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Global property rights and land use efficiency

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The study investigates the global impact of land property rights on land use efficiency (LUE), as measured by the key indicator for United Nations Sustainable Development Goal 11.3.1, namely Land Consumption Rate to Population Growth Rate. By utilizing human-land change data from 165 countries spanning the period between 1990 and 2020, we have developed a fixed effects model and employed legal origins as an instrumental variable to examine the influence of land property rights security on LUE. Our findings demonstrate that the security of land property rights significantly influences LUE, with common law countries exhibiting higher levels of LUE compared to civil law countries while controlling for other variables. Stability in property rights encourages long-term investments in infrastructure and sustainable land management practices, thereby enhancing land productivity and mitigating urban sprawl. Furthermore, safeguarding property rights limits governments' power to expropriate lands, facilitating rational and efficient land transactions that contribute towards achieving Sustainable Development Goals.

With the acceleration of global urbanization, the land is facing a multitude of challenges, including increased competition for limited land resources, conflicts, and compromises in land use decisions. Meanwhile, rapid urban expansion and industrialization exert substantial pressure on ecosystems, food systems, and natural resources, making land use change a primary driver of global environmental transformations[1,2]. Efficient land use is associated with benefits like energy conservation[3], effective waste management[4], and increased economic productivity[5].To monitor the change in the human-land relationship, the United Nations' Sustainable Development Goal (SDG) proposes key indicators such as the land consumption rate (LCR), population growth rate (PGR), and the ratio of LCR to PGR (LCRPGR)[6] to measure the land use efficiency (LUE). A higher LCRPGR indicates a lower LUE. It is important to note that LCRPGR concerns not only the growth of urban areas[6], but also the expansion of rural construction land, addressing the need for an integrated approach to assess urban-rural land use.

The relationship between human activities and land use has been extensively researched, with a particular focus on the impact of urbanization, industrialization, foreign direct investments (FDI), labor migration, transportation, and natural resource endowment on land use.

Urbanization and industrialization have played crucial roles in land use change[7]. For instance, urbanization in Ethiopia[8] demonstrates how land use changes to accommodate a growing urban population, resulting in the conversion of agricultural lands into residential and commercial areas. Meanwhile, Eastern Europe experiences urban shrinkage with population decline[9], while Southern Europe expands into croplands. In Western Europe, higher LUE is observed due to industrial clustering effects[10]. Industrialization in East Asia particularly

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in China highlights the profound shift from agrarian landscapes to industrial zones, and the land use became fragmented and scattered[11].

Globalization, driven by labor mobility[12–14] and FDI[15,16], notably shapes LUE. In countries like the USA, European countries, China, and India, increasing incomes prompt individuals to move from city centers to suburbs, thus expanding urban living space[14]. FDI leads to urban growth in developing nations through enhanced technology transfer, infrastructure development, and market integration[15]. In Africa, FDI facilitates the transfer of land from landowners with abundant resources to investors, ultimately enhancing LUE[16].

Transportation and natural resources also play crucial roles in land use change. For cities such as Seoul[17], Madrid[18], and Chinese megacites[19], have led to reduced commute times and the development of denser, more efficient urban layouts. These advancements have facilitated the creation of mixed-use areas and decreased the reliance on expansive suburbs. Furthermore, the availability of natural resources strongly impacts land use decisions. In Australia, ample land allows for extensive agricultural activities[20], unlike Japan where limited space necessitates meticulous planning to optimize LUE[21].

The existing literature in urban studies, environmental studies, and geography has extensively examined the impacts of various factors on LUE. However, a crucial determinant that strongly influences LUE - land property rights (LPRs) - has been somewhat overlooked. Traditional growth theory fails to consider the incentives of stakeholders and private property rights in driving changes in land use[7]. Although socio-economic literature extensively discusses the role of property rights in economic growth and national wealth, it often separates these discussions from their implications for land use[22]. A substantial body of research has explored how institutions shape human-land relationships[23–30] and emphasizes that a well-defined property rights regime with clear boundaries and equitable resource allocation can substantially reduce transaction costs and enhance land resource management[23–25]. Conversely, ineffective land lease policies have led to large portions of urban land remaining vacant or underutilized for extended periods[26]. Nevertheless, there is an inadequate exploration of the profound impact of institutional frameworks, particularly LPRs, on LUE. Recent studies such as Koroso's investigation into Ethiopia's institutional credibility[26] shed light on this issue but do not delve into the deeper legal origins and specific mechanisms through which property rights affect LUE.

This research employs an interdisciplinary approach to address identified gaps, focusing on the influence of property rights on global LUE across different countries. Our hypothesis posits that secure and well-established property rights play a crucial role in enhancing LUE, and we explore whether such security has led to improved LUE by promoting investment and safeguarding against threats like armed bandits, powerful neighbors, or governmental overreach[31,32]. No cross-national comparative analysis has been conducted to examine the impact of property rights on land use worldwide. To understand this, this paper analyzes the LCRPGR at the country level using spatial data from the Global Human Settlement Layer (GHSL) spanning from 1990–2020[33]. Our objective is to investigate changes of LCRPGR across various countries and assess how the security of property rights influences LUE. This research aims to contribute to sustainable land development studies while providing insights for policymakers regarding the environmental implications of property rights regimes.

Results

A global pattern of LCRPGR change from 1990 to 2020

While presenting an overview of the global change of LUE, we employ four classification systems to elucidate the variations among countries: the value changes of LCRPGR, growth intervals, income level, and legal system, illustrated as following:

Value Changes of LCRPGR by Continent and Country: The expansion of urban land (LCR of 0.622) outpaced population growth (PGR of 0.391) from 1990 to 2020, resulting in an average LCRPGR value of 1.591 (Fig. 1). This discrepancy between land and population growth highlights a decline in LUE. Yearly LCRPGR data demonstrate fluctuations in the relationship between human settlement expansion and land availability, with a general downward trend observed for global LUE.

Meanwhile, it is important to note that this global trend may obscure substantial regional disparities. Figure 1 also illustrates the changes in global LUE from 1990 to 2020 across different continents. In Africa, Asia, and Oceania, there was a noticeable upward trend in annual LCRPGR, indicating a decline in LUE. Conversely, North and South America showed a downward trend in LCRPGR, suggesting improvements in LUE; however, these improvements were slightly more pronounced in North America compared to South America. The LCRPGR for Europe remained relatively stable over the years. It increased from 34.617 in 1998 to 143.663 in 1999 but experienced a substantial decline of -309.877 by 2019 due to population decreases. These large positive or negative values primarily stem from shifts in population dynamics which were recorded as being at 0.0001 in 1999 and decreased to -0.00002 by 2019. Meanwhile, high-LUE countries were predominantly located within Africa back in 1990; however, by 2019, high-LUE countries became more geographically diverse encompassing regions such as Africa, Asia, Oceania, and North America.

Growth Interval Change of LCRPGR by Continent and Country: According to the research conducted by the Joint Research Centre of the European Commission[6], LCRPGR can be categorized into five intervals based on numerical values: high growth ($LCRPGR > 2$), medium growth ($1 < LCRPGR \le 2$), low growth ($0 < LCRPGR \le 1$), low decrease ($LCRPGR \le -1$), and high decrease ($-1 < LCRPGR \le 0$). When the LCR is lower than the PGR, LCRPGR indicates low growth ($0 < LCRPGR \le 1$), suggesting efficient land use. When the LCR slightly exceeds the PGR, LCRPGR demonstrates medium growth ($1 < LCRPGR \le 2$), reflecting inefficient utilization of land. In cases where the LCR significantly surpasses the PGR or when there is negative population growth, LCRPGR signifies high growth ($LCRPGR > 2$), low decrease ($LCRPGR \le -1$), and high decrease ($-1 < LCRPGR \le 0$), representing highly inefficient land use.

In 1990, driven by land expansion, European nations such as Sweden, Germany, and Poland were located in the high growth interval ($LCRPGR > 2$). However, by 2019, there was a noticeable shift towards a lower LUE interval in Europe, and countries, including Poland, Italy, and Greece primarily fell within the low decrease interval ($LCRPGR < -1$). Conversely, North America demonstrated a distinct reversal in trend over the same period. Initially, countries such as Guatemala and Nicaragua were predominantly situated within the low growth interval ($0 < LCRPGR \le 1$) in 1990. By 2019, this trend underwent a dramatic shift with regions like Greenland and Mexico falling into the high growth interval ($LCRPGR > 2$), indicating a movement towards lower LUE. Furthermore, in both 1990 and 2019, Asia, Africa, South America, and Oceania consistently maintained the highest proportions in the low growth interval ($0 < LCRPGR \le 1$), including countries such as Indonesia, the Central African Republic, and the Solomon Islands (Fig. 2).

LCRPGR changes by income level: According to the World Bank's income level classification, low and lower-middle-income countries such as Yemen, Comoros, Bolivia, and India predominantly clustered in the low to middle growth intervals over the past 30 years (1990–2020), demonstrating relatively high LUE. In contrast, upper-middle and high-income countries including Brazil, the USA, Canada, and China were primarily situated in the middle to high growth intervals during this period, indicating lower levels of LUE (Fig. 3).

LCRPGR changes by legal system: Legal origin refers to whether a country's legal system can be traced back to British common law or French civil law[34–37]. Comparative global analyses demonstrate that

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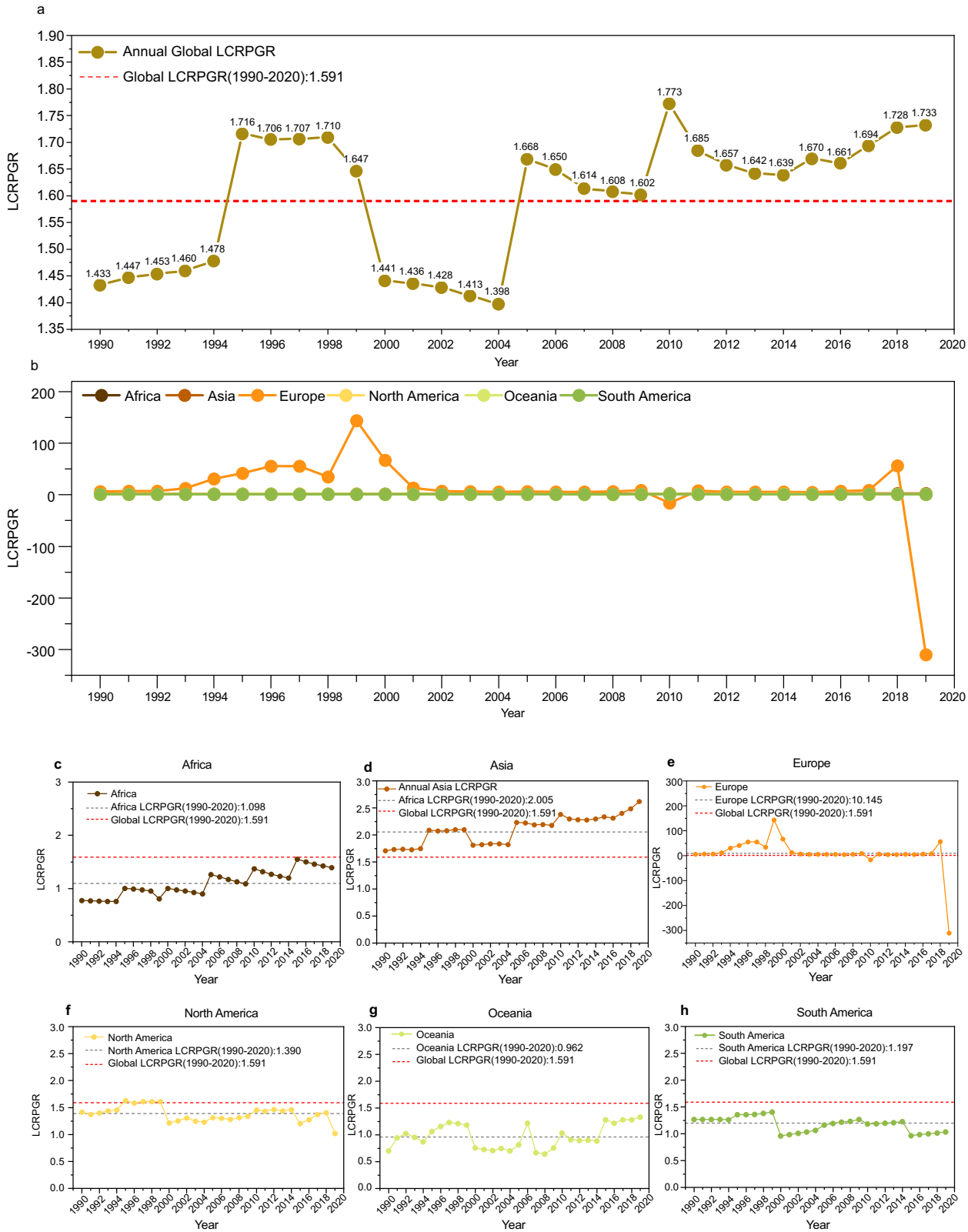

Fig. 1 | Value changes in LCRPGR by continent and country (1990–2020). **a** Global Trends: Shows annual global LCRPGR from 1990 to 2019 and the interval change from 1990 to 2020.**b** Continental Comparison: Displays the annual LCRPGR for six continents—Africa, Asia, Europe, North America, South America, and Oceania. **c** Africa: Annual and overall changes of LCRPGR from 1990 to 2020. **d** Asia: Annual and overall changes of LCRPGR from 1990 to 2020. **e** Europe: Annual and overall changes of LCRPGR from 1990 to 2020. **f** North America: Annual and overall changes of LCRPGR from 1990 to 2020. **g** Oceania: Annual and overall changes of LCRPGR from 1990 to 2020. **h** South America: Annual and overall changes of LCRPGR from 1990 to 2020.

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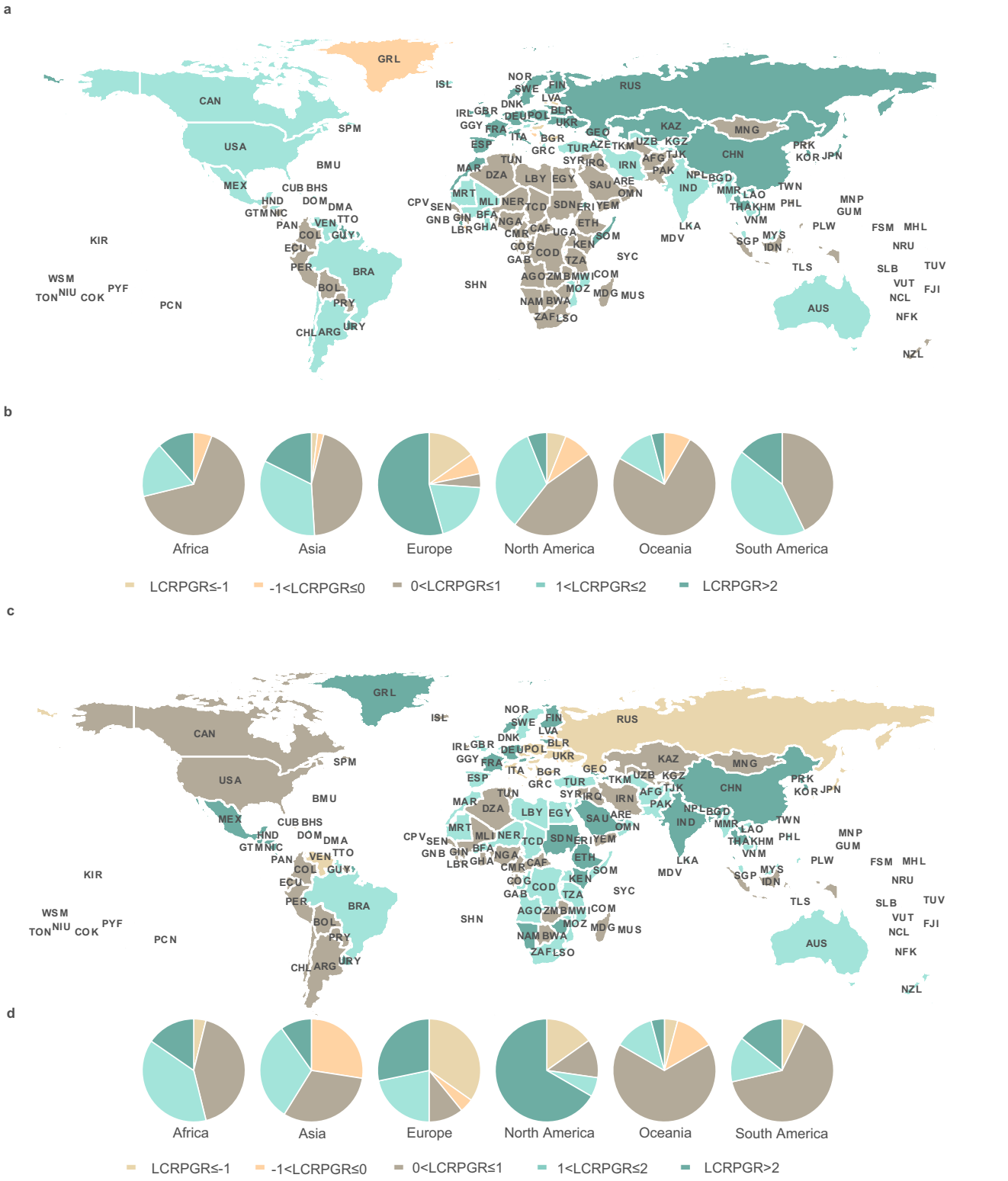

Fig. 2 | Growth interval changes of LCRPGR by continent and territory in 1990 and 2019. a Distribution of global LCRPGR in 1990, with countries and territories labeled using their ISO 3166−1 alpha-3 codes. **b** LCRPGR on each continent in 1990. **c** Distribution of global LCRPGR in 2019, with countries and territories labeled using their ISO 3166−1 alpha-3 codes. **d** LCRPGR on each continent in 2019.

civil law countries typically exhibit lower levels of economic growth, encompassing high, middle, and low growth intervals. Examples include China, France, and Germany. In contrast, common law countries such as the USA and Australia have a smaller proportion in the high growth interval, indicating relatively higher levels of LUE. Furthermore, major demographic challenges such as aging populations and declining birth rates in civil law countries like Russia may further impact their LUE. Annual data from 1990 to 2019 on LCRPGR confirm

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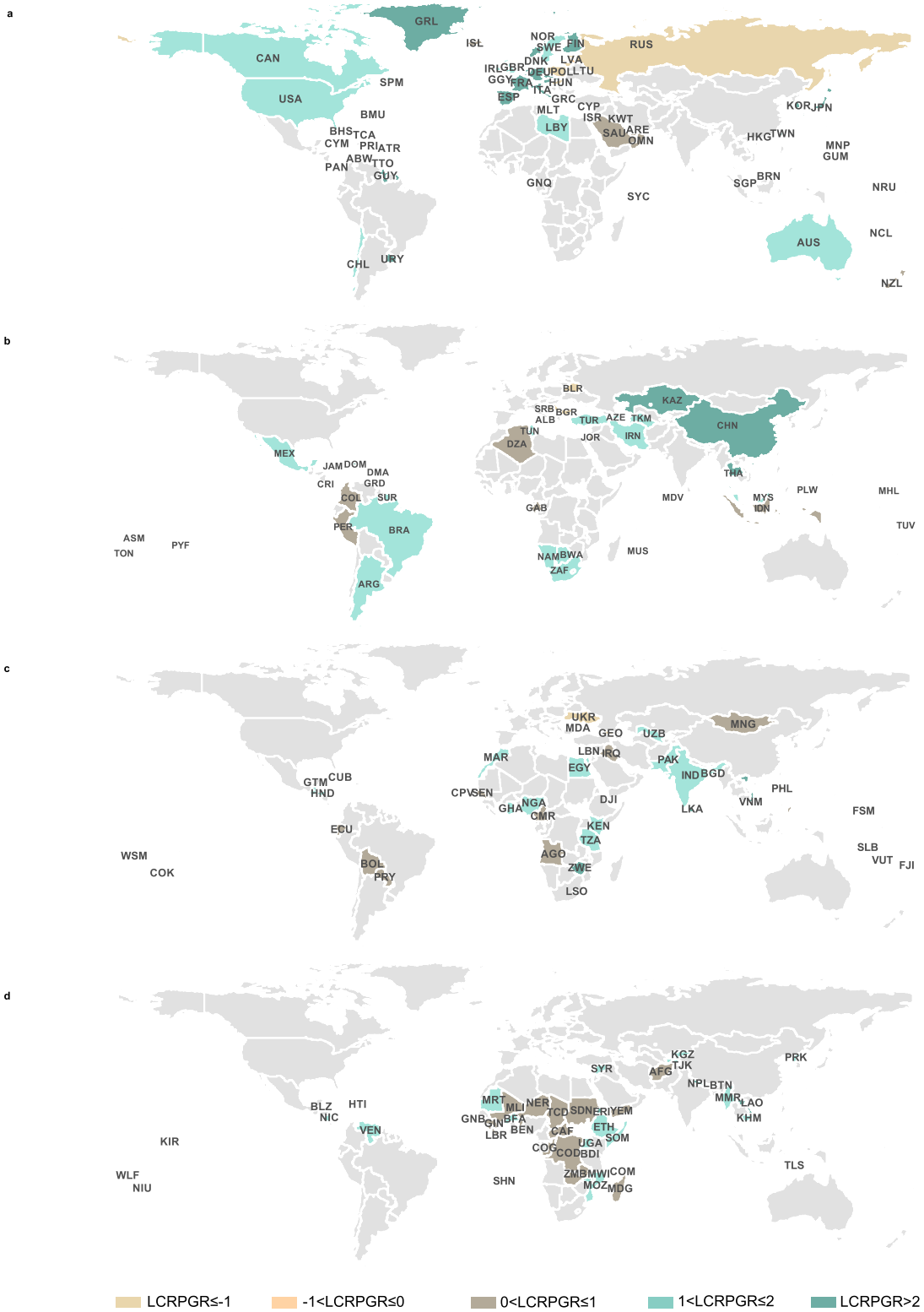

Fig. 3 | LCRPGR changes by income level (1990–2020). a LCRPGR change in high-income countries, with countries and territories labeled using their ISO 3166–1 alpha-3 codes. **b** LCRPGR change in upper-middle-income countries, with countries and territories labeled using their ISO 3166–1 alpha-3 codes. **c** LCRPGR change in lower-middle-income countries, with countries and territories labeled using their ISO 3166–1 alpha-3 codes. **d** LCRPGR change in low-income countries, with countries labeled using their ISO 3166-1 alpha-3 codes.

that civil law nations generally present lower levels of LUE compared to common law nations (Fig. 4).

Impacts of SLPR on LUE

Baseline regression results: The results of the global baseline regression model for countries with LCRPGR > 0 are presented in Fig. 5a. A significant correlation is observed between the security of land property rights (SLPR) and LUE. When LCRPGR > 0, higher values of LCRPGR correspond to lower levels of LUE. The coefficient for SLPR is estimated to be -5.554 (confidence interval: -11.523, 0.416), suggesting that a 10% increase in *lnSLPR* score leads to a decrease in LCRPGR by 0.555 and an increase of LUE, supporting our hypothesis that higher SLPR enhances LUE. The coefficient of the *Cons* (intercept term) in the baseline model is 83.317, representing the baseline LUE when all independent variables are zero and inefficient.

The regression analysis results indicate that none of the independent variables in the baseline regression for the group with LCRPGR < 0 exhibit statistical significance. Countries experiencing population decline have not witnessed a corresponding reduction in built-up areas, leading to a negative value of LUE. In these countries, SLPR has not played a crucial role in augmenting LUE.

Instrumental Variables model results: Fig. 5b presents the instrumental variables (IV) regression results for the group with LCRPGR > 0. In Column 1, we examine the influence of legal origin on SLPR and find a positive effect of *Common_mean* on SLPR, with each unit increase in *Common_mean* resulting in a logarithmic score increase of 0.180 for SLPR. Moving to Column 2, we investigate the impact of SLPR on LUE and observe that the coefficient of *lnSLPR* as the main explanatory variable is -0.211, significant at $p < 0.05$ level. Consequently, our research reveals that SLPR significantly enhances LUE, which aligns with the results obtained from Fixed effects panel regression analysis. Compared to the baseline regression model, the IV model yields smaller absolute value coefficients, providing more conservative and realistic impact estimates. Therefore, it can elucidate more realistic causal relationships. Meanwhile, Hansen J statistic's p-value is 0.0659 at a significance level of 10%, and thus the IV can be considered exogenous[38] and therefore deemed effective.

Robustness test results: The robustness of the causal relationship is further demonstrated by replacing the key explanatory variable x from SLPR to Property Rights Protection (PRP)[39]. In the panel fixed-effects regression depicted in Fig. 5c, the coefficient for *lnPRP* is -48.459, indicating that a 10% increase in a country's *lnPRP* score leads to an approximate decrease of 4.846 units in its LCRPGR. This finding also implies an improvement in LUE. Thus, these findings provide additional evidence supporting the notion that SLPR can enhance LUE.

The robustness of the causal relationship is also demonstrated by replacing the dependent variable y. According to Fig. 5d, the coefficient for *lnSLPR* is 8.294, indicating a strong impact of SLPR on LUE. The positive coefficient of SLPR suggests that as SLPR increases, LUE improves.

Discussion

A plethora of studies have demonstrated the crucial role played by LPRs in determining LUE[40–42]. The research conducted by North[43] and de Soto[44] on property rights has shown that SLPR has been critical for investment and economic growth. Our empirical evidence strongly supports the positive influence of SLPR on LUE. The property rights regime can shape the behavior of government, developers, and individuals through land ownership distribution, land resource allocation, and investment facilitation.

Secure property rights incentivize investment of developers and individuals, thereby promoting efficient land transactions and increased productivity. Stakeholders are inclined to engage in long-term land management practices, such as soil conservation or sustainable forestry, due to their vested interest in maintaining the productivity of their land. Additionally, an effective price mechanism can facilitate the transition towards higher productivity through market transactions. The active transfer activities in land expand opportunities for large-scale land management, thus contributing positively to economic development.

The government plays a pivotal role in determining the SLPR and allocating land resources. Insecure property rights can lead to underutilization of land, as landowners may hesitate to invest in productive activities due to worries about expropriation or eviction. Meanwhile, restrictive property rights can impede landowners' ability to adapt to evolving market conditions, thereby diminishing their motivation to embrace novel technologies or practices aimed at enhancing LUE. Unequal distribution of land can lead to the concentration of ownership, wherein large-scale landholders might prioritize short-term gains over long-term sustainability, leading to excessive exploitation of natural resources and diminished LUE (Fig. 6). Therefore, policymakers should focus on establishing and safeguarding secure property rights, ensuring equitable distribution of land, and fostering an environment that promotes sustainable land management practices.

The regression results have aligned with our hypothesis that secure LPRs are beneficial for efficient land use, and legal origin plays an essential role in the SLPR. La Porta et al.[34,35] sparked extensive cross-country empirical research on the implications of different legal origins in countries. A substantial body of literature demonstrates that common law jurisdictions foster financial and economic institutions that are more conducive to property rights, investor protection, contract enforcement, market regulation, capital accumulation, and foreign investment compared to civil law jurisdictions[36,45–47]. Mahoney[48] suggests that common law systems promote faster growth through enhanced security of property rights when compared to civil law systems. Meanwhile, La Porta et al.[34] and Levine[49] argue that common law systems provide greater safeguards against state interference with property rights and represent an institutional improvement. Civil law countries typically exhibit lower levels of bureaucratic development, heightened corruption, and weaker enforcement of contracts[50]. Common law countries, on the other hand, tend to have lower property registration costs[51], and demonstrate increased political and civil liberties compared to other nations[52,53]. Collectively, common law nations are characterized by less hierarchical regulations and a greater emphasis on market-oriented processes for social control, while civil law nations lean towards increased government intervention and regulation with relatively weaker protection of property rights[54–56]. In summary, common law often provides more robust safeguards for property rights than civil law systems do.

The countries that exemplify common law and robust protection of property rights, such as the United States, Australia, and Canada, prioritize government responsibility in providing equitable compensation to landowners when their actions greatly devalue properties. A well-established title ensures stable taxation while imposing taxes on vacant land increases holding costs for inefficient use of land[57]. Strong property rights act as a check on governmental power by limiting encroachment upon private property. Furthermore, clearly defined property rights mitigate corruption among local officials and collusion between governments and businesses, striking a balance between public regulation and private property rights in the real estate market[58]. In the US, reorganization of land rights enables more efficient utilization and transfer of land, thereby enhancing its value[59,60]. Similarly, incremental reforms through legal instruments have guaranteed an efficient system for land use in the UK[61]. Australia boasts a robust framework for protecting and transferring property rights with an efficient registry system that ensures transparency and security during transactions[62].

Countries with civil law, such as France, Germany, China, Russia, and Brazil, exhibit a higher prevalence of ambiguous property rights compared to common law countries. This ambiguity contributes to an

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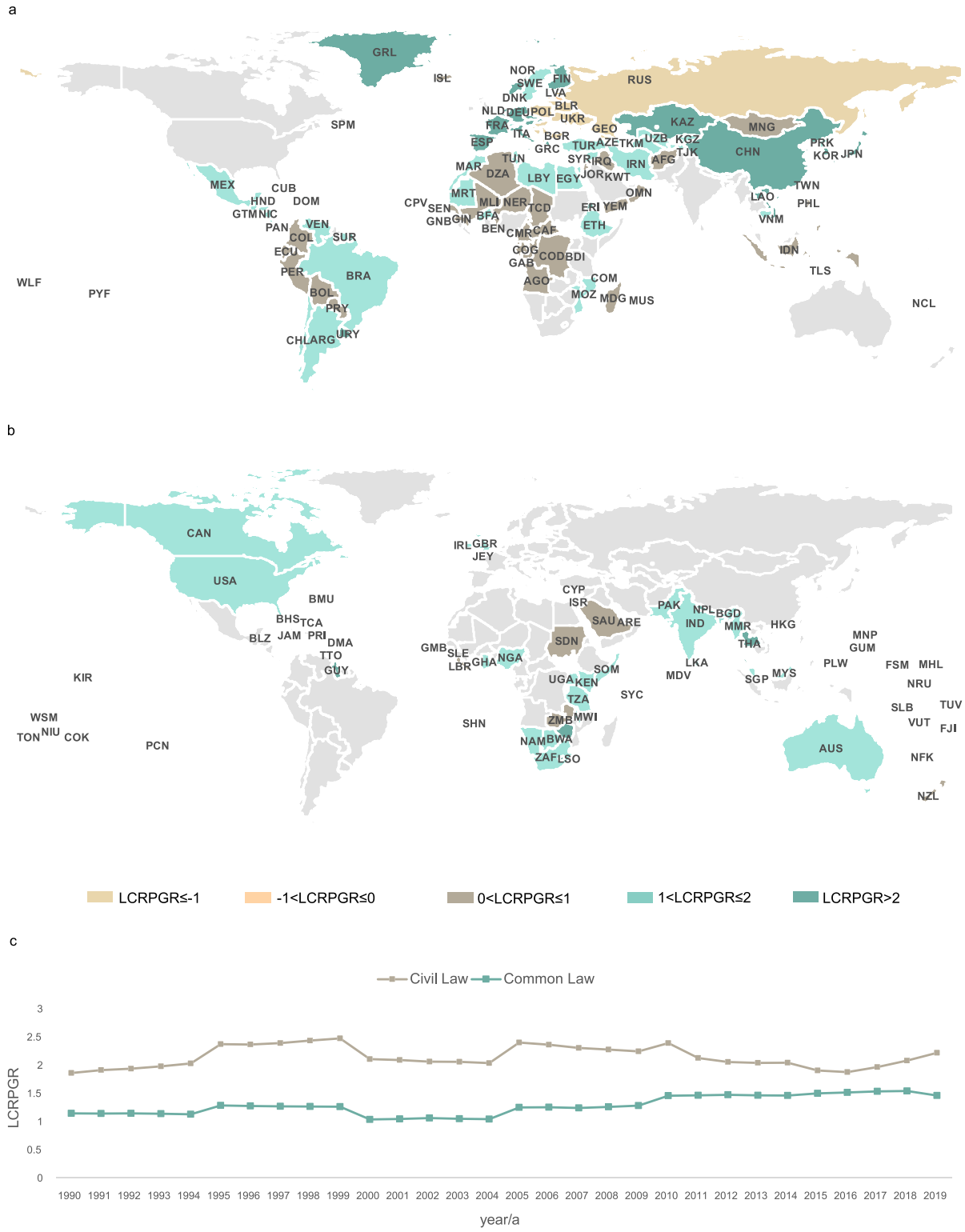

Fig. 4 | LCRPGR changes by legal system (1990–2020). a LCRPGR change in civil law countries, with countries and territories labeled using their ISO 3166-1 alpha-3 codes. **b** LCRPGR change in common law countries, with countries and territories labeled using their ISO 3166-1 alpha-3 codes. **c** Annual LCRPGR changes in both civil law and common law countries.

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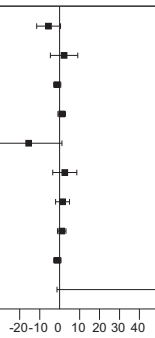
a

(n=1209)

LCRPGR	Coefficient	95% conf. interval	t-value	P-value
ln_SLPR	-5.554	(-11.523- 0.416)	-1.840	0.068
ln_ALPC	2.241	(-4.639- 9.122)	0.640	0.520
ln_GDP	-1.247	(-3.006- 0.512)	-1.400	0.163
ln_IVA	0.991	(-0.898- 2.880)	1.040	0.301
ln_UR	-15.501	(-32.180- 1.178)	-1.840	
ln_QOI	2.581	(-3.447- 8.608)	0.850	0.399
ln_RQE	1.458	(-2.004- 4.920)	0.830	0.406
ln_FDIRATE	0.991	(-1.122- 3.104)	0.930	0.355
ln_NMIRATE	-1.153	(-2.985- 0.679)	-1.240	0.215
cons	83.317	(-1.320- 167.953)	1.950	0.054



b

Fixed Effects 2SLS-IV

	(1) First stage (n=1291)			(2) Second stage (n=1095)		
	Coefficient	t-value	p-value	Coefficient	z-value	p-value
common_mean	0.180	2.770	0.006***			
ln ALPC	-0.540	-0.440	0.663	2.477	0.930	0.353
ln GDP	0.990	1.920	0.055*	-1.713	-2.200	0.028**
ln IVA	-1.012	-1.540	0.123	1.184	1.460	0.143
ln UR	-15.741	-5.150	0.000***	-11.993	-1.980	0.047**
ln QOI	0.080	0.110	0.915	2.290	1.030	0.301
ln RQE	5.714	6.210	0.000***	1.617	1.470	0.141
ln FDIRATE	0.676	1.410	0.160	1.789	1.730	0.084*
ln NMIRATE	0.019	0.040	0.969	-0.899	-1.360	0.173
ln SLPR_time				-0.211	-2.490	0.013**
cons	92.411	7.480	0.000***			

***p < 0.01, **p < 0.05, *p < 0.1

c

(n=877)

LCRPGR	Coefficient	95% conf. interval	t-value	P-value
ln_PRP	-48.459	(-101.223- 4.305)	-1.800	0.072
ln_ALPC	-0.418	(-4.973- 4.136)	-0.180	0.857
ln_GDP	-0.786	(-2.564- 0.993)	-0.870	0.386
ln_IVA	-0.094	(-2.209- 2.020)	-0.090	0.930
ln_UR	-9.501	(-20.238- 1.236)	-1.740	0.083
ln_QOI	0.197	(-2.482- 2.877)	0.140	0.885
ln_RQE	0.888	(-1.814- 3.589)	0.650	0.519
ln_FDIRATE	-0.319	(-1.576- 0.938)	-0.500	0.619
ln_NMIRATE	-1.475	(-3.982- 1.033)	-1.150	0.249
cons	231.672	(24.252- 439.092)	2.190	0.029

d

(n=484)

NEW LCRPGR	Coefficient	95% conf. interval	z-value	P-value
ln_SLPR	8.294	(6.863- 9.725)	11.360	0.000
ln_ALPC	12.890	(5.933- 19.847)	3.630	0.000
ln_GDP	-0.845	(-1.780- 0.090)	-1.770	0.077
ln_IVA	1.128	(0.151- 2.105)	2.260	0.024
ln_UR	15.443	(10.434- 20.452)	6.040	0.000
ln_QOI	-3.425	(-4.884- -1.966)	-4.600	0.000
ln_RQE	-2.981	(-4.842- -1.121)	-3.140	0.002
ln_FDIRATE	-0.876	(-1.876- 0.124)	-1.720	0.086
ln_NMIRATE	0.120	(-0.516- 0.756)	0.370	0.711
cons	-19.522	(-36.734- -2.310)	-2.220	0.026

Fig. 5 | Regression results. a Baseline fixed-effects panel regression results for LCRPGR > 0. The sample size is $n = 1209$ (independent country-year observations). Bars represent regression coefficients (center points) with 95% confidence intervals (error bars). Statistical significance was assessed using a two-sided t-test. **b** Instrumental variables regression results for LCRPGR > 0. The first stage has a sample size of $n = 1291$, and the second stage has a sample size of $n = 1095$ (independent country-year observations). Statistical significance was assessed using a two-sided t-test in the first stage and a two-sided z-test in the second stage. Exact p-values are provided, with significance levels indicated. **c** Baseline fixed-effects panel regression results for LCRPGR > 0, using property rights protection as the key explanatory variable. The sample size is $n = 877$ (independent country-year observations). Bars represent regression coefficients with 95% confidence intervals. Statistical significance was assessed using a two-sided t-test. **d** Probit model results. The sample size is $n = 484$ (independent country-year observations). Bars represent regression coefficients with 95% confidence intervals. Statistical significance was assessed using a two-sided z-test.

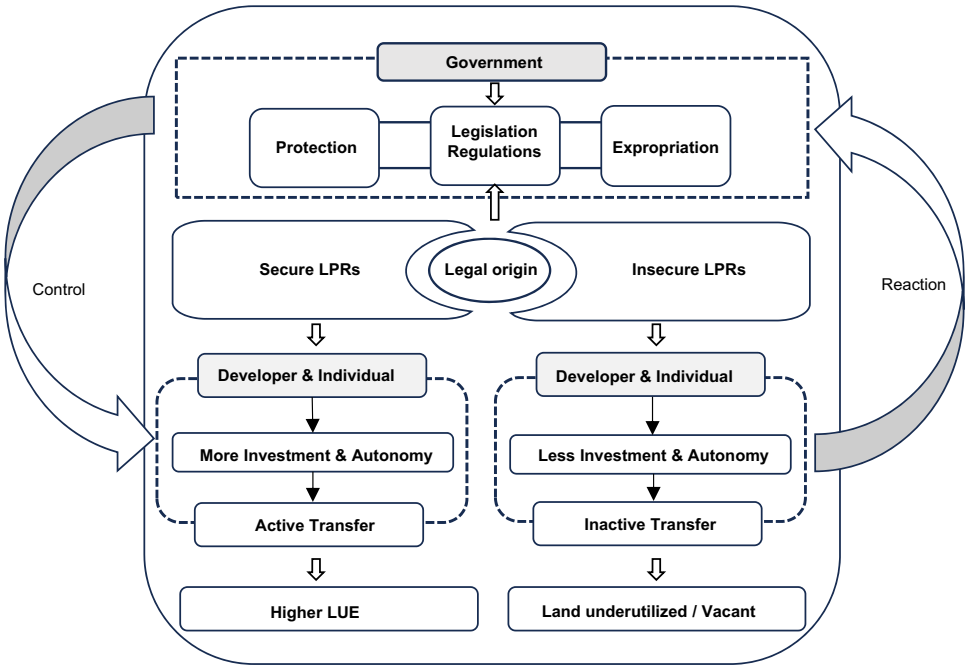


Fig. 6 | Impact of Land Property Rights (LPRs) on Land Use Efficiency (LUE). This diagram illustrates the interactions among the market, society, and government, focusing on how these interactions influence the security of LPRs and, consequently, LUE. The government's role, through legislation, regulation, protection, and expropriation, is highlighted, showing its impact on whether LPRs are secure or insecure. Secure LPRs lead to higher investment and autonomy among developers and individuals, facilitating active land transfer and resulting in higher LUE. Conversely, insecure LPRs diminish investment and autonomy, causing inactive land transfer and leading to land underutilization or vacancy.

increase in land conflicts and a decrease in productivity[42]. For example, in China, land ownership is categorized into state-owned land and collective-owned land. Rural collective-owned land lacks the right to generate income from development or be transferred to other users. This lack of clarity has facilitated low-compensation acquisitions by local governments and is considered as a major factor contributing to urban sprawl across China[63]. In Russia, despite transitioning to a market economy after the dissolution of the Soviet Union, many lands remain uncertainly defined, potentially leading to misuse. This uncertainty hampers effective land management and conservation efforts while widespread corruption and fraud impede property rights protection effectiveness, and thereby negatively hinder economic development[64–66]. Brazil's property system has been profoundly influenced by high concentration of land ownership and large estates (latifundia) since the 19th century which exacerbates social inequality. The instability of property rights affects investment opportunities and long-term land development while violent conflicts related to disputes over ownership threaten social stability and environmental quality[67].

In civil law countries with weak state capacity, the prevalence of low LUE is more pronounced. Venezuela's land reform and agricultural policies have sparked intense disputes between the state and rural workers, leading to profound conflicts and disparities in rural areas that underscore the tension between state policies and peasant needs[68]. Haiti, as a fragile state grappling with poverty, weak governance, natural disasters, and environmental degradation, experiences exacerbated land use inefficiencies due to weaknesses in civil law and property rights[69]. However, recent efforts towards land registration in Ethiopia demonstrate that formalizing land rights can substantially enhance investments related to land and foster greater participation in the land rental market[70].

This study, which primarily investigates the relationship between secure land property rights and LUE, incorporates control variables such as GDP per capita, infrastructure quality, and regulatory quality to account for the impact of various external factors. However, it is essential to acknowledge that property utilization is also significantly influenced by a wide array of social and political factors. While our research has considered the effects of economic development and state capacity by proxy variables, the role of social attitudes in shaping land use patterns on a macro scale has not been thoroughly examined. Indigenous perspectives on collective land management, for example, are deeply rooted in cultural, spiritual, and historical connections to the land, emphasizing stewardship, sustainability, and the incorporation of traditional knowledge into land-use practices—a critical aspect that our study has not yet addressed. Furthermore, the state's capacity and societal attitudes may impact property usage through complex mechanisms, suggesting that their broader implications warrant more

in-depth investigation in future research. Another limitation is that while case studies on typical studies provide valuable data support, their representativeness may not fully capture the impact of all legal types, especially for high-income countries like France. Therefore, it is recommended that future research include important civil law countries such as France in case analyses to further validate the conclusions of this study. Additionally, due to limited information, this paper has not conducted an in-depth investigation into the role of property rights in countries that have undergone substantial population decline. Future research should focus on conducting further studies on these countries. Lastly, if a more suitable index for measuring SLPR can be identified to replace the Fraser index, it would enhance the credibility of research findings, which will be discussed in the following section.

Methods

Our study employed a fixed-effects panel regression model as the baseline to examine the global impact of the SLPR on the LCRPGR (Fig. 7). To address potential endogeneity concerns, we employed an Instrumental Variable (IV) regression model with fixed effects. Furthermore, we conducted sensitivity analyses by substituting key explanatory variables *x* and *y* to validate the robustness of our findings.

Baseline Model

The fixed-effects panel regression model effectively controls for constant characteristics across countries, allowing for the isolation of the impacts of explanatory variables and reducing biases arising from time-invariant but country-specific factors[71]. The baseline regression model is as follows:

$$LCRPGR_{i,t} = \delta_0 + \delta_1 * \ln SLPR_{i,t} + \beta * \ln Control_{i,t} + \sum_{t=1990}^{2020} \gamma t \cdot D_t + \alpha_i + \varepsilon_{i,t} \quad (1)$$

In Eq. (1), where $i = 1, 2 \ldots n$ represents countries, and $t = 1990, 1991 \ldots n$ represents years. The variable $LCRPGR_{i,t}$ signifies the quantified value of LUE. Moreover, the term $\ln SLPR_{i,t}$ represents the natural logarithm-transformed SLPR for a specific country i during the year t. The comprehensive set of control variables is denoted by $Control_{i,t}$, which includes ALPC, GDP, IVA, UR, QOI, RQE, FDIRATE, and NMIRATE. These variables account for a total of 8 distinct components and are all in logarithmic form. The specific variable names are provided in Table 1. In this context, δ_0 serves as the intercept while δ_1 denotes the coefficient associated with the key explanatory variable $\ln SLPR_{i,t}$. The symbol β encompasses the coefficients linked to the control variables, while $\varepsilon_{i,t}$ represents random disturbances within the model. The term α_i captures fixed effects that reflect individual characteristics of i which remain constant over time but may influence the dependent variable. D_t is a dummy variable for year t, representing each specific year to control for time effects. γt denotes the coefficient linked to the year dummy variable, indicating the unique impact of each specific year.

Dependent variable. The dependent variable, LCRPGR, was analyzed using a primary dataset that encompasses global built-up area and population data from 1990 to 2020. A total of 220 countries were selected based on data availability, with population data obtained from the World Bank. The built-up area information utilized in this study was derived from the GHSL, a dataset disseminated by the European Commission and generated through satellite imagery analysis. In comparison to other platforms such as Google Earth Engine or the Global Land Cover Share Database, GHSL stands out as a tailored dataset specifically designed for studying built-up regions. It provides a detailed delineation of the progression of built-up surfaces between 1975 and 2030 at five-year intervals. This unique dataset was created through spatio-temporal interpolation techniques using multisensory satellite images acquired from various platforms: Landsat data (including MSS, TM, and ETM sensors) supported epochs in 1975, 1990, 2000, and 2014; while Sentinel-2 (S2) image composite (GHS-composite-S2 R2020A) supported the epoch in 2018.

We initially extracted GHSL spatial data spanning from 1990 to 2020, while maintaining a consistent spatial resolution of 1 km × 1 km. By employing the Zonal Statistics tool in GIS and incorporating national boundaries as input, we computed the cumulative built-up areas across grid cells for each nation. These national boundaries were derived from the 1:10 m vector data provided by Nature Earth. Subsequently, we employed a mean interpolation method to transform the dataset into a continuous format, utilizing the subsequent formula:

$$Urbt = Urbx_1 + (Urbx_2 - Urbx_1)/5 * (t - x_1) \quad (2)$$

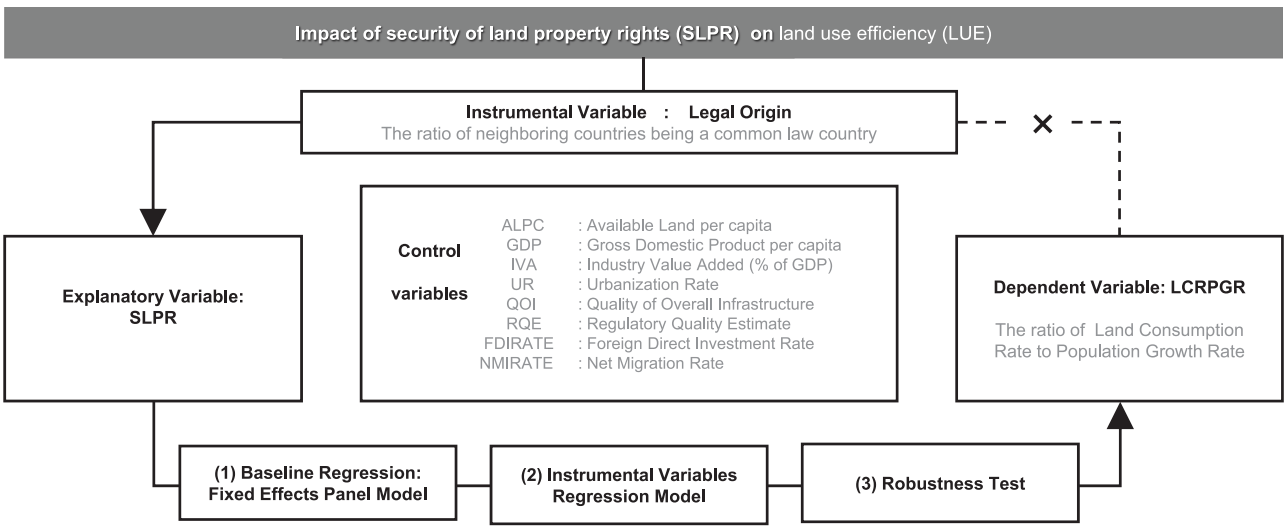


Fig. 7 | Methodological path diagram. Assessing the Impact of SLPR on LCRPGR. The impact of legal origin on LUE can only be realized through the pathway of SLPR. The analysis begins with the construction of a baseline model, followed by the development of an Instrumental Variables Regression Model, with legal origin as the instrumental variable. Finally, the model results are validated to ensure robustness.

Table 1 | Variables and their data source

Variable name	Abbreviation	Variable type	Data source
The ratio of LCR to PGR	LCRPGR	Dependent variable	https://jeodpp.jrc.ec.europa.eu/ftp/jrcopendata/GHSL/GHS_BUILT_S_GLOBE_R2023A/ https://data.worldbank.org.cn/indicator/SP.POP.TOTL?view=chart
Security of Land Property Rights	SLPR	Key explanatory variable	https://www.fraserinstitute.org/economic-freedom/approach
Legal origin	Legal_origin	Instrument variable	https://www.sipotra.it/old/wpcontent/uploads/2017/01/The-Long-Economic-and-Political-Shadow-of-History.pdf#page=122[81]
Available Land Per Capita	ALPC	Control Variable	https://www.fao.org/faostat/en/#data 1980–2020 https://data.worldbank.org.cn/indicator/AG.SRF.TOTL.K2 https://data.worldbank.org.cn/indicator/SP.POP.TOTL?view=chart
Gross Domestic Product per capita	GDP	Control Variable	https://data.worldbank.org.cn/indicator/NY.GDP.PCAP.CD?view=chart
Industry Value Added (% of GDP)	IVA	Control Variable	https://data.worldbank.org.cn/indicator/NV.IND.TOTL.ZS?view=chart
Urbanization Rate	UR	Control Variable	https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS
Quality of Overall Infrastructure	QOI	Control Variable	https://prosperitydata360.worldbank.org/en/indicator/WEF+GCIHH+EOSQ056
Regulatory Quality Estimate	RQE	Control Variable	http://info.worldbank.org/governance/wgi/
Foreign Direct Investment Rate	FDIRATE	Control Variable	https://data.worldbank.org/indicator/BX.KLT.DINV.CD.WD
Net migration Rate	NMIRATE	Control Variable	https://www.migrationdataportal.org/international-data?i=stock_abs_&t=2020

Where x_1 refers to the initial year value (such as 1990) and x_2 refers to the year value five years later (i.e. 1995). The calculation of LCRPGR[6] is in accordance with Indicator 11.3.1 of the United Nations SDGs Monitoring and Evaluation Framework. The specific formula is below:

$$LCRPGR = LCR/PGR \tag{3}$$

$$LCR = \ln\left(Urb_{t+n}/Urb_t\right) \tag{4}$$

$$PGR = \ln\left(Pop_{t+n}/Pop_t\right) \tag{5}$$

Where Urb_t and Urb_{t+n} represent the built-up area in the initial year and the end year, respectively, while Pop_t and Pop_{t+n} indicate the total population in the initial year and the end year, respectively.

Key explanatory variable. The key explanatory variable is the SLPR. The paper uses the Security of Property Right index edited by the Fraser Institute covering 165 countries or economic entities, as a proxy for SLPR[72], ranging from 0 to 10. The Security of Property Right Index consists of four components, with the Quality of Land Administration Index directly associated with LPRs and the remaining three indicators - perceived property rights, intellectual property protection, and Property Rights & Rule-Based Governance - indirectly linked to LPRs. Unfortunately, specific values for these four indices are not provided separately. Given that existing databases such as The LANDex database and the Global Property Rights Index have limited coverage in terms of countries or years, we consider the Fraser Index as an ideal long-term and global measure for assessing the security of property rights.

The key issue lies in determining whether the Fraser index can serve as a surrogate of SLPR, and whether the correlation between the Fraser index and SLPR is positive[39]. In general, the Quality of Land Administration index assesses legal tenure security through dimensions such as infrastructure reliability, information transparency, and land dispute resolution effectiveness, and exhibits a close correlation with SLPR. Intellectual property protection is intrinsically tied to state capacity for law enforcement and order maintenance[73,74] while sharing moral foundations with LPRs; thus, countries with robust intellectual property protection are likely to provide a secure environment for LPRs[75]. The Governance index evaluates foundational legal protections, economic laws, and business activities that enhance SLPR[76,77]. Therefore, the Fraser Institute's Security of Property Right index, despite its inherent limitations, serves as a robust proxy for examining property rights due to its comprehensive nature and diverse range of sources.

Control variables. We categorize the control variable into four distinct types: firstly, natural resources endowment, as indicated by available land resources per capita; secondly, socio-economic factors encompassing gross domestic product per capita, the proportion of industry value added in GDP, urbanization rate, and overall infrastructure quality. The third type pertains to regulatory measures represented by the estimate of regulatory quality. Lastly, the fourth type encompasses external forces such as net migration rate and FDI rate. Table 1 provides a comprehensive list of variables along with their respective data sources.

IV Regression Model

The key explanatory variable, SLPR, is correlated with other control variables, as well as the residual, leading to inaccuracies in the baseline regression model. To solve the endogenous bias, we use legal origins as an IV and construct a two-stage regression model.

IV. The concept of legal origin has commonly served as an IV in various studies. For instance, Yasar et al.'s research employs legal origin as an IV to investigate the relationship between firm performance and institutional quality across 52 countries[78]. Similarly, Levine et al.'s study treats legal origin as an IV when examining financial development[79], while Mahoney utilizes it to measure judicial quality and property/contract rights security[48]. To mitigate endogeneity concerns, we adopt neighboring countries' legal origins as our IV. While a country's legal origin may be correlated with its own socio-economic development, the legal origins of neighboring countries are more suitable as IV based on the following reason: (1) Although connected to this country's legal origin distribution, neighboring countries' legal origins do not directly affect its socio-economic development. Henceforth, utilizing the distribution of neighboring countries' legal origins as an IV is suitable. (2) The legal origins are more likely to emerge in an environment where there is a greater number of countries sharing similar legal origins, as suggested by Michael Albertus[80]. In other words, for a given country, its neighboring countries tend to follow a similar legal origin. Consequently, the distribution of legal origins among neighboring countries

is connected to this country's own legal origin but does not directly impact its socio-economic aspects. Therefore, the distribution of neighboring countries' legal origins qualifies as an appropriate IV.

To accurately capture the dynamic impact of time-varying factors used as IV, we have incorporated an interaction term between the IV and time into our model. This approach enables us to rigorously analyze how changes in legal origin over time affect the dependent variable, thereby enhancing the precision of our estimates. To ascertain a specific country's legal origin, we rely on the research and database provided by La Porta, Lopez-de-Silanes, Shleifer, and Vishny (LLSV). A country is classified as either having a common law or civil law origin. The variable *Common* takes a value of 1 if this country has a common law system and 0 if it follows civil law principles. The variable *Common_mean* for a certain country equals the average proportion of neighboring countries that are common law countries. It serves as an indicator representing what proportion of its neighboring countries follow common law principles. The precise formula is as follows:

$$Common_{meani} = \left(Common_{i,1} + Common_{i,2} + \cdots + Common_{i,n}\right)/n * Time_i \quad (6)$$

In Eq. (6), $Common_{i,n}$ represents whether the *n-th* neighboring country of the *i-th* country is a common law state. $Time_i$ indicates the time variable associated with the *i-th* individual.

IV model construction. The first-stage IV regression uses *Common_mean* as an IV, which is related to SLPR but independent of the error term. This enables us to disentangle the exogenous component from the endogenous variable $\ln SLPR_{i,t}$. To capture the time-varying dynamic impact of $\ln SLPR_{i,t}$, we introduce an interaction term, denoted as $\ln SLPR\_time_{i,t}$, obtained by multiplying $\ln SLPR_{i,t}$ by time and incorporate it into our model. The specific formulation for the first stage is presented below:

$$\ln SLPR\_time_{i,t} = \alpha_0 + \alpha_1 * Common_{mean_i} + \beta * lnControl_{i,t} + \sum_k \gamma_k * D_k + \alpha_i + \varepsilon_{i,t} \rightarrow \widehat{lnSLPR\_time_{i,t}} \quad (7)$$

In Eq. (7), $Common_{meani}$ is the IV. γ_k is the regression coefficient for the k year's dummy variable D_k, indicating that year's effect on the dependent variable. The meanings of the symbols for the remaining variables are consistent with Eq. (1). The second stage entails the insertion of the fitted values $\widehat{lnSLPR_{i,t}}$ obtained from Eq. (7) into the model specified in Eq. (8) for regression, which is formulated as follows:

$$LCRPGR_{i,t} = \delta_0 + \delta_1 * \widehat{lnSLPR\_time_{i,t}} + \beta * lnControl_{i,t} + \sum_k \gamma_k * D_k + \alpha_i + \varepsilon_{i,t} \quad (8)$$

After completing the two-stage IV regression, we conduct a weak IV test to analyze the validity of the IV.

Robustness Test

Replacing Key Explanatory Variable *x*: To further validate the robustness of our baseline regression results, we substituted the *x* indicator with the PRP index. This index quantifies a country's legal efficacy in safeguarding private property rights and enforcing these laws, including addressing the risk of property expropriation. Our aim was to examine whether the previously identified causal relationships between property rights and LUE remain robust within this more comprehensive framework.

Replacing Variable *y:* We constructed a Probit model to assess the robustness of the entire model. In this context, LCRPGR is represented as a binary variable with values 0 and 1. When LUE falls within the high-efficiency range ($0 < LCRPGR \leq 1$), LCRPGR is assigned a value of 1. For low-efficiency cases ($LCRPGR < 0$ or $LCRPGR > 1$), it is assigned a value of 0. The Probit model estimates the probability that an observation belongs to either the high-efficiency or low-efficiency category, thereby verifying whether the observed relationship in fixed effects regression models holds true when assessing LUE.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data generated in this study, encompassing the LCRPGR value changes by continent and country (Fig. 1), changes in LCRPGR growth intervals for 1990 and 2019 (Fig. 2), LCRPGR changes by income level (Fig. 3), LCRPGR changes by legal system (Fig. 4), and the data used for analysis and visualization in Fig. 5, have been deposited in the Figshare database. These datasets are freely accessible at https://doi.org/10.6084/m9.figshare.26028955.v3. The original data, sourced from publicly available databases as detailed in Table 1, are openly accessible and not subject to data privacy laws. The map boundaries used in Figs. 2–4 were created using resources from Natural Earth. Free vector and raster map data are available at https://www.naturalearthdata.com/downloads/.

Code availability

The Stata code for generating, analyzing, and visualizing the research data can be found in the figshare repository at https://doi.org/10.6084/m9.figshare.26028955.v3.

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Author contributions

L.T., and W.O. conceived and designed the research; J.M., Y.Z., X.Y., and Z.L. performed the research; J.M., Y.Z., X.Y., Y.L., L.Z. and Z.W analyzed the data; J.M. and L.T. contributed analysis tools; J.M., L.T., Y.Z., X.Y., Z.L., and W.O. wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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