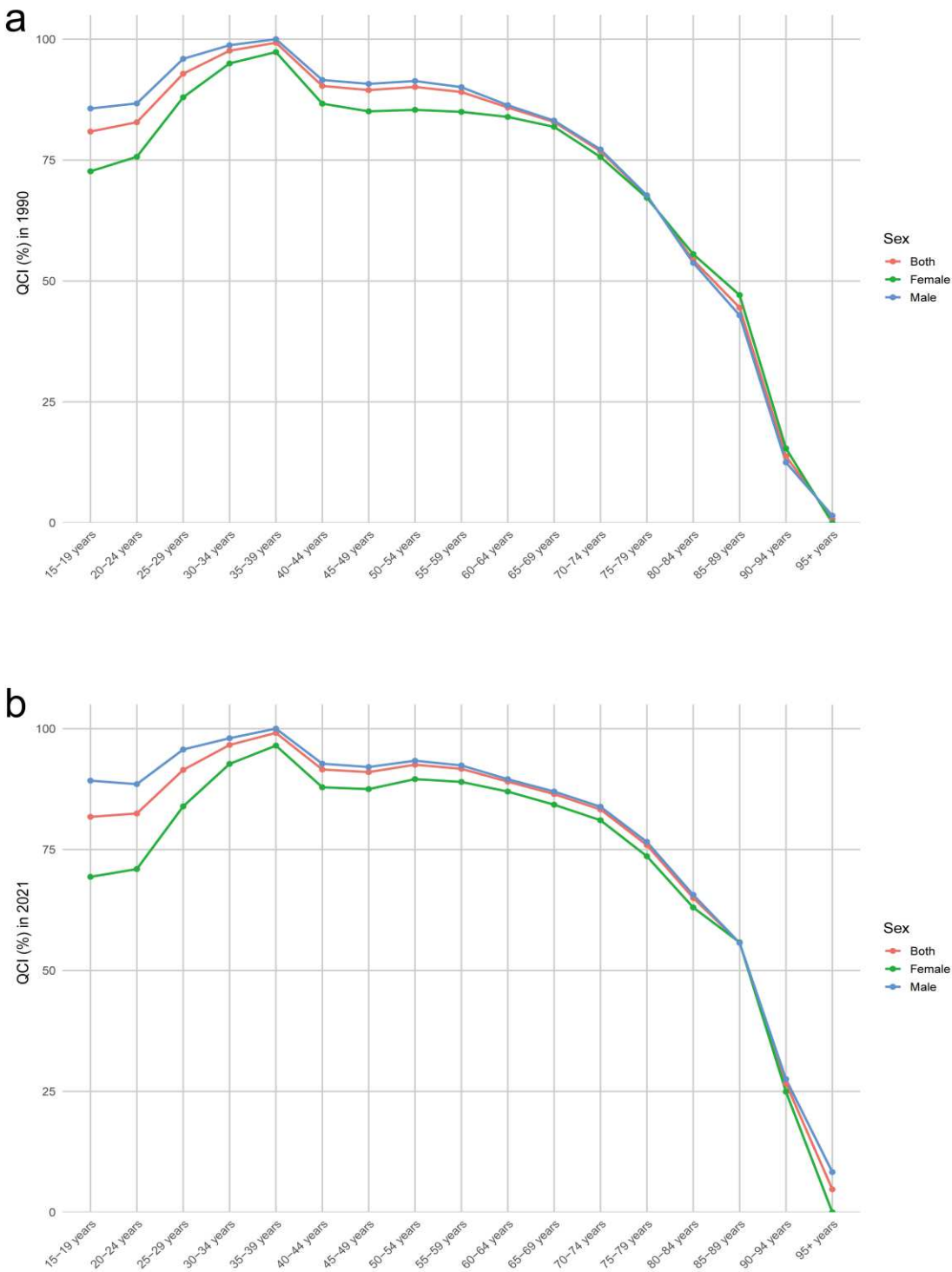
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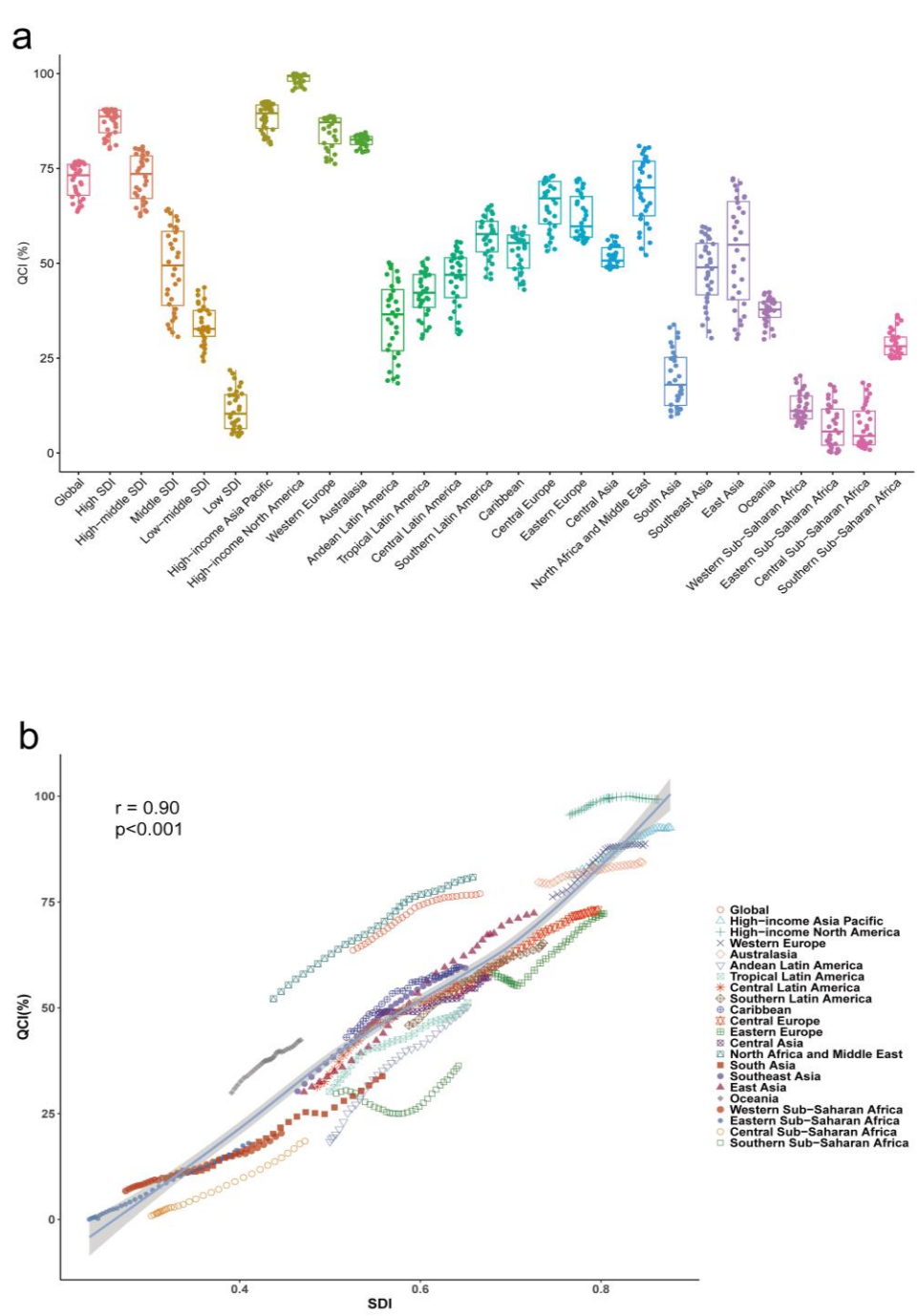
441 **Figures**



442

443 **Fig 1** Global bladder cancer QCI in 1990 and 2021 stratified by gender and age group.

444 Abbreviations: QCI, quality of care index



446

447 **Fig 2** Global bladder cancer QCI distribution and association with SDI from 1990 to 2021.

448 a. Distribution of bladder cancer QCI in 1990-2021 across global, 5 SDI regions, and 21 regions.

449 b. Association between bladder cancer QCI and SDI in 1990-2021 across global, 5 SDI regions,

450 and 21 regions. Abbreviations: QCI, quality of care index; SDI, sociodemographic index

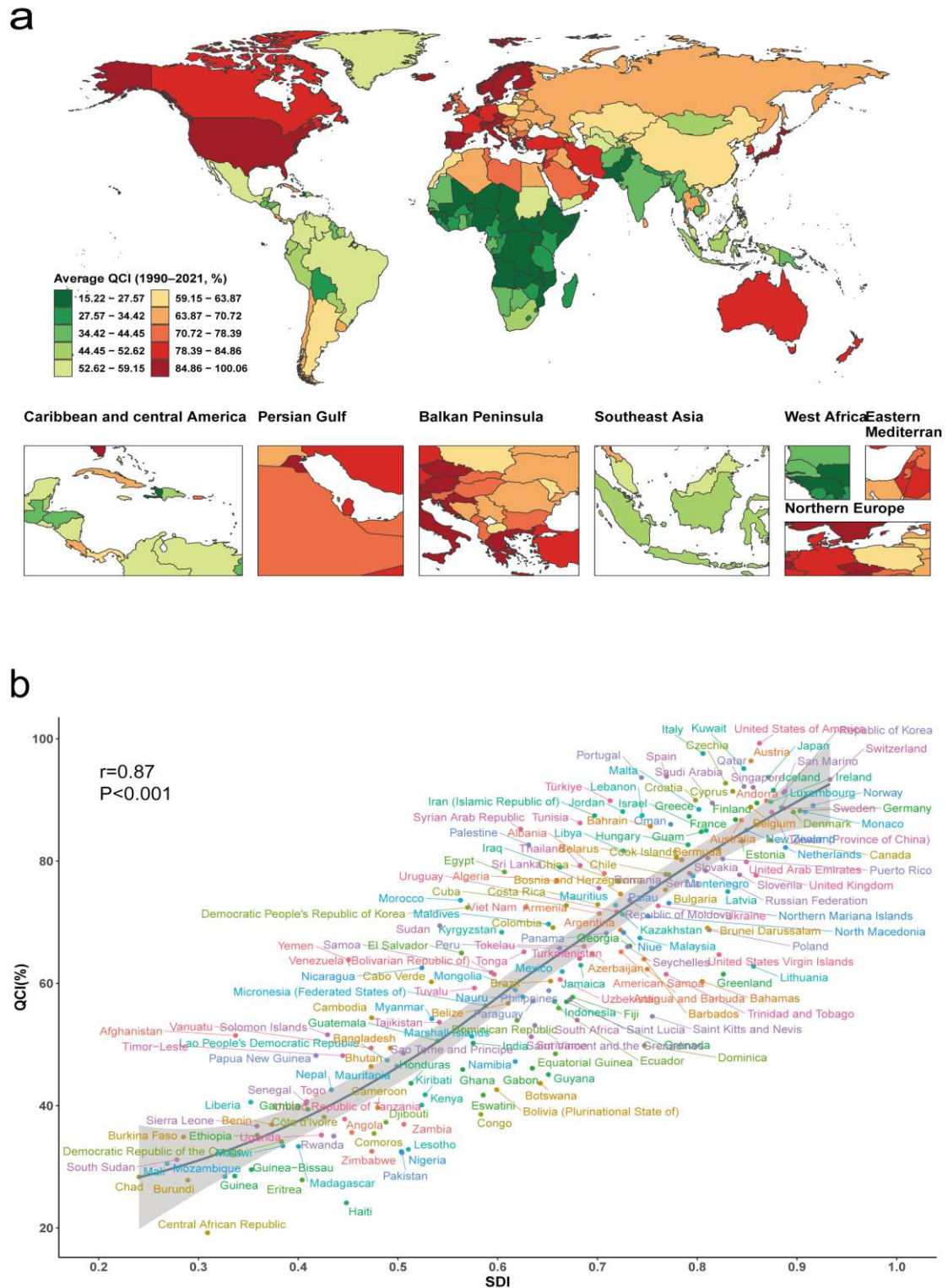


Fig 3 Geographic distribution of bladder cancer average QCI from 1990–2021 and association with SDI. a. Geographic distribution of QCI across 204 countries and territories. b. Association between QCI and SDI across 204 countries and territories in 2021. Abbreviations: quality of care index, SDI, sociodemographic index

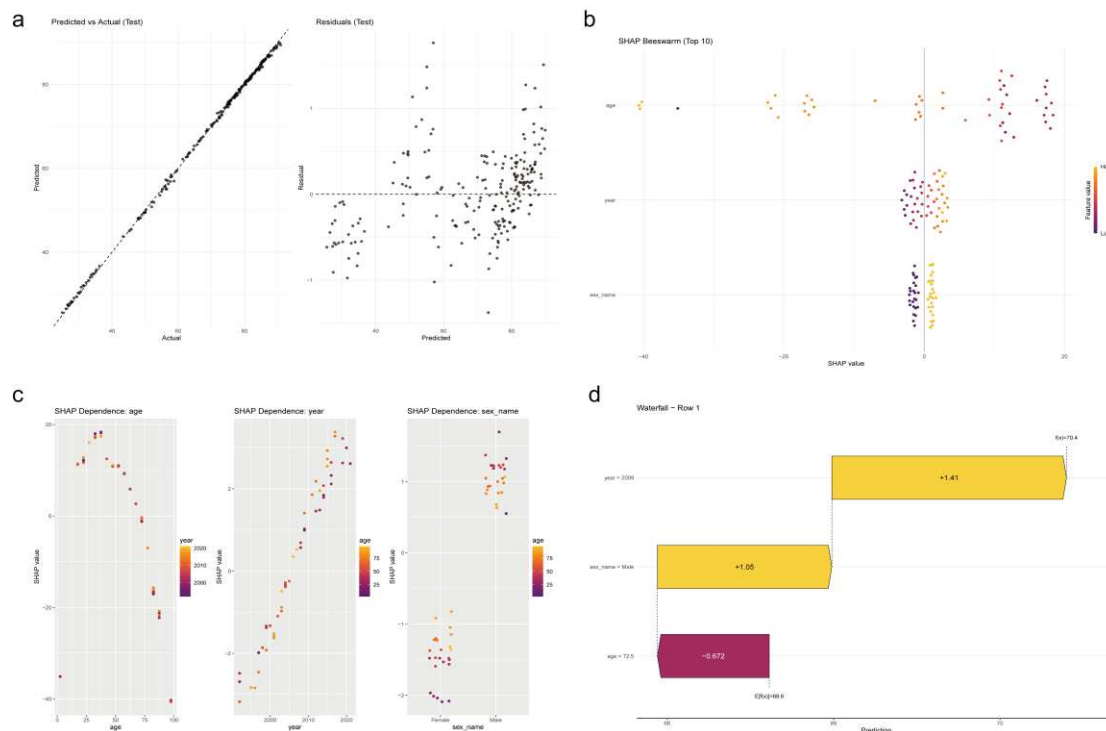
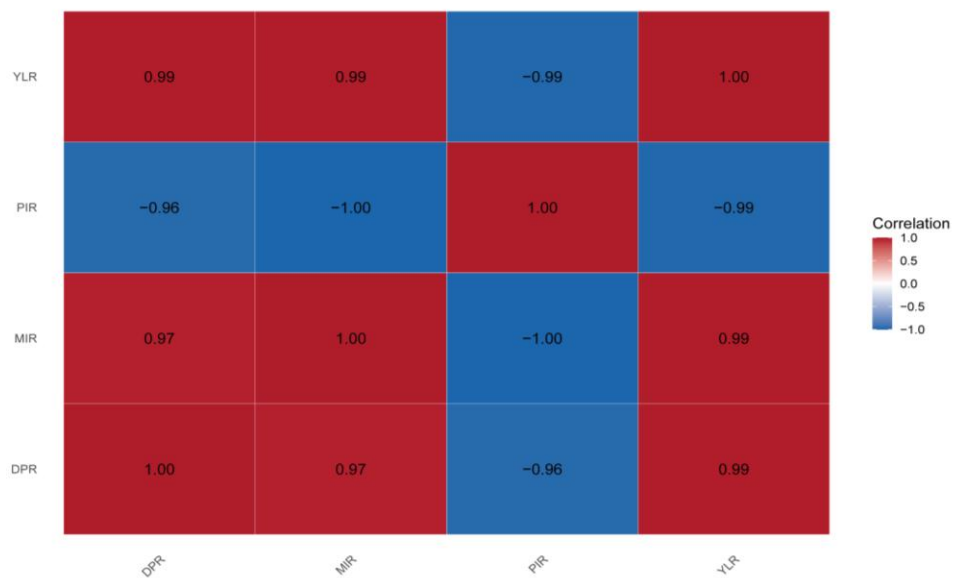
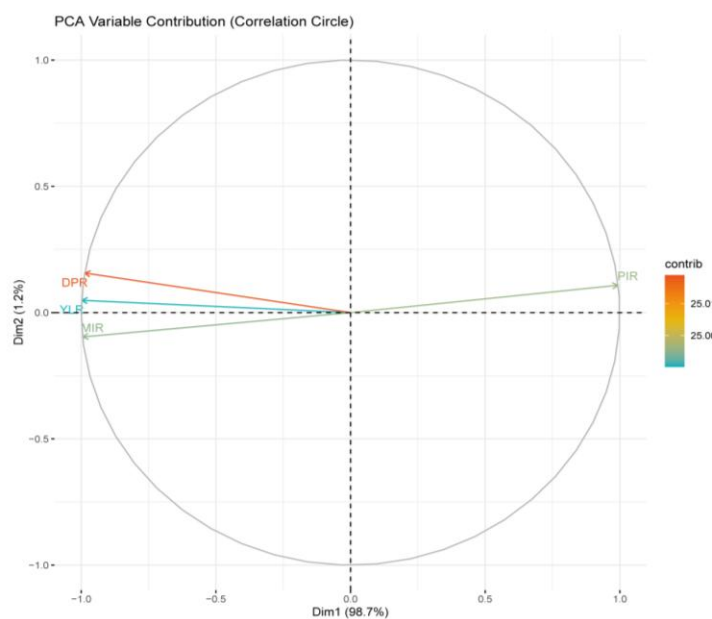


Fig 4 Random Forest model performance and SHAP-based interpretation of factors influencing the bladder cancer QCI. a. Predictive performance of the Random Forest regression model. b. Global feature importance based on mean absolute SHAP values, ranking the overall impact of age, year, and gender on QCI. c. SHAP dependence plots illustrating the nonlinear effect of each variable on the QCI prediction. d. SHAP waterfall plot explaining an individual prediction by decomposing the contributions of each feature. Abbreviations: SHAP, SHapley Additive exPlanations; QCI, quality of care index

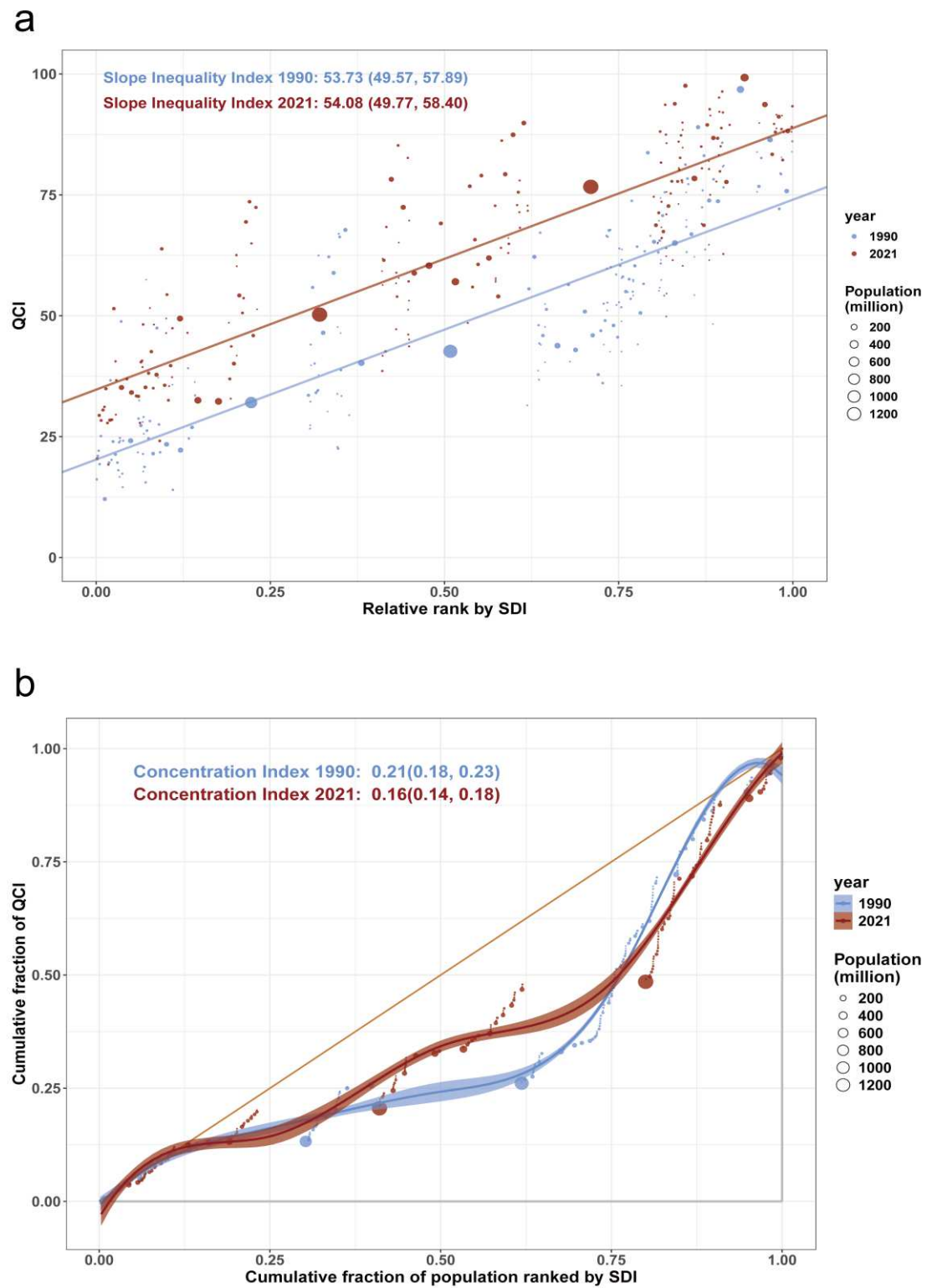
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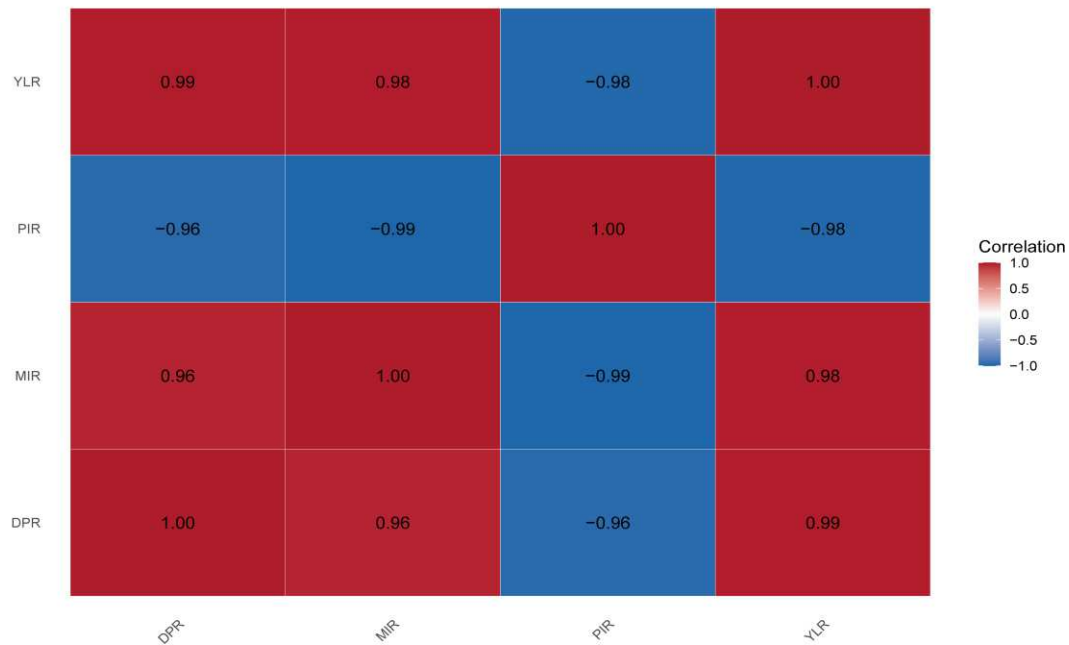


Supplementary Fig 1 Correlation matrix and PCA of derived indicators for bladder cancer quality of care by region. a. Correlation matrix showing the relationships among the four derived indicators (YLR, MIR, DPR, and PIR). b. PCA biplot displaying the contribution of the four derived indicators (YLR, MIR, DPR, and PIR) to the first two principal components. Abbreviations: PCA, principal component analysis; YLR, YLLs-to-YLDs ratio; MIR, mortality-to-incidence ratio; DPR; DALYs-to-prevalence ratio; PIR, prevalence-to-incidence ratio

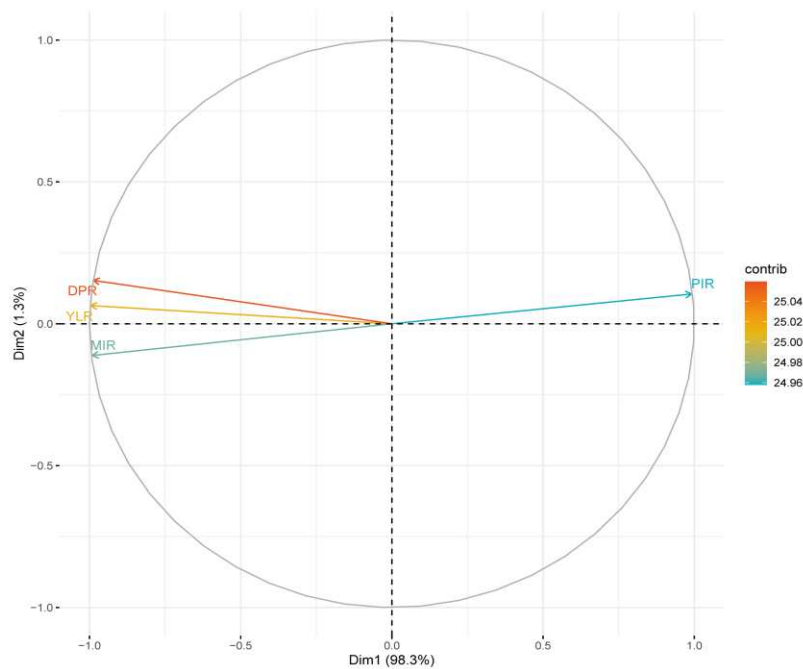


Supplementary Fig 2 Socioeconomic inequality in the global burden of bladder cancer QCI across 204 countries and region, 1990–2021. a The absolute inequality; b The relative inequality. Abbreviations: QCI, quality of care inde; SDI: sociodemographic index

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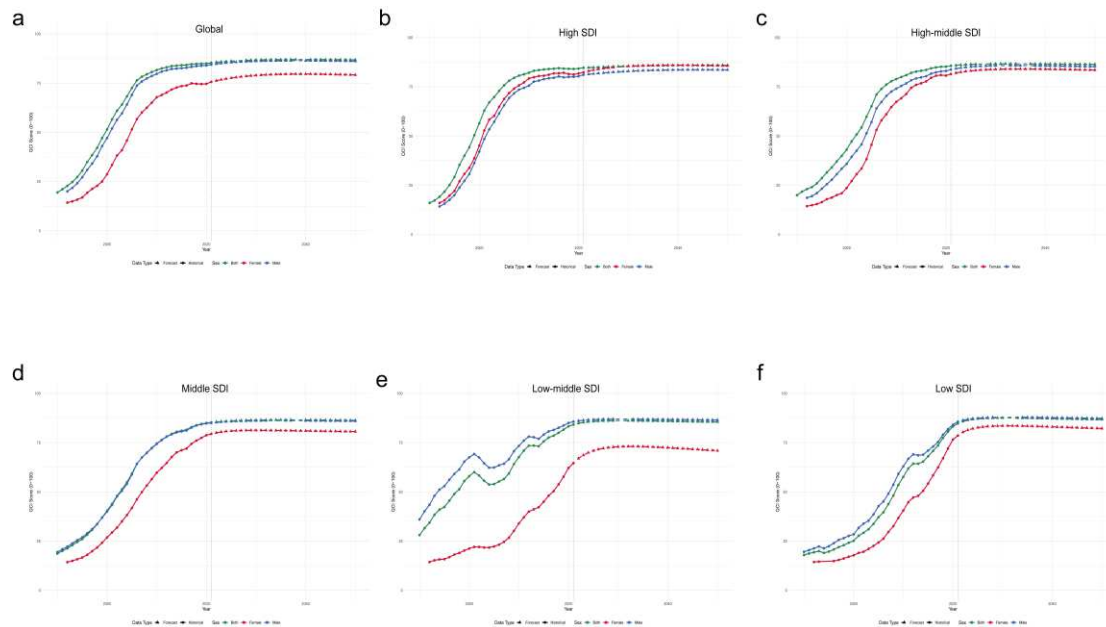


b



Supplementary Fig 3 Correlation matrix and PCA of derived indicators for bladder cancer quality of care by country. a. Correlation matrix showing the relationships among the four derived indicators (YLR, MIR, DPR, and PIR). b. PCA biplot displaying the contribution of the four derived indicators (YLR, MIR, DPR, and PIR) to the first two principal components.

Abbreviations: PCA, principal component analysis; YLR, YLLs-to-YLDs ratio; MIR, mortality-to-incidence ratio; DPR; DALYs-to-prevalence ratio; PIR, prevalence-to-incidence ratio



Supplementary Fig 4 Projected trends in the bladder cancer QCI to 2050 based on the Holt-Winters triple exponential smoothing method, globally and for 5 SDI regions. Abbreviations: QCI: quality of care index; SDI, sociodemographic index