Volume 10, Number 3, 2023

REGION

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REGION
The Journal of ERSA
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Volume 10, Number 3, 2023, 1–18
DOI: 10.18335/region.v10i3.417
journal homepage: region.ersa.org
ISSN: 2409-5370

Credit market development and agricultural production in selected African countries: Climate change perspective

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Received: 13 February 2022/Accepted: 22 May 2023

Abstract. This study aimed to examine the long and short-run relationships between credit market development and agricultural production using the Autoregressive Distributed Lags (ARDL) Bounds test for cointegration, as well as the direction of causality by using the Granger causality test. The results of the ARDL Bounds test revealed that institutional credit development had a significant long-run effect on agricultural production in all countries under examination, except for Tunisia; that is: Benin, Kenya, and Nigeria. In the short run, credit market development had a significant and positive effect on agricultural production in Nigeria. By contrast, the effect of credit market development on agricultural production was negative in the short-run in Benin, Kenya, and Tunisia. The result of granger causality test revealed the existence of significant bi-directional causal links between institutional credit development and agricultural production in Benin, Kenya and Nigeria, no significant interdependence was found between the two variables in Tunisia. Capital formation had a significant and positive effect on agricultural production in the long-run and short-run in all countries. Climate change was negatively associated with agricultural production in all countries except for Nigeria. The exchange rates and real interest rates had a negative effect on agricultural production in the long-run and short-run in all countries.

JEL classification: F33, Q11, Q14

Key words: agricultural production, credit market development, real interest rate, agricultural loan supply, climate change

1 Introduction

Agricultural policies (Shikur 2020a), industrial policies (Shikur et al. 2020, Shikur 2020b), irrigation utilization (Shikur 2021a,b), adoption of technology (Shikur 2020a), information asymmetry (Habte et al. 2016), sector linkage (Habte et al. 2017, 2020), market coordination (Shikur 2021a,b), agricultural product export (Shikur 2022a,b), and labor and capital supply (Shikur 2022c) are cited as influential factors related to agricultural production and productivity at country level. A large body of literature argues that agricultural production substantially depends on climate change (UNFCCC 2007) as well as credit market development (Badibanga, Ulimwengu 2019, Zhu et al. 2021). Thus, this study is useful to contribute to the scarce literature on the role of climate change and credit market development played in agricultural production.

Climate change could cause reduced productivity of agricultural land, labor, capital, and agricultural technologies by shortening growing periods and reducing crop and pasture yields (UNFCCC 2007). This implies that agricultural credit loans have not been transformed into agricultural productivity due to climate change. Climate change may influence agricultural production by altering ecosystem services like water/rainfall availability, animal feed availability, and disease outbreak (Vining 1990). Warming climate causes increased heat, reduction in water supplies and the quantity and quality of animals' feed supplies; and results in insect and pest outbreaks (Ayal, Leal-Filho 2017). However, the effect of climate change on agricultural production may vary across countries due to environmental policy differences. As a result, the empirical findings are inconsistent across countries. So including the environmental control variable in the model is very useful for improving financial policy and its application; and influencing credit utilization and resource allocation efficiency across sectors of the economy. Moreover, the impact of climate change on agricultural growth has not been thoroughly researched in earlier empirical studies.

Credit market development substantially determines agricultural growth and productivity by increasing farmers' purchasing power of agricultural technologies and resource allocation efficiency (Anetor et al. 2016, Badibanga, Ulimwengu 2019, Zhu et al. 2021). Thus, subsidized credit loans have widely been employed in many developing countries to reduce poverty (Chandio et al. 2020, Kaya, Kadanalı 2021). However, there has been continued debate on the impact of financial development on economic growth in the literature. The magnitudes and signs of financial development coefficients in the agricultural sector differ across countries. The impact of financial development on agricultural growth significantly varies across levels of economies (An et al. 2020). They identified the positive and negative effects of financial development on agricultural growth in low and high-income countries, respectively.

The study chooses nations like Benin, Kenya, Nigeria, and Tunisia to bridge the gap between theory and practice. The effect of financial market development on agricultural production is yet unknown in the selected countries, despite the fact that agricultural loans, exchange rates and interest rates are the major drivers of agricultural productivity and production. This study differs from earlier studies by investigating the impact of credit market development on agricultural growth, where the real interest rates and the agricultural credit loans were not used as proxy variables for financial development in the empirical literature related to this sector. This literature on bank-based financial systems provides new insights into the possible mechanisms through which agricultural lending interest likely affects rural economic development.

The empirical findings show that there is also no clear consensus on the causal direction between financial development and economic growth. Also, there is a lack of empirical evidence on the causal direction of this topic in selected African countries. For instance, empirical studies have shown the existence of a bi-directional relationship between the two variables (Mukhopadhyay et al. 2011, Kaya, Kadanalı 2021). Financial development leads to economic growth (Boulila, Trabelsi 2002); a unidirectional causality running from economic growth to financial development (Lian, Teng 2006). Other empirical findings show that there is no causal relationship between financial development and economic growth (Boulila, Trabelsi 2004). Therefore, to fill this scientific gap, it is important to investigate the relationships between credit market development and agricultural production.

The paper is structured as follows. This paper critically reviews the theoretical and empirical literature on the nexus between financial development and economic growth at country and sector levels in Section 2. The study explains each variable and describes the methods of analysis in Section 3. Section 4 presents the findings, and provides interpretations of the results. Finally, the policy implications are presented in the conclusions (Section 5).

2 Literature review

The conceptual framework for this study is primarily framed by the theory of McKinnon (1973) and Shaw (1973). The McKinonn-Shaw model argues that there are two main components of financial development that have an impact on economic growth. Developing domestic financial markets could benefit from increasing the effectiveness of capital formation is one way. On the other hand, financial intermediation might contribute to an increase in savings rate, which would then raise the investment rate.

The McKinnon-Shaw hypothesis states that there should be a close association between the level of financial intermediation and the current real interest rate. When the real interest rate is kept below normal competitive levels, it shows the severity of financial repression. According to this argument, a high real interest rate promotes savings and financial intermediation, which raises the quantity of credit supply to the private sector (Fry 1997). This promotes investment and economic growth in turn. The McKinnon-Shaw theory (McKinnon 1973, Shaw 1973) emphasizes real interest rates' effects on savings as the primary route of transmission, but it is also recognized that positive real interest rates boost the efficiency of how investable funds are distributed, having a further positive impact on economic growth. Real interest rates have an impact on savings rates, according to the McKinnon-Shaw hypothesis, but it is also known that higher real interest rates stimulate more efficient use of investable capital.

The theory assumes that money supplied as loans to the private sector is referred to as inside money since it is backed by the internal debt of the private sector investors. Saving is a function of nominal interest rate and predicted inflation rate. Saving at real economic growth rate is positively affected by the real interest rate (nominal interest rate minus predicted inflation rate). Throughout this process, the rate of economic growth rises, and both the volume and quality of investment are increasing, which together have a positive impact on the growth rate.

The competitive free-market equilibrium deposit rate of interest may be raised without harming the lending rate by reducing reserve requirements or by paying the competitive loan rate on required reserves. The actual credit supply will rise as a result, accelerating economic development (McKinnon 1973, Shaw 1973). The rate of economic growth is influenced by real deposit rate of interest in the steady state by both quantity and average productivity of investment (Fry 1997). Changes in the real deposit rate have an impact on both short-term growth and inflation through the availability of working capital finance.

A high level of monetization should be positively correlated with economic growth, according to the original McKinnon-Shaw hypothesis, because in theory, a monetized economy indicates a highly developed capital market. The fundamental issue with this argument derives from the fact that financial markets' two main goals are to transfer money from savers to those in need and to provide liquidity (or transactional services). More importantly, the banking sector's ability to successfully supply and distribute loans is as a measure of financialization.

The extent of the credit market's development may be more closely connected with these measures when compared to more limited definitions of money (M_l), but other factors besides financial depth may still be significant. Neal (1988) in particular relied on indicators of quasi-liquid assets by leaving out M_l and M_2 because M_3 still contains liquid assets (M_l). Even though credit seems to be the strongest indicator of how much financial intermediation takes place through the banking system, it may be a less reliable indicator of financial development overall because a sizable portion of financial development takes place outside the banking sector. This trend seems to be more prominent in industrialized countries where non-bank financial innovation has been substantial (Goldstein et al. 1992). Similar to real interest rates; there are problems with substituting monetary aggregates for the degree of financial intermediation. These aggregates are most likely to result in major problems. In contrast, the majority of financial progress in emerging countries has occurred within the banking sector. As a result, credit is arguably a stronger indicator of overall financial progress in these countries.

Although there is no consensus on financial development indicators, the size of the formal financial intermediary sector relative to GDP, the importance of banks relative to the central bank, the percentage of credit allocated to private firms, and the ratio of credit granted to private firms to gross domestic economic growth are commonly used as indicators of the level of financial development (King, Levine 1993). Credit to the private sector is also a frequently used variable in the literature (Beck et al. 2000, Levine 2005). Similarly, this study uses the amount of credit granted to the agriculture sector as an indicator of financial sector intermediation. The main benefit of credit over other monetary aggregates is that it more correctly captures the function of financial intermediaries in distributing funds to private market participants by excluding credit to the government sector. Financial intermediation should be defined in this way to better understand how investment levels and efficiency relate to economic growth.

Many scholars argue economic growth is retarded by indiscriminate distortions of financial prices such as interest rates and foreign exchange rates (McKinnon 1973, Shaw 1973, Greenwood, Jovanovic 1990, King, Levine 1993). Financially restrictive regulations, such as restrictions that result in negative real interest rates, reduce the households' incentives to save. Lower savings also have an adverse effect on growth and investment. They come to the conclusion that higher interest rates resulting from financial liberalization induce households to save more money. Saving at the real economic growth rate is positively affected by the real interest rate. Throughout this process, the rate of economic growth rises, and both the volume and quality of investment increase, which together have a positive impact on the growth rate.

In general, the McKinnon-Shaw theoretical arguments are supported by some empirical works (Anwar, Nguyen 2011, Arestis et al. 2015). The empirical results confirm that financial development leads to economic growth in Indonesia, Singapore, the Philippines, China, and India (Mukhopadhyay et al. 2011), Egypt, Mauritania, and Turkey (Boulila, Trabelsi 2002). The relationship between financial development and sectors of economic growth has also been studied in Africa (Adu et al. 2013, Ustarz, Fanta 2021). In general, empirical results provide divergent results concerning the strength and sign of the coefficient or connection of two variables in the agricultural sector. These arguments and empirical evidence oppose Keynes' arguments.

Numerous scholars have criticized the McKinnon-Shaw theory's empirical validity. For instance, the Latin American experience suggests that financial depth increases the marginal productivity of capital rather than the amount of savings and investment (Diaz-Alejandro 1985). The literature underlines that real interest rates may be high even when they are unrelated to the marginal productivity of capital because of elements such as public expectations of inflation, outright rejection of government obligations, and, more broadly, lack of credibility of economic policy. These elements include explicit opposition to government commitments and public expectations of inflation. A number of factors, including the presence of a precarious financial structure, a lax regulatory environment, and the absence of an effective legal framework to protect property rights, can affect real interest rates in the case of Eastern European countries (Calvo, Coricelli 1992).

Keynes argued that the role of interest rates in the process of the functioning of financial systems is relatively unimportant for economic development. He argues that investment finance does not depend upon the level of savings. Money needed for private sector investment could largely be supplied by the banking system. His argument is supported by the work of Demetriades et al. (1998). They argue that financial policies, specifically controlled interest, directed credit programs to specific industries, and high reserve and liquidity requirements, have a statistically significant influence on average capital productivity in five Southeast Asian economies: India, South Korea, Sri Lanka, the Philippines, and Thailand.

The supporters of the neoclassical view argue that financial development has little or no role in the process of economic growth and wealth creation because the financial system operates efficiently. They believe that economic growth is mainly derived from physical capital formation; human capital, and technological changes. A large body of literature points out that the neoclassical perspectives do not operate in the real-world situation due to financial market failures, such as unfair terms on loans, higher interest rates, and unfamiliar characteristics of production risks. On the other hand, investment finance in developing countries is expected to be financed by producers (Mathieson 1980, Fry 1997).

Despite advances in the growth literature, the question of whether financial development plays a causal role in economic growth remains debatable. Probably, the opposite is true: According to Robinson (1952), financial development is derived from economic growth. It is supported by other scholars (Stiglitz 1994, Lian, Teng 2006). High economic growth tends to produce large, privately funded financial systems and increase demand for financial services.

On the other hand, scholars argue that financial development is derived from economic growth and vice versa. Specifically, the findings show that institutional credit development leads to higher agricultural growth in developing countries (Iqbal et al. 2003, Kar et al. 2011, Chandio et al. 2020, Kaya, Kadanalı 2021). Abu-Bader, Abu-Qarn (2008) identify unidirectional causality running from financial development to economic development in five out of the six countries (Algeria, Egypt, Israel, Morocco, Syria, and Tunisia). Only weak support could be found for causality running from economic growth to financial development, but no causality in the other direction in Israel. This argument is in line with the empirical findings of Lian, Teng (2006).

Also, there is no evidence of a causal relationship between financial development and economic growth in Algeria, Jordan, Kuwait, and Saudi Arabia (Boulila, Trabelsi 2002). Previous research, on the other hand, has largely focused on aggregate growth, with little evidence on whether impact of financial development varies across industries. Previous empirical studies extensively focused on aggregate economic growth and the assumption that the agriculture sector or agricultural growth responds in the same way to financial development. Therefore, sectoral-based evidence could help policymakers in developing sector-specific policies to boost growth across a wide range of industries. This study fills the research gap by analyzing the direction of causality between institutional credit development and agricultural growth for each of the four selected countries simultaneously, to determine whether the development process is financial supply-driven or financial demand-driven in each context.

3 Data and Method of Analyses

3.1 Sources of data

Annual time series data on agricultural production, agricultural loans, agriculture capital stock formation (i.e., physical investment in agriculture), climate changes and the exchange rate are collected covering the 1991-2020 periods in this study. This study uses the agricultural credit loans and real interest rate as proxies for credit market development. Agriculture credit provided to the agriculture sector by commercial banks, private banks, and micro-financial institutions is used as proxy for the degree of credit market development. Real interest rates are used as a proxy for the degree of financial intermediation. Sources of data and all the details of the variable measurements for Benin, Kenya, Nigeria, and Tunisia are described in the appendix Table A.1.

3.2 Methods of analyses

Before analyzing data using the Autoregressive Distributed Lag (ARDL) bounds test, unit root tests were carried out to test the existence of non-stationary time series data and exclude the probability of dealing with I(2) variables using the Augmented Dickey-Fuller test.

The existence of long-run cointegration among time-series data, as well as long-run and short-run relationships between institutional credit development and agricultural production, was investigated using ARDL bound tests. The ARDL approach was developed by Pesaran, Shin (1999), Pesaran et al. (2001), and it has advantages over traditional cointegration analyses. For example, the ARDL bound tests for cointegration offer several advantages over other approaches to cointegration, such as Engle, Granger (1987), Johansen (1988), and Johansen, Juselius (1990). ARDL bound tests to cointegration not only distinguish between dependent and independent variables (i.e., it overcomes endogeneity problem), but they can also estimate long-run and short-run dynamic relationships at the same time. ARDL model delivers unbiased long-run model estimations (Harris, Sollis 2003). The ARDL test is more effective in the case of small ($n \leq 30$) samples or finite-sample observations. The ARDL error correction representation becomes relatively more efficient. The ARDL bounds testing approach to cointegration can be applied irrespective of whether the regressors are of 1(0) or 1(1). However, the dependent variable must be of level I(1), and none of the independent variables must be of level I(2) or higher. The following formula is the ARDL bounds tests for cointegration:

$$\begin{aligned}\Delta Y_t = \alpha + \gamma_1 Y_{t-1} + \gamma_2 X_{t-1} + \gamma_3 R_{t-1} + \gamma_4 Z_{t-1} + \gamma_5 C_{t-1} + \gamma_6 E_{t-1} + \\ \sum_{i=1}^{p} \beta_{1i} Y_{t-i} + \sum_{i=1}^{q} \beta_{2i} X_{t-i} + \sum_{i=1}^{r} \beta_{3i} R_{t-i} + \sum_{i=1}^{s} \beta_{4i} Z_{t-i} + \sum_{i=1}^{v} \beta_{5i} C_{t-i} + \\ \sum_{i=1}^{w} \beta_{6i} E_{t-i} + \epsilon_t\end{aligned} \tag{1}$$

where γ and β are coefficients, α is constant, p, q, r, s, v, and w are optimal lag orders, the lengths for p, q, r, s, v, and w are not the same, ϵ_t captures the disturbance term. First, we run equation (1) to test the presence of long-run cointegration equilibrium. Then, each dependent variable in the remaining five cointegration equations has been regressed on dependent variable (agricultural production) and other independent variables, such as agricultural credit loans, agricultural capital formation, real interest rate, exchange rate, and climate change in the model to check the existence of long run cointegration. For instance, agricultural loan has been regressed on agricultural production, agricultural capital formation; real interest rate, exchange rate, and climate change in the model (see Table 3).

Under the null-hypotheses of no cointegration, the bounds test is primarily based on the joint F-statistic, which has a non-standard asymptotic distribution. The first step in ARDL bound test is to estimate the six equations by employing Ordinary Least Square (OLS). The next step of the ARDL bounds test procedure is to test for a long-run relationship among the variables by conducting the F-statistic test for the joint significance of the coefficients of the lagged levels of the variables i.e., H_0: $\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = 0$ (i.e., suggesting the absence of a long-run relationship) against an alternative hypothesis (i.e. presence of cointegration) of H_A: $\beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq \beta_6 \neq 0$. The calculated F-statistics are compared with tabulated F-statistics (95% bounds and 99% bounds) values estimated by Pesaran et al. (2001) which are split into lower critical bounds (I(0)) and upper critical value bounds (I(1)) that result in correct conclusion about cointegration. If the calculated F-statistic value is greater than the upper tabulated value, the null hypothesis of no cointegration is rejected independent of the order of integration of the series, otherwise, the null is accepted.

ARDL Bounds test for cointegration is used to estimate the long-run relationships and short-run dynamic relationships among the variables of interest (agricultural production, credit to agriculture, real interest rate, climate change, fixed capital investment and exchange rates). This study utilized the autoregressive distributed lag (ARDL) approach of Pesaran et al. (2001) to evaluate the existence of a long-run relationship between agricultural production and agricultural credit supply. The ARDL long-run model for agricultural production and agricultural credit supply can be expressed as:

$$\begin{aligned}Y_t = \alpha_{01} + \sum_{i=1}^{p} \beta_{1i} Y_{t-i} + \sum_{i=1}^{q} \beta_{2i} X_{t-i} + \sum_{i=1}^{r} \beta_{3i} R_{t-i} + \sum_{i=1}^{s} \beta_{4i} Z_{t-i} + \\ \sum_{i=1}^{v} \beta_{5i} C_{t-i} + \sum_{i=1}^{w} \beta_{6i} E_{t-i} + \epsilon_t\end{aligned} \tag{2}$$

where β_1, β_2, β_3, β_4, β_5, β_6 are ARDL long-run coefficients, and ϵ_t is the white noise error term.

Following Pesaran, Shin (1999), and Pesaran et al. (2001), the error-correction version of ARDL model is specified as follows:

$$\Delta Y_t = \alpha_{0j} + \theta \text{ECT}_{t-i} + \sum_{i=1}^{p} \gamma_{1i} \Delta Y_{t-i} + \sum_{i=1}^{q} \gamma_{2i} \Delta X_{t-i} + \sum_{i=1}^{r} \gamma_{3i} \Delta R_{t-i} + \sum_{i=1}^{s} \gamma_{4i} \Delta Z_{t-i} + \sum_{i=1}^{v} \gamma_{5i} \Delta C_{t-i} + \sum_{i=1}^{w} \gamma_{6i} \Delta E_{t-i} + \epsilon_t \quad (3)$$

where θ is the speed of adjustment and the coefficient of error correction term which is obtained as residual from the long-run relationship in equation (3). γ_1, γ_2, γ_3, γ_4, γ_5 and γ_6 are the short-run dynamic coefficients of the model's convergence to equilibrium, and ϵ_t is the white noise error term. The Δ denotes the difference operator.

Granger (1969) suggested Granger causality analysis examines causal relationships between two time-series data. The presence of long-run and short-run relationships between two variables only implies the presence of causality in at least one direction (Granger 1988). However, the cointegration test and error correction model is not sufficient to determine the direction of causality between two-time series data. To test whether credit market development Granger causes agricultural production or not, this study used the Granger causality test suggested by Granger (1969). This Granger causality test consists of two variables, institutional credit development, and agricultural production written as:

$$X_t = \alpha_1 + \sum_{j=1}^{k} \beta_j X_{t-j} + \sum_{i=1}^{k} \beta_i Y_{t-i} + u_{1t} \quad (4)$$

$$Y_t = \alpha_2 + \sum_{i=1}^{k} \beta_i Y_{t-i} + \sum_{j=1}^{k} \beta_j X_{t-j} + u_{2t} \quad (5)$$

where X_t and Y_t are institutional credit development and agricultural production, respectively.

Both null hypotheses and alternative hypotheses are derived from the literature review. Based on coefficients (β_j and β_i) of equations (4) and (5), four different hypotheses about the association between institutional credit development and agricultural real GDP growth can be specified as follows.

1. Granger causality is unidirectional: Granger causality runs from agricultural production to institutional finance development. In this situation, agricultural production causes an increase in the availability of institutional credit, but not the other way around. As a result, $\beta_i \neq 0$ and $\beta_j = 0$.
2. Granger causality is unidirectional: Granger causality runs from institutional credit development to agricultural production. In this scenario, institutional credit development boosts agricultural real GDP forecasting, but not the other way around. Thus, $\beta_i = 0$ and $\beta_j \neq 0$
3. Bidirectional causality: Agricultural production and institutional credit development are both affected by feedback causality. Agricultural production is derived from institutional credit development, and vice versa in this situation. As a result, $\beta_i \neq 0$ and $\beta_j \neq 0$.
4. Independence: There is no feedback between agricultural production and institutional loan supply in this situation. Thus, $\beta_i = 0$ and $\beta_j = 0$.

4 Results and Discussions

4.1 Results of descriptive statistics

The average value of agricultural credit in Benin increased from \$7.82 million in 1991–1999 to \$41.83 million in 2009–2020. The average value of Tunisian agricultural credit

Table 1: Summary statistics for all study countries

Variable	1991–1999	2000–2008	2009–2020
Benin AC	7.82(12.13)	14.64(3.67)	41.83(9.00)
Benin AP	615.87 (135.51)	984.54 (325.32)	1779.75 (132.50)
Benin AFCF	20.81 (3.52)	38.86 (8.92)	60.16 (13.81)
Benin CH	0.58 (0.30)	0.87 (0.23)	1.17 (0.19)
Kenyan AC	322.89 (25.09)	383.75 (57.61)	697.87(159.34)
Kenyan AP	3073.99 (689.88)	4342.57 (1094.52)	12690.55 (4039.59)
Kenyan AFCF	183.44 (19.052)	323.98 (122.41)	1094.80 (392.18)
Kenyan CH	0.34 (0.15)	0.67 (0.13)	1.06 (0.27)
Nigeria AC	407.64 (77.68)	541.740 (267.49)	1733.78 (797.42)
Nigeria AP	13227.89 (1893.33)	39167.08 (26475.19)	95543.5 (12125.11)
Nigeria AFCF	364.436 (56.70)	1683.63 (886.28)	3988.545 (601.49)
Nigeria CH	0.66 (0.32)	0.84 (0.31)	1.13 (0.23)
Tunisian AC	1123.00 (180.35)	961.61(70.00)	1112.89 (55.09)
Tunisian AP	2189.34 (244.43)	2662.46 (561.40)	3928.49 (398.17)
Tunisian AFCF	301.33 (52.92)	506.55 (201.71)	708.26 (53.59)
Tunisian CH	0.78 (0.59)	1.34 (0.34)	1.53 (0.52)

Notes: AC stands for the amount of credit to the agriculture sector (value US millions of dollars using constant 2015 prices) to agriculture, forestry and fishing. AP stands for agricultural production (value US millions of dollars using constant 2015 prices), and AFCF stands for agriculture fixed capital formation (value US millions of dollars using constant 2015 prices). CH refers to climate change.
Source: Author's calculations based on the FAOSTAT and World Bank Indicators databases (2022).

decreased from \$1123.00 million in 1991–1999 to \$1112.89 million in 2009–2020. On the other hand, Tunisian average real agricultural production increased from \$2189.34 million in 1991–1999 to \$3928.49 million in 2009–2020. Agricultural loans granted in Tunisia experienced a negligible reduction in the amount of agricultural loans granted over the periods (Table 1). This implies that investment finance is financed by producers in Tunisia. The reasons for little links between agricultural production and institutional credit supply in Tunisia can be explained by Islamic motives and state-owned banks (Boulila, Trabelsi 2004). Since Islam disallows interest, producers may be hesitant to borrow from the state-owned banks.

The level of reduction in agricultural loan supply over periods in Tunisia (Table 1) implies that financial development assumptions do not work for the case of Tunisia. The theory argues that financial development stimulates economic growth by increasing the rate of capital accumulation. It also justifies fact that the financial systems promote productivity. Financial systems determine selection of higher-quality entrepreneurs and projects, mobilization of external financing for these entrepreneurs, provision of superior vehicles for diversifying the risk of innovative activities, and more accurate explanation of large profits associated with the uncertain business of innovation. The fixed agricultural capital formation significantly increased agricultural production from \$2189.34 million in 1991–1999 to \$3928.49 million in 2009–2020 (see Table 4).

4.2 Augmented Dickey-Fuller test and ARDL bounds test for cointegration results

The results of unit root tests showed that all variables such as agricultural production, credit to agriculture, fixed capital formation, real interest rate, climate change and exchange rate were stationary at the first difference (FD), but not stationary at the level (Table 2).

The findings of the model shown the existence of the long-run cointegration among agricultural production, agricultural credit supply, agricultural fixed capital formation, exchange rates, real interest lending rates and climate change for all countries except for Tunisia (Table 3).

Table 2: Augmented Dickey-Fuller test for following variables with constant (H0: unit root)

Variable	Benin T value		Kenya T value		Nigeria T value		Tunisia T value	
	Level	FD	Level	FD	Level	FD	Level	FD
AP	-1.55	4.97***	-0.60	-4.92***	-0.35	-4.01**	-0.35	-4.12***
	(0.91)	(0.00)	(0.98)	(0.00)	(0.91)	(0.02)	(0.91)	(0.00)
AC	-2.78	-6.76***	-2.04	-4.36***	-1.02	-3.57**	-1.02	-3.87**
	(0.20)	(0.00)	(0.58)	(0.00)	(0.75)	(0.03)	(0.75)	(0.04)
AFCF	-0.61	4.89***	-1.58	-4.70***	-0.46	-4.11***	-0.46	-3.10**
	(0.98)	(0.00)	(0.80)	(0.00)	(0.59)	(0.4)	(0.89)	(0.05)
EXCR	-2.17	-4.80***	-2.69	-4.45***	-0.28	-3.05**	-2.28	-4.71***
	(0.50)	(0.00)	(0.24)	(0.00)	(1.43)	(0.04)	(0.43)	(0.00)
RI	-1.34	-4.37***	-1.21	-3.99***	-1.28	-3.31**	-1.87	-5.11***
	(0.71)	(0.00)	(0.14)	(0.00)	(0.43)	(0.03)	(0.73)	(0.00)
CH	-2.88*	-7.80***	-2.69*	-6.39***	-2.11	-5.25***	-1.98	-6.01***
	(0.07)	(0.00)	(0.04)	(0.00)	(0.53)	(0.00)	(0.21)	(0.00)

Notes: FD refers to the first difference. AC stands for the amount of credit to the agriculture sector. AP stands for agricultural production, and AFCF stands for agriculture fixed capital formation. EXCR stands for the exchange rate. RI stands for the real interest rate. CH refers to climate change. Values of probabilities are in parenthesis. ** and *** represent statistically significant at 5% and 1%, respectively.

4.3 Results of ARDL bound test and Granger causality

The results showed that institutional credit availability had a long-run impact on agricultural production. The findings supported the theory and earlier empirical findings that expanding agricultural financing led to higher agricultural output in Benin, Kenya, and Nigeria (King, Levine 1993, Levine 2005, Chandio et al. 2020). The findings were also consistent with the work of Ustarz, Fanta (2021) in all countries except for Tunisia, (Table 4). They found that agricultural and service sector growth was significantly and positively influenced by the financial market and financial institution development in Sub-Saharan Africa. Credit supply, on the other hand, has a negative impact on middle-income African and sample Sub-Saharan African countries (An et al. 2020).

Table 4 demonstrated that a 10% increase in agricultural credit supply resulted in about a 19.9% increase in agricultural production in the long run in Benin. The long-run coefficients of error correction terms were significant with the right signs (i.e., negative) in all cases except for Tunisia (Table 4). The negative ECM coefficients (-0.69, -1.33, -0.19, and -0.26) indicated that production equilibrium was stable with the highest in Kenya and the lowest speed of adjustments in Tunisia (Table 4). The magnitude of the equilibrium error correction coefficient (-0.69) indicated that 69% of the previous year's deviation from the equilibrium position was corrected in a particular year. The dynamic speed of adjustment for Kenyan agricultural production was relatively the fastest (-1.33), in absolute value than other countries and it was a reflection of the quicker transformation of agricultural credit loans in productivity concerning speed in one year. Nigerian agricultural production relatively adjusts slowest, and it was lesser flexible than other countries to restore the long-run equilibrium.

In the short run, the credit market development had a significant and positive effect on agricultural production in Nigeria due to the input subsidy policy. Production in agriculture is significantly impacted by input subsidies (Shikur 2020a). As a result, farmers may use credit to finance agricultural technologies to increase their profit since agricultural input subsidies decrease the costs of inputs as well as production.

On the contrary, the effect of institutional credit development on agricultural production was negative in the short-run in Benin, and Kenya. The coefficients of lagged agricultural credit supply and agricultural credit supply in Table 4 are -3.43 and -3.12, respectively, indicating a 10% rise in lagged agricultural credit supply and agricultural credit supply would result in a 34.3% and 31.2% decline in agricultural production in the short run in Benin. Agricultural credit loans may not lead to positive change in the agricultural production situation where farmers may not use the loans to purchase agricultural technologies. Many farmers in Africa did not use credit to finance agricul-

Table 3: Results of bound test for cointegration

Country	Equation	F-statistic	Decision
Benin	AP_F/ AC, AFCF, ECXR, CH	5.56***	Cointegration
Benin	AC_F/ AFCF, AP, ECX, CH	3.75**	Cointegration
Benin	$AFCF_F$ / AC, AP, ECXR, CH	2.99	No cointegration
Benin	$ECXR_F$ / AP, AC, AFCF, CH	5.41***	Cointegration
Benin	CH_F / AP, AC, AFCF, ECXR	5.41***	Cointegration
Kenya	AP_F/ AC, AFCF, ECXR. RI, CH	11.54***	Cointegration
Kenya	AC_F/ AFCF, AP, ECXR, RI, CH	3.35**	Cointegration
Kenya	$AFCF_F$/ AC, AP, ECXR, RI, CH	2.61	No cointegration
Kenya	$ECXR_F$ / AC, AFCF, AP, RI, CH	15.38***	Cointegration
Kenya	RI_F/ AP, AC, AFCF, ECXR, CH	5.03***	Cointegration
Kenya	CH_F/AC, AFCF, AP, ECXR, RI	3.67**	Cointegration
Nigeria	AP_F/ AC, AFCF, ECXR, RI, CH	18.30***	Cointegration
Nigeria	AC_F/ AFCF, AP, ECXR, RI, CH	3.49**	Cointegration
Nigeria	$AFCF_F$/ AC, AP, ECXR, RI, CH	1.14	No cointegration
Nigeria	ECXR / AC, FCF, AP_F. RI, CH	3.41**	Cointegration
Nigeria	RI_F/ AC, AFCF, AP. ECXR, CH	4.11**	Cointegration
Nigeria	CH / AC, AFCF, AP,. ECXR, RI	3.99**	Cointegration
Tunisia	AP_F/ AC, AFCF, ECXR, CH	1.03	No cointegration
Tunisia	AC_F/ AFCF, AP, ECXR, CH	5.22**	Cointegration
Tunisia	$AFCF_F$/ AC, AP, ECXR, CH	1.75	No cointegration
Tunisia	$ECXR_F$ / AC, AFCF, AP, CH	1.05	No cointegration
Tunisia	CH_F/ AC, AFCF, AP, ECXR	1.87	No cointegration

Notes: Subscript F represents "function of independent variables".AC stands for the amount of credit to the agriculture sector. AP stands for agricultural production, and AFCF stands for agriculture fixed capital formation. EXCR stands for the exchange rate. RI stands for the real interest rate. CH refers to climate change.Lower-bound critical and upper-bound critical values are 3.23 and 4.35 at 5%, respectively. Lower-bound critical value and upper-bound critical value are 4.29 and 5.61 at 1%, respectively. Regarding the lower critical bound, it is assumed that all the variables are I(0) (i.e., no cointegration among variables), and regarding the upper critical bound, it is assumed all the variables are I(1) (i.e., cointegration among variables). ** and *** represent statistically significant at 5% and 1%, respectively.

tural technologies or external inputs purchases due to fear of climate and market risks (Adjognon et al. 2017, Nakano, Magezi 2020). Farmers in Benin have experienced the absence of fertilizers, improved vegetable seeds, and other crops, and exposed high production and market risks like climate change, high input prices, and limited input supply (Adjimoti et al. 2017). Price support and stabilization policies were not effective in many African countries to address price fluctuation, low agricultural technology adoption and low agricultural productivity (Shikur 2022c). By contrast, these policies increase the extensive utilization of agricultural technologies as well as production by addressing price fluctuation in several Asian and Latin American countries (Shikur 2020a).

Climate change was negatively associated with agricultural production in the long and short runs in all countries except for Nigeria. Climate change reduces livestock production and crop production by altering ecosystem services like water/rainfall availability; livestock feed quality and quantity availability; and disease outbreaks (Vining 1990, UNFCCC 2007). Tunisian agricultural production has declined with rising temperatures, sea level and aridity, and low precipitation (Prior, Santomá 2010). This implies that without environmental policy, the effect of the adoption of agricultural technologies may not be manifested in agricultural productivity in the short run in the three countries (Nelson et al. 2009).

On the contrary, the effect of climate change has not been manifested in agricultural production in Nigeria since a number of institutional and programmatic reforms and innovations have been adopted by the Nigerian government to promote the use of small and large-scale irrigation systems. This implies that irrigation policies in Nigeria might remove the effect of climate change on agricultural production by reducing the effect of climate change on animal feed and water/rainfall availabilities in regions (Carter et al. 2016). So, an irrigation policy could reduce the effect of little or inconsistent rainfall on agricultural production and productivity.

The real interest lending rates had a negative effect on agricultural production since

Table 4: Results of bound test for cointegration

Variable	Benin	Kenya	Nigeria	Tunisia
		Long-run relationship		
AC	1.99***(0.71)	5.04**(1.99)	0.14***(0.05)	0.25 (0.32)
AFCF	0.34 (0.23)	0.45*(0.03)	0.22*(0.12)	0.47**(0.19)
Exchange rate	-1.12***(0.32)	-5.70*(4.14)	0.31*(0.16)	0.23 (0.50)
Real interest rate	–	-1.28 (5.58)	-4.83 (5.21)	–
Climate change	-3.23(9.98)	-2.13 (12.21)	2.45** (.98)	-2.78**(1.29)
		Short-run dynamics		
AP (L_1)	0.9 8**(0.48)	0.55** (0.27)	-0.18 (0.21)	-0.15 (0.23)
AC	-3.12(2.73)	-25.55*(2.44)	0.18*(0.09)	-0.36 (0.67)
AC(L_1)	-3.43(2.56)	-19.49*(1.95)	0.25***(0.07)	–
AFCF	0.7 3**(0.30)	0.45**(0.13)	0.67** (0.23)	0.69*** (0.21)
AFCF(L_1)	0.89***(0.33)	0.89***(0.33)	0.89***(0.33)	0.89***(0.33)
Exchange rate	-0.34 (2.01)	-1.34 (1.67)	2.20 (2.01)	-0.87 (1.31)
Exchange rate (L_1)	-0.83(1.95)	-0.99 (1.32)	0.67(0.85)	-0.76 (1.41)
Real interest rate	–	-1.25 (1.65)	-7.07 (10.16)	–
Real interest rate (L_1)	–	-1.56(13.87)	-4.34 (9.67)	–
Climate change	-3.36 (2.86)	-8.60(5.87)	1.99** (2.86)	-3.44(4.87)
Adjustment (ECT)	-0.69***(0.18)	-1.33**(0.10)	-0.19**(0.07)	-0.26 (0.15)
Constant	2.91**(1.14)	3.14(10.23)	10.16**(4.00)	12.28 (31.03)

Note: * … significant at 10%, ** … significant at 5%, *** … significant at 1%. L_1 denotes lag one. Values of standard errors are in parenthesis.
Source: Author's calculations based on the FAOSTAT and World Bank Indicators databases (2022).

Table 5: Results of Granger causality tests (F-statistics)

Variable	Benin	Kenya	Nigeria	Tunisia
Credit market development led	4.31*	7.06**	13.40***	0.84
agricultural productivity	(0.09)	(0.03)	(0.00)	(0.66)
Agricultural productivity led	7.42**	10.61***	7.00**	0.14
credit market development	(0.02)	(0.00)	(0.03)	(0.93)

Note: *** … significant at 1%, ** … significant at 5%, * … significant at 10%. Probabilities in parenthesis.
Source: Author's calculations based on the FAOSTAT and World Bank Indicators databases (2022).

it increases the cost of production and decreases profitability. As a result, a high-interest rate reduces farmers' credit utilization for technologies. The exchange rate was negatively associated with agricultural production (Table 4). The devaluation of the exchange rate is one of the indirect taxation mechanisms used by the government to tax producers that increase the costs of agricultural production (Shikur 2020a). The scholars argued that moderate agricultural taxation has a significant effect on aggregate agricultural productivity. Still, high or low rates of agricultural taxation do not affect agricultural productivity (Hu, Antle 1993).

Capital formation had a significant and positive effect on agricultural production in the long-run and short-run. Whereas the effect of agricultural credit development on agricultural production was positive and insignificant in the long-run, but insignificant and negative in the short-run in Tunisia due to extensive and over-government interventions in financial, input, and output markets. For instance, the government fixes the high-interest rate cap and guaranteed minimum output prices (Prior, Santomá 2010).

Granger causality test identified significant bi-directional causal relationships between credit market development and agricultural productivity in Benin, Kenya, and Nigeria. This result implied that agricultural credit loans were a basic input in the process of agricultural production; therefore, financial development enhances agricultural production significantly. Similarly, the previous empirical studies support the existence of a feedback causal relationship between these two variables (Demetriades, Hussein 1996, Anwar, Nguyen 2011, Mukhopadhyay et al. 2011, Hassan et al. 2011, Jedidia et al. 2014, Kaya, Kadanalı 2021).

The empirical results strongly support the hypothesis that financial development leads to growth in Algeria, Egypt, Morocco, and Tunisia (Kar et al. 2011), and Ghana (Adu et al. 2013). In the agriculture sector, the findings show that an increase in institutional credit development leads to higher agricultural growth in developing countries (Iqbal et al. 2003, Isial et al. 2011, Chandio et al. 2016, 2020, Chaudhry, Hussain 1986).

There was no significant causal relationship between agricultural productivity and institutional credit development in Tunisia. This finding corroborated the findings of Boulila, Trabelsi (2002) in Algeria, Jordan, Kuwait, and Saudi Arabia and the works of Mukhopadhyay et al. (2011). The reasons for little links between agricultural production and institutional credit supply in Tunisia can be explained by agricultural policies, Islamic motives, and the state-owned banks (Boulila, Trabelsi 2004). Since Islam disallows interest, producers may be hesitant to borrow from owned banks. The credit supply in this country has been highly dominated by state-owned micro-financial institutions leading to lower access to credit services as well as lower credit demand (Prior, Santomá 2010).

5 Conclusions

The findings of models showed that agricultural production was positively and significantly associated with institutional credit supply in all countries in the long run except for Tunisia. To ensure faster agricultural growth, governments in emerging nations should significantly increase agricultural credit loans as well as adopt directed credit with a soft interest rate to the agricultural sector to achieve faster agricultural productivity growth.

The Granger causality test identified two patterns in the causal relationship between the two factors in these countries. A first pattern, there was a significant bi-directional causal relationship between credit market development and agricultural production in Benin, Kenya and Nigeria. The empirical results provide important implications for policymakers to use agricultural policies and financial market development policies at a time. The results encourage the country to follow an integrated approach that may be very useful to obtain more successful production due to the causal interactions of agricultural policies and financial market development policies.

The financial policies should focus on developing financial systems by expanding many financial institutions and supplying various financial products and services to promote financial development, thereby accelerating agricultural growth. In such a context, governments should adopt integrated agricultural production and credit market policies to achieve faster growth in agricultural productivity in all countries.

The second pattern is described by the relationship between agricultural production and institutional credit supply being too weak to determine the direction of causality in Tunisia. The study suggests the Tunisian government should promote financial liberation and self-investment financing to enhance agricultural productivity and production. The conclusion regarding one country is that financial credit development does not explain agricultural growth. This implies that the results appear inconsistent across countries. Credit market development acts as a facilitator for agricultural production in Benin, Kenya and Nigeria whereas it retards agricultural growth in Tunisia.

Governments in the study countries should encourage continuous supervision and training of farmers to use credit to finance agricultural technologies and secure adequate credit supply to achieve faster agricultural growth. The variations in the findings across countries imply policies, degree of financial regulation, and supervision, the extent of agricultural credit and capital supplies, climatic conditions, and so forth are the main determinants of agricultural productivity.

The manifestation of credit market development impact in agricultural production may not be seen in the absence of agricultural input and product market policies. Thus, considering agricultural input and product markets in development policies can make a country more effective at increasing agricultural production than a country considering credit market development policy alone. It has to do with developing stable input and output markets around the introduction of new, better methods, routes, innovative financial systems, and interventions required to achieve policy objectives. The policy requires new skills and competencies to adopt new organizational structures, introduce, disseminate farm practices, and upgrade the value chain.

The result indicated that climate change was negatively associated with agricultural production in long- and short-runs in all countries except for Nigeria. It is consistent with theoretical arguments that climate change adversely influences livestock production and crop production by altering ecosystem services like water/rainfall availability, livestock quality and quantity, feed availability, and disease outbreaks. Agricultural production was positively influenced by climate change in Nigeria in both long- and short-runs. A number of small- and large-scale irrigation policy reforms adopted by the government could remove the effects of climate change on agricultural production effectively in the case of Nigeria. This implies that climate-smart agricultural practices are needed to neutralize the effect of temperature change on agricultural input/technology productivity in the short-run and long-run agricultural production. In addition to these justifications, the combination of environmental and agricultural support policies implemented by the Nigerian government has enabled farmers to more easily access agricultural inputs as well as enabled them to translate agricultural credit loans into agricultural productivity. The study suggests further research on the association between livestock production and financial market development.

Competing interests

There are no conflicts of interest to declare.

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A Appendix:

Table A.1: Data Description

Variable	Description of the variables	Source
Y_t	The agricultural production, which is measured by real value of agriculture value-added, is noted by Y_t in equation (1).	WDI database
X_t	Agricultural credit loan (X_t) is measured by the real amount of agricultural loans provided to the agriculture sector.	FAOSTAT databases
R_t	Real interest rate (R_t) is the lending interest rate (%) adjusted for inflation which is measured by the GDP deflator. Real interest rates are used as a proxy for the degree of financial intermediation.	WDI database
Z_t	Capital stock (Z_t) is measured by real gross fixed capital formation/physical investment in agriculture, forestry, and fishing with using the System of National Accounts (SNA) concept. Gross capital stock is the total value of all fixed assets in use, regardless of age, based on the cost of new assets.	FAOSTAT databases
C_t	Climate change (C_t) is proxied by annual mean temperature anomalies, i.e., temperature change with respect to baseline climatology. So, climate change is measured as annual mean temperature anomalies. Temperature change refers to ozone. Since, higher temperatures are generally associated with higher ozone levels, while higher relative humidity is generally associated with lower ozone levels This happens when pollutants emitted by cars, power plants, industrial boilers, refineries, chemical plants, and other sources chemically react in the presence of sunlight.	FAOSTAT databases
E_t	Annual exchange rates (E_t) are obtained by dividing Standard Local Currency Units (SLC) by the US dollar. Annual exchange rates reflect financial repression.	FAOSTAT databases

Note: WDI refers to World Development Indicator Database. FAOSTAT refers to FAO Statistical Databases (Food and Agriculture Organization of the United Nations).

REGION
The Journal of ERSA
Powered by WU

Volume 10, Number 3, 2023, 19–30
DOI: 10.18335/region.v10i3.490

journal homepage: region.ersa.org
ISSN: 2409-5370

Spatial Economics and Totalitarian Temptations: The Complex Biography of August Lösch (1906-1945)

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Received: 20 April 2023/Accepted: 25 June 2023

Abstract. Among the German spatial economists August Lösch is arguably the one who has had the biggest lasting influence on international academic literature. After his death in May 1945, a legend was created according to which he was a fierce opponent to national socialism. This was part of the attempts of his former colleagues and of the German economics community at large to disguise the extent of their own involvement and their agency in advising economic and social policies of the Nazi regime. The political context of spatial planning during the Second World War was particularly damning as it in many cases presupposed genocides on nations such as Poles and Russians and on religious groups such as Jews. It was precisely with regards to Eastern Europe that Lösch's theoretical contributions were deemed to be particularly valuable. However, the legend of his supposed opposition contained a grain of truth as he was indeed appalled by central aspects of Nazi ideology. Yet, the ability of a totalitarian regime such as the "Third Reich" to integrate the contributions of a brilliant mind and somebody who saw himself as an independent and unpolitical scholar into its decentralized and collaborative spatial research apparatus is what makes Lösch's biography particularly interesting and relevant today.

1 Introduction

It has been argued that August Lösch (1906-1945) "is the German spatial economist who has had the biggest lasting influence on international academic literature, far beyond the discipline of economics" (Bröcker 2014, p. 223). His contributions to the emerging field of spatial economics, as well as to demography and monetary economics, were well received not only in the late Weimar Republic and in the "Third Reich", but also in the USA by prominent scholars such as Joseph Schumpeter who took him under his wing. Since the 1940s, Lösch's own work and the more practically oriented Central Places Theory of his close colleague Walter Christaller were adapted by spatial planners in very different countries such as Sweden, communist Poland, and Israel (Trezib 2014, Venhoff 2000). Christaller's contributions to national socialist spatial planning are well documented, as is his political opportunism with successive memberships in the leftist USPD/SPD, the national socialist NSDAP, the communist KPD and the centre left SPD. Lösch's biography is less well known and his character seems much more complex, ambiguous, and in his constant quest for meaning in life also very relatable. Thus, his life constitutes a suitable historical case study for reflecting on the manifold application possibilities of spatial economics and on the authoritarian or even totalitarian temptations that scientists might face today.

Lösch was an independent-minded intellectual but at the same time he craved for the praise of his fellow academics and "practitioners". Among his estate is a carefully assembled collection of positive reviews of his magnum opus *The Economics of Location* (1940b, posthumously translated into English in 1954). One of those is an assessment by state secretary Hermann Muhs, head of the Reich's office for regional planning (RfR). According to Muhs, Lösch's book "contains an abundance of scientific insights which are of the upmost importance for the tasks of the RfR"[1]. This was no empty rhetoric. After a meeting with Muhs in December 1942, the time when the German armies had just reached their greatest expansion, Lösch agreed to publish a second edition (Lösch 1944). It was supposed to be even more suited to the needs of those who drew up concrete plans for the newly conquered territories in central and eastern Europe. In his diary, Lösch expressed his excitement: "I am not expected to describe what *is* but to map out what *should be*" (Riegger 1971, p. 109). Like other economists such as John Maynard Keynes (Keynes 1936), he understood that big ideas such as his vision for ultra-rational spatial planning could be very powerful even if he remained in his "unpolitical" role as a technocrat.

Despite seeking collaborations with figures such as Muhs and his attempts to optimize the totalitarian German administrations, Lösch was heralded as an opponent to Nazi rule and even depicted as a martyr immediately after his death in late May 1945. An unlikely coalition of his former German colleagues, his widow, and his American friends and acquaintances created a myth around him (Take 2019, p. 387–389). Whereas the latter were merely careless in trusting Lösch's self-portrayal and ignoring the contexts of his work during the Second World War (Kegler 2015, Barnes 2016), the former had a discernible agenda. In order to be able to continue their research after 1945, they put much effort in turning Lösch into a beacon of integrity which in turn let their own dark activities during the "Third Reich" seem as a publicly acceptable grey area. Thus, they circumvent a reckoning with the fraught history of German spatial research which has only recently begun in earnest (Baumgart 2020, Werner 2022).

Even nowadays, Lösch is often viewed in a positive light: "Lösch in contrast [to Christaller], was not only a great scientist but also a clear sighted, honest, and steadfast man" (Todt 2014, p. 204, Nijkamp 2020). In this article I argue that Lösch was indeed opposed to central aspects of the fascist ideology and that he felt liberated when the Second World War ended. That should not, however, deflect from the historical truth that he worked together with influential und staunch Nazis and that his work was highly valued by them until the very end. In fact, the ability of a totalitarian regime such as the "Third Reich" to integrate the contributions of somebody who regarded himself as an independent and unpolitical scholar, sometimes even as an opponent of the regime, into its decentralized and collaborative spatial research and planning apparatus is what makes Lösch's biography particularly interesting and relevant today. In the following, I will pay particular attention to his youth during the turbulent Weimar Republic, to the opportunities he enjoyed and the pressures he faced in the course of his adult life, and to the contexts of his research in the 1930s and 1940s.

2 Youth and Education

Lösch was born on 16 October 1906 in Württemberg, a state in the south of the German Reich. After his mother and his father, a merchant, split up two years later, he was raised at his maternal grandparents' home in the small city of Heidenheim an der Brenz. In sharp contrast to older generations, he experienced significant political and economic turbulences during his childhood, not only during World War I (1914-1918), but also with regard to the hyperinflation (1922-23) and the Allied occupation of the Ruhr (1923-25). However, he grew up in the relative security of the upper middle class and belonged to the privileged few who were given the opportunity to visit a gymnasium. Entries in his diary suggest that he began searching for a purpose in life already in his childhood and that class affiliation influenced his identity: "I do not hate the workers, they are

[1] Muhs to Wirtschaftsstelle des Deutschen Buchhandels, 3 July 1942. Stadtarchiv Heidenheim, estate of August Lösch (henceforth: Lösch estate), box XV

deplorable, misled. [...] The middle classes are best equipped to think objectively"[2]. Those early entries also reveal patriotic feelings and a devout Christianity, both of which influenced his opinions on current political events such as the ongoing disputes about reparations after the Treaty of Versailles[3].

After his graduation (*Abitur*) in 1925, Lösch completed a commercial apprenticeship at a factory for medical products in Heidenheim. From 1927 to 1932, he studied economics and law – a typical combination at the time – while also taking courses on a wide variety of subjects such as history, philosophy, sociology, French, and English. His enormous studiousness and willingness to broaden his horizons earned him one of the very few scholarships. Switching universities remarkably often (in chronological order: Tübingen, Freiburg, Kiel, Bonn, Freiburg, Bonn), he was able to attend lectures of most of Germany's leading economists such as Walter Eucken, Gerhard Colm, Adolph Lowe, Joseph Schumpeter and Arthur Spiethoff. Common themes during these lectures were the use of statistics and an involvement in the emerging field of business cycle theory.

Lösch's academic excellence soon opened up many opportunities for him. He worked at Spiethoff's social and economic research institute in Bonn, he became part of Schumpeter's study group, and he participated in the intellectual and leisure activities of the inner circle around the philosopher Martin Heidegger. His first economic paper was published in a leading German journal in 1930 (Lösch 1930), a year before he earned his diploma. Besides these achievements, he was engaged in the self-government of the student service in Tübingen, was chairman of a student body of a faculty in Bonn, and frequently wrote letters, political memoranda, and speeches about matters such as socialism and the state of political education. Many of them were pessimistic in tone, showing great discontent with the state of German academia and revealing a deeply felt struggle to find meaning in life.

Lösch clearly felt proud of being en route to becoming a member of the academic elites. At the same time, he wanted to remain a free-thinking outsider and – rather paradoxically, but not atypically for a German during this period – longed for a feeling of national unity during the turbulent domestic and international political struggles of the late Weimar Republic. Averse to party politics and to the involvement of the less educated classes in the political opinion-forming process, he advocated for a higher sense of responsibility among academics in combination with a more aristocratic form of leadership to solve the manifold political and social divisions[4]. Lösch neither joined the growing far-right student groups nor was he close to center-left student organizations which regarded the political arena as a legitimate forum for class struggles and aimed at preserving democracy. Instead, he belonged to the conservative elites. Their longing for an authoritarian regime unlimited by a separation of powers is seen as a decisive factor in the Fascists rise to power (Herbert 2016, p. 32).

Among other issues, Lösch took a stance on the question of German reparations for the damages caused during the First World War. He demanded not to "silently pay those unprecedented tributes"[5], but to break international treatises instead by terminating remittances. He expected detrimental effects that would go beyond the economic sphere, but more importantly, he anticipated "the invaluable benefit that Germany regains its pride and a unified will [...] <u>one</u> will!"[6]. This signals a shift to the right and stands in contrast to Lösch's earlier positions during his youth. Back in 1923, 16-year-old Lösch had accepted "that Germany would not play a role as a superpower for 100-200 years. It will be succeeded by Europe"[7].

[2] August Lösch, diary entry, 18 March 1923. Lösch estate, box XII

[3] A week after the French occupation of the Ruhr in January 1923, 16-year-old Lösch wrote: "Love should even be felt towards the French". Lösch, diary entry, 23 January 1923. Ibid.

[4] August Lösch: Politische Bildung?, June 1929. Lösch estate, box XIII

[5] Mehr Stolz! Eine Bemerkung zur Reparationspolitik von August Lösch, undated (probably between 1929-1932). Lösch estate

[6] Ibid.

[7] August Lösch, diary entry, 23 January 1923. Lösch estate, box XII

3 Early Career in the Weimar Republic, in Nazi Germany and in the USA

For his dissertation and his *Habilitation*, Lösch looked for a hotly contested political topic (Lösch 1932, foreword). He chose demographic change in Germany, analyzing it first from a macroeconomic and political standpoint and then with regards to business cycle theory. Written in 1930 and published in 1932, the leading question of his dissertation was: "How should one view the decreasing birth rates?" According to Lösch's analysis, the effects were overwhelmingly positive, raising individual wealth, decreasing social tensions, and stabilizing liberal democracies by reducing the unpropertied and supposedly easily radicalized working class (Lösch 1932). Initially, the political right valued his work. In 1930, he won the precious Karl Helfferich Prize, named after a leading right-wing and antisemitic politician. Lösch had been careful to include an assessment of the question most important to nationalists and those wanting to reverse the effects of the lost first World War, namely whether decreasing birth rates would be detrimental to Germany's future military potential. He concluded that slower growth rates on average lead to more educated, intelligent, and also more determined individuals, as even the poor would have something to fight for (Lösch 1932).

Initially after the Nazis' seizure of power, Lösch's positions were deemed to be inside the range of opinions permitted by the regime's censorship. For example, he was allowed to publish a mixed review of the new and ideologically highly charged journal *Deutscher Lebensraum – Blätter für neue deutsche Raum- und Bevölkerungspolitik*[8]. He doubted the asserted lack of space and pointed out that on the contrary, a lack of people was much more likely in the near future (Lösch 1933). Thus, Lösch rejected the Nazis' claim of a detrimental German overpopulation and did not supply scientific support for the ideological demands for acquiring new territories. Instead, he saw increased population density as a driving force for technical and economic progress (Lösch 1932). However, he himself published three times in said journal in 1933/34, hence contributing to the "lively engagement with those highly political issues" (Lösch 1933, p. 158) which he regarded as necessary.

In 1936 things changed and Lösch's dissertation was put on a list of "detrimental and unwanted literature" by the Reich's ministry for propaganda. This was probably due to a combination of a narrowing range of permitted opinions and a crackdown on self-publishing – a method which Lösch had used to stay independent. Yet, a document probably written in 1937 or 1938 raises the question whether he subsequently changed his mind or whether he developed or at least experimented with political opinions that differed from his scientific views. The document in question is a four-page manuscript which sketches out a historical narrative and is easily compatible with Nazi ideology. In it, Lösch argued that "we [the Germans] have long lived in an unbearable density, the fight for more space is old and the main theme of our history, a tragic story. [...] Due to our political palsy, our brave and growing people was continually thrown back to its old state: being a people without space"[9]. It is unclear in how far this position was in line with Lösch's stance towards the German annexations and conquests since the late 1930s. It has to be noted that he did not publish this essay, even though doing so would likely have had a beneficial impact on his career.

During the mid-1930s, Lösch mostly conducted research on causal links between changes in population and business cycles. While many other scholars suffered cuts to their funding due to the Great Depression or the manifold political disruptions in the German academic landscape in 1933, Lösch was in the privileged position to be able to fully concentrate on his research and to publish his second book in 1936. He hugely profited from the support of the Rockefeller Foundation, which not only paid his wages at Spiethoff's institute in Bonn[10], but also gave Lösch a significant personal grant, allowing

[8] German living space – journal for a new German spatial and demographical politics

[9] Die Erweiterung unseres Lebensraumes im Lauf der Geschichte von August Loesch, undated (probably 1937/38). Lösch estate, box IV

[10] v. Beckerath: Bericht über die Gemeinschaftsarbeiten zur Frage der neuesten Handelspolitik in ihren Beziehungen zum Wirtschaftssystem und in ihrer Bedeutung für die gegenwärtige Weltwirtschaftskrise, 19 December 1932. Rockefeller Archive Center (RAC), RF, RG 1.1, S. 717.S, b. 20, f. 188

him to travel through the USA from late November 1934 to early December 1935[11]. The purpose was to connect with America's leading economists and to study the "[i]nfluence of political frontiers upon the territorial division of labor"[12], thus initiating his next research project. This would result in his most important work: the economics of location (1940b).

Therefore, it has to be concluded that until early 1936, Lösch's career and his scientific achievements continued to progress without any negative impact from the Nazis' seizure of power. Being financially independent helped, but it was not the sole factor. He also largely kept his head down and did not join those who spoke out against the demolition of democracy and human rights and those who openly opposed the discriminations and killings for political and racial reasons which were initiated in March and April 1933. There seems to have been one exception, though. Lösch himself later recalled in a letter written in May 1945 to the emigrant Hans Singer how he himself had pushed for the conviction of a person guilty of antisemitic smearings twelve years ago, despite the perpetrator having belonged to the SS[13]. Lösch apparently had spoken out on behalf of the Jew Singer in a public meeting of the student body of his faculty, arguing that "their [the Jews'] fathers had fought for Germany [in the First World War] exactly like our fathers did"[14].

Lösch's attitude towards the events of 1933 was ambivalent. Surviving letters and contemporary entries in his diary bespeak his strong rejection of antisemitism and of restrictions of academic and religious freedoms, personal rights, and the anti-scientific rhetoric of the Nazis (Riegger 1971). However, he clearly wrestled with his various partial identities. On the one hand, he was a devout Christian and a "Southern German"[15], which meant that he belonged to a liberal tradition opposed to militaristic northern Prussianism. On the other hand, he could not escape the allure of re-emerging German greatness and the propagated feeling of national unity which he had longed for since his childhood. In a letter to Schumpeter (Harvard University) Lösch wrote in June 1933: "Quite a few of my old dreams are now fulfilled"[16]. By this he meant "national community, order, pride!"[17] The term "national community" (*Volksgemeinschaft*) is key, as it contained the notion of racial (Aryan) cohesion, repudiated the innate clash of interests in industrializing modern societies, and functioned as a bulwark against (supposedly Bolshevik) class struggles (Bajohr, Wildt 2009), which Lösch detested.

In another letter to Schumpeter in September 1933, Lösch wrote: "I can feel the deeper meaning in what is now emerging [in Germany]; it is thrilling to see hope returning to the eyes of so many; and there is even a breath of fresh air at the universities. [...] I wrestle with a calm and clear stance, because I do not only see the dark side, but the bright side as well"[18]. Lösch saw a "greater good" in national socialism and hoped that "negative plebeian side effects"[19] such as the dismissals of antifascists and people of "non-Aryan descent" from public service and the burning of books would pass. The surviving diary entries and his letters do not give evidence of him acknowledging the extent of the first wave of killings and the massive street violence all across Germany in Spring 1933.

Simultaneously to his partial appraisal of Nazism, Lösch considered himself to be among its victims. This is certainly true to some degree, since he decided not to join any NS organizations and thus was not able to fully achieve his dreams of becoming a profes-

[11] Lösch "is looked upon by the German Committee as the ablest of this year's appointees." RAC, RF, fellowship recorder cards, RG 10.2, Disciple 5: Humanities Fellows, Germany, August Lösch

[12] Ibid.

[13] Lösch to Hans Singer, 1 May 1945. Stadtarchiv Heidenheim, estate of Lösch, box XIII. Lösch depicted the story slightly differently in a diary entry from July 1933. See the Online Lösch Archive compiled by Dr. David Bieri: 385-386 (https://www.august-loesch.org, last accessed 30 September 2022)

[14] Lösch to Hans Singer, 1 May 1945. Lösch estate, box XIII. These claims were later supported by Wolfgang F. Stolper, although details remain contradictory. Stolper: Begegnung mit August Lösch. In Riegger (1971, p. 56f)

[15] Lösch to Joseph Schumpeter. Bonn, 28 September 1933. Online Lösch Archive: 55

[16] Lösch to Schumpeter, 8 June 1933. Lösch estate, box XIII

[17] Lösch: diary entry July 1933. Online Lösch Archive: 388

[18] Lösch to Schumpeter. Bonn, 28 September 1933. Online Lösch-Archive: 55

[19] Lösch to Irmgard, 8 June 1933. See the collection "August Lösch: Briefe & andere Korrespondenz" compiled by Dr. David Bieri: 57 (https://www.august-loesch.org, last accessed 30 September 2022)

sor. However, his self-perception of suffering a "purgatory"[20] seems exaggerated. This self-victimization served a purpose though. To solitarily endure suffering for a greater good – the greatness of his fatherland, "for that Germany which will come thereafter [after the "Third Reich"], if God wishes"[21] – in a way provided a solution for Lösch's life long search for a purpose in life. This in turn allowed him to remain impassionate towards the suffering of those who have to be regarded as the real victims of national socialism, those whose livelihoods were destroyed, who were forced into exile, or those hundreds of thousands of Germans and millions of other Europeans who were killed for political and racist reasons.

In his diary in 1933 and later in retrospect in May 1945, Lösch claimed that he had abruptly and completely abandoned his academic career when the Nazis seized power. Yet, that is not quite the case. In fact, he decided to submit his second book as a *Habilitation* at the University of Bonn, which elevated him to "Dr. habil." in 1936. Nevertheless, Lösch did not automatically acquire the license to teach (*Venia Legendi*). To become a professor or at least a lecturer, he would have had to visit an ideological academy, join at least one or two lesser national socialist organizations, and put some ideological phrases in his publications. Lösch decided not to follow this easy conformist path[22]. Still, it has to be noted that his *Habilitation* later enabled him to progress from a university assistant to leader of a research group in 1940, thus opening up a career at a research institute albeit not at a university.

After an interim stay in Bonn from December 1935 to November 1936 which the Rockefeller Foundation had mandated, Lösch was given the means for a second voyage through the USA. Again, he collected data for his research on spatial economics and visited scholars in Harvard, Chicago, Washington D.C., and elsewhere. Lösch was particularly interested in studying the American Midwest, as "it is hard to find such a case study in Germany, where regions are smaller, everything is determined by long histories, and economic factors cannot exert their influence as cleanly and simply"[23]. There is no indicator that Lösch reflected on the fact that this supposedly blank slate on which American capitalism was able to operate had been created by genocides of the indigenous peoples. He also does not seem to have recognized the profound racism which the USA was built on. As a well-off white man, he naively celebrated American freedom and enterprise and looked down on "the negroes, sitting on swings in the middle of the day like children"[24].

Prior to both returns to Germany in December 1935 and in February 1938, Lösch had agreed secret codes with Schumpeter. They were to be used in case his passport was confiscated, he wanted to flee Germany, or he was imprisoned[25]. Feeling unsafe – although it is debatable whether he had reasons to – and not wanting to pursue a career at the nazified universities, the question arises why he returned twice at all. He had very much enjoyed (academic) life in the USA, and he had offers for jobs at renowned universities there and elsewhere[26]. His motives are unclear. Homesickness probably played a part. It could also be argued that he needed to support his family. His grandmother had died in debt in early 1938, his single mother was still alive, and he was engaged with a younger woman (Erika Marga Müller, 1914-2002) since May 1936. However, back in Germany he did not seek a lucrative position in the private sector but prioritized finishing his book on the economics of location, which he accomplished in the autumn of 1939 (Lösch 1940b). Meanwhile, Lösch remained impassive towards political events such as the increasing discriminations against "non-Aryans" and political nonconformists. Although he anticipated the outbreak of a large-scale war, he followed the call for a

[20] Lösch to Schumpeter, October 1933. Riegger 1971: 84

[21] Lösch: diary entry, April 1933. Riegger (1971, p. 78, emphasis by Lösch)

[22] However, Lösch volunteered for becoming a group leader in the paramilitary sports (Wehrsport). Lösch to Schumpeter, 8 June 1933. Lösch estate, box XIII

[23] Lösch to Eucken, 21 June 1935. Online Lösch Archive: 87

[24] Lösch: diary entry, October 1937. Riegger 1971: 97–98

[25] Lösch to Schumpeter, undated [late 1935] and 17 February 1938. Online Lösch Archive: 122, 198–199

[26] Lösch also discussed becoming an adviser to the Venezuelan government. Lösch to Joseph Schumpeter, 30 April 1937, and June 1938. Online Lösch Archive: 167–169, 203

two-month-long military training in the summer of 1938[27]. Thus, as a man in his early 30s, he sleepwalked into a dilemma which then manifested itself in September 1939, when Germany invaded Poland. Apart from emigrating, an option which was still open to him, he could either face the increasingly likely risk of getting called up to military service or find a safe job, one which was deemed relevant for the German war effort. He chose the latter.

4 Leader of a Research Group during World War II

On 15th January 1940, Lösch moved to Kiel, a port city in the north of Germany where he had briefly studied in 1929/30. There, he was employed by the Kiel Institute for the World Economy, first as a research assistant and from April 1940 onwards as leader of a research group consisting of five to six scientists and four to five non-academic members[28]. Lösch's work during the second World War can be divided into three parts: research on spatial economics, other independent research, and commissioned work. The latter was by far the most time consuming. Until 1944, the "Lösch Research Group" finished roughly 30 reports of various sizes. More than half were commissioned by the Wehrmacht's Bureau for Economic Warfare, five by the Foreign Office, some by national agencies for spatial economic research, and a few by the Reich's Ministry for Armament. Lösch occupied a leadership position, represented the institute in dealings with its customers and was hard-working, receiving more overtime allowances than any of his roughly 140 colleagues[29].

Lösch was well aware of the reasons why the different state agencies commissioned these reports. Only some can be highlighted here. The Wehrmacht for example wanted information on how to conduct its wars of aggression and annihilation most efficiently. While other research groups at the Kiel Institute were responsible for supplying data on the economic and social situations of current and future enemies, Lösch's group did the more demanding research. In the beginning, it analyzed international commercial contracts of Great Britain and France, the family support of draftees in both countries, English food supply, and many other topics. In July 1940, Lösch answered the important question "Can England be starved out?" with a resolute no[30]. One could interpret this as an attempt to prevent another period of attritional economic warfare such as both countries had experienced in the First World War. However, given the context of Lösch's and the institute's other work, it is more likely that he felt an obligation to deliver applied science of the highest quality and that he did not want Germany to lose the war. In his first report in March 1940, Lösch had argued that it was impossible for the German navy to disrupt British arms manufacturing by cutting it off from imports. This seems to have been the only report in which the institute's director, Andreas Predöhl, intervened for political reasons. A paragraph was added, claiming a crucial lack of American supplies for Britain. In all later reports, Lösch was allowed to speak truth to power, since the Wehrmacht valued honest assessments and analyses of the highest scientific standards.

In early 1941, Lösch consulted with the Foreign Office (*Auswärtiges Amt*) and negotiated two orders. The first consisted of brief analyses of weaknesses in American shipbuilding, aircraft construction, and machine manufacturing. This information was intended to be used for propaganda purposes[31]. The second assignment had a similar purpose. Lösch's group was to analyze British trade politics and to highlight everything that was deemed "unpleasant" for its trading partners[32]. The resulting report contained a narrative of how Britain had supposedly betrayed its free trade ideals, had already

[27] "1933 I sensed: Hitler means war. 1935 it became clear to me which side the mighty USA would join." Lösch to Fehling, December 1940. Riegger 1971: 103. See also Lösch's diary entry 24 September 1938.

[28] Predöhl: An alle Dienststellen!, 13 January and 24 December 1940. Archive of the Zentralbibliothek für Wirtschaftswissenschaften in Kiel (ZBW), 470: 102, 147

[29] Predöhl to Reichserziehungsministerium, 20 November 1943. Bundesarchiv Berlin, R 4901/14814: 315. Lösch considered himself to have been the most industrious employee at the Kiel Institute. Cf diary entry in January 1945 Riegger (1971, p. 115).

[30] Lösch: Die englische Nahrungsmittelversorgung, July 1940. Archive of the ZBW, E 118: 37–38

[31] Lösch estate, box XIV and folder "Verschiedenes"

[32] Wilmanns (Auswärtiges Amt) to Predöhl, 7 January 1941. Lösch estate, box XIV

lost its status as a world power, and was now fighting for a lost cause (Lösch 1941, p. 338-340). The Foreign Office considered the report to be "excellent"[33], agreed to its publication in the institute's journal *Weltwirtschaftliches Archiv* in September 1941, and requested 500 copies which it distributed abroad.

This publication has to be seen in the context of two earlier articles in spring of 1940, in which Lösch had hailed German successes in disrupting British trade and in which he had labelled the combined wars of aggression against Denmark and Norway as "bold German endeavors" (Lösch 1940a,c). Compared to other German propaganda, this seems rather mild. However, that propaganda was a collaborative effort. It was agreed with the Foreign Office that Lösch's job should not be to ignite hatred against the British, but specifically to help convince conservative Germans and members of the elites of other countries that Germany was definitely going to win the war against Britain and that the latter did not have anything to offer economically to its (potential) allies[34]. Lösch seems to have had no trouble either with the wording of these articles or with their purpose. In 1943 he reassured himself by writing in his diary: "I have never published anything that I did not find to be true after careful analysis"[35].

Particularly noteworthy among the later research projects is a four-part report on the human resources of the USA. In 1943, the Wehrmacht and a newly established Planning Office within the Ministry for Armament wanted to assess the military potential of Germany's main enemies in order to evaluate whether the war could still be won (Fremdling 2016, p. 271-283). Lösch's research group concluded that American industrial productivity alone was more than twice as high as Germany's. It can be assumed that Lösch hoped that by highlighting the hopelessness of the situation he might help to convince the German leadership to seek peace, a task which the director of said Planning Office also tried to achieve (Müller 1999, p. 124). Yet, this was quite naïve, considering the decision-making processes within the Nazi regime. All Lösch achieved was to give valuable information to the middle management of the German war machine.

5 Spatial Research and Genocides

Highly engaged in consultancy activities for the military and various ministries, Lösch often complained that he did not find enough time to conduct independent research. Among the topics he managed to tackle was a spatial theory of currency which was published posthumously (Lösch 1949, cf. Bieri 2020). He also wanted to build on his opus magnum and was keen to publish a second edition of his economics of location (Lösch 1944). On his own accord, he contacted high ranking officials such as the above mentioned Muhs, head of the RfR. It was agreed that Lösch should revise his book "with a practical orientation" and discuss "applications in regional planning"[36]. The RfR was one of many state agencies within the "organized chaos" of the Nazi regime fighting for influence with regards to the spatial planning of the Reich and especially of the newly conquered territories in eastern Europe (Flachowsky 2010). Lösch's task was to supply a theoretical framework for ultra-rational approaches. Particularly in 1942 and 1943, he held close contact with Muhs, a number of his division managers within the RfR, and other scholars such as Walter Christaller whom he cited more frequently than anybody else and who impressed him to the upmost degree (Lösch 1944, Todt 2014). They in turn were managing the process of combining such scientific theories with Nazi ideology in order to put both to practical use (Trezib 2014).

Lösch was well informed about the specific plans on what was to be done in the conquered areas. For example, he praised a design for the area around the Polish city of Kutno, which was published by Konrad Meyer's Planning Office of Heinrich Himmler's Reich Commissariat for the Consolidation of German Nationhood (Lösch 1944, p. 93). Himmler's and Meyer's vision, the "general plan for the east", presupposed genocides on nations such as Poles and Russians and on religious groups such as Jews (Werner 2022,

[33] Wilmanns (Auswärtiges Amt) to Predöhl, 7 May 1941. Lösch estate, folder "Verschiedenes"
[34] Wilmanns (Auswärtiges Amt) to Predöhl, 7 January 1941. Lösch estate, box XIV
[35] Lösch: diary entry in 1943. Riegger (1971, p. 110)
[36] Köster to Lösch, 3 July 1942. Online Lösch Archive: 256

p. 147-149). This genocidal vision is clearly visible in the detailed projects. Lösch knew that the Nazi regime had almost no interest in his ultra-rational concepts with regards to Germany or Northern and Western Europe with their "Aryan" populations, but only in its dealings with the supposedly racially inferior people in the east who were to be mass murdered. Tellingly, the head of an economics research department in Cracow wrote in a review of Lösch's book that it was of high value, because the conquered areas in the east should be considered "almost a tabula rasa", a blank slate (Meinhold 1942).

Additionally, one has to consider those who organized and executed the evictions, enslavements, and killings. Their motivations varied, but it is without a doubt that a significant number of those perpetrators were not only driven by hatred or a destructive rage, but also wanted to make a constructive and positive contribution to what Konrad Meyer called "the Germanization of new territories, to organize, shape, and develop new spaces and landscapes as a future homeland of Germans" (Meyer 1941). The Nazi regime lacked resources and the time to implement most of their plans which would have involved the killing of even more tens of millions of people. However, the mere existence of concepts of such an ultra-rational economic prosperity and of a "positive" and scientifically substantiated vision of a post-genocidal future contributed to the high level of self-motivation on which the complex and collaborative governmental killing apparatus depended.

In assessing Lösch's behavior, one question is key: How much did he know about the atrocities committed in connection with spatial planning? It has to be assumed that he knew a lot, since the Kiel Institute functioned as an information hub, even being supplied with newspapers from neutral and hostile countries by the Gestapo as well as receiving secret studies such as the one mentioned above by Meyer (Take 2019, p. 365–370). Lösch must have grasped that the political, social, religious, cultural, and economic institutions of tens of millions of people were to be destroyed in order to replace them with new Germanic institutions. He might even have learned the neologism "genocide" which Raphaël Lemkin had coined in the USA (Lemkin 1944), as Lösch's latest task as head of a newly formed America-department at the Kiel Institute in 1944/45 involved reading US newspapers. Those newspapers had also reported on the existence of gas chambers and of the killings of millions of Jews and other "non-Aryan" people[37].

6 Death and Afterlife

Lösch enjoyed the respect he received in Nazi Germany for his scientific achievements, not only from the scientific community, but also from government officials in the field of spatial planning[38]. However, he never attained his life's ambition of becoming a full university professor since he refused to give the necessary open endorsements of the totalitarian regime. From his point of view, this step – and not the supposedly a-political research – would have meant leaving the realm of scientific objectivity and betraying his political beliefs. Over the years, he grew enormously discontent with his situation at Kiel, feeling unfree and not allowed to pursue the research projects he would have liked to. Still, he stayed put and carried out all research projects the government demanded of him, probably in large part because he was relatively secure at Kiel, whereas most other men his age had to serve in the army. Regarding his academic aspirations, he waited for things to change. Accordingly, when Germany finally lost the war, Lösch felt truly liberated. He celebrated the end of the Nazi era and immediately started to search for funding and academic partners in order to initiate the many projects he had mapped out in the years prior. Hence, his contemporaries considered it particularly tragic when he suddenly died of scarlet fever on 30 May 1945, aged 38. He left behind his wife Marga, whom he had married after a four-year-long engagement in March 1940, immediately after securing the position at Kiel, and a daughter born in June 1944.

Immediately after his death, a legend was created which continues to have an effect

[37] Poles Ask U.S. to Seize Nazis. In: New York Times, 10 July 1942. Allies Describe Outrages on Jews. In: New York Times, 20 December 1942

[38] See his diary, letters and also his collection of 50 pages worth of positive reviews on the first edition of his first volume of *The Economics of Location*. Lösch estate, box XV

until today[39]. Lösch was considered to have been a "steadfast opponent of every tyranny and oppression" (Zottmann 1971, p. 32), an "incautiously outspoken anti-Nazi" (Funck 2007, p. 408) "who was unwilling to agree to only the slightest compromise with the regime" (Todt 2014, p. 204). This legend had three roots: First, there were Lösch's diary entries and the letters he sent to his German and American friends in May 1945, in which he described himself as an uncompromising opponent and a martyr. Second were the American economists, many of them German emigrants, who believed the stories that Lösch himself and later his widow had told them about his conduct during World War II. They considered this supposed behavior to correspond to the character they had got to know in the 1930s. Third were Lösch's colleagues at Kiel and in the German economics community at large who were very keen for a resistance fighter to have been amongst them. Telling the story of how one of their leading figures stood in fierce opposition to the regime allowed them to frame their own cooperation with civilian and governmental organizations and their participation in questionable research programs in a much brighter light. With regards to spatial economics, this applied particularly to those who belonged to Lösch's and Christaller's geographic and technocratic school of thought and not to the organic and *völkisch* (ethnic) school (Gutberger 1996) which had utilized a much higher degree of pseudo-scientific rhetoric and had more political activists among their ranks.

Today's perspective on Lösch's biography depends to a large degree on what time period one focuses on and how much attention one pays to the contexts of his research. On the one hand, he experienced enormous political, social, and economic turbulences during the formative years of his life. The son of a single mother simultaneously developed a desire for independence but also for belonging. His religiousness seems to have morphed into an entrenched technocratic *Weltanschauung* (worldview) which functioned as a secular religion. In the 1930s, Lösch rejected vital aspects of national socialism, e.g. the abolition of democratic institutions, of the rule of law, of free speech, and its antisemitism, and expansionism. However, the "Third Reich" also provided ample support for spatial research and enabled it to grow and become a scientific discipline (Münk 1993). Until 1939, the conditions were such that Lösch was largely able to avoid compromising himself. His scientific excellence secured him American funds, he was willing to accept a rather precarious financial position for a significant period of time, and he did not continue to pursue his dream of becoming a university professor. On the other hand, Lösch's decision to return and stay in Germany and to seek a job at the Kiel Institute for the World Economy meant that he had to contribute to the German war effort with his scientific expertise. He told his friends and wrote in his diary that he did so reluctantly. But if one looks at his output, he has to be regarded as the most eager and able economist of the institute. Moreover, Lösch decided of his own accord to spread his economic theories and to work together with Nazi spatial planners. He was attracted to the ample opportunities that the genocides in Central and Eastern Europe opened up and made significant steps to engage in the ultra-rational economic rebuilding which was to follow in accordance with brutal Germanization.

Lösch surely knew less about the crimes committed by Nazi Germany than we now do. But given his frequent interactions with many civilian and military government officials in Berlin and elsewhere and as he was himself working at an information hub, Lösch certainly knew more about current events in Germany and in the occupied territories than most Germans at the time. Crucially, alternative ways of behavior were open to him. At the very least, he could have contributed less to the German war machine and to the inhuman spatial planning – without running any risk of suffering negative consequences. By reflecting on Lösch's complex character and biography, we can learn much about what makes dictatorships or authoritarian and even totalitarian regimes attractive for scientists and about how easy it is to deceive oneself on matters of moral integrity.

[39] Wilhelm Gülich: Grabansprache (funeral speech), 2 June 1945. Lösch estate, box XIII. Lösch was supposedly "opposed till the end to the Nazi party." Message from Marga Lösch to the Rockefeller Foundation, undated (probably 1945 or soon after). RAC RF, fellowship recorder cards, RG 10.2, Disciple 5: Humanities Fellows, Germany, August Lösch

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REGION
The Journal of ERSA
Powered by WU

Volume 10, Number 3, 2023, 31–44
DOI: 10.18335/region.v10i3.455
journal homepage: region.ersa.org
ISSN: 2409-5370

COVID-19 Morbidity and Mortality Factors: An International Comparison

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Received: 25 August 2022/Accepted: 14 April 2023

Abstract. This study investigates the scope of morbidity and mortality from SARS-COV2 virus at a country-wide level based on three central risk factors: population density, median age, and per capita hospital beds. Given that the relative weight following a change in equal units of measurement has not been examined on a country-wide level, we use empirical models with standardized coefficients. Information for this study was obtained from the World Health Organization (WHO) data base, which encompasses 162 countries, and spans five continents from January 22, 2020, to January 21, 2022. Referring to projected COVID-19 infection and mortality rates, and following a one standard deviation increase, the influence of these independent variables may be ranked as follows: Infection – 1) the median age of the country's population; 2) number of hospital beds per thousand persons; 3) population density. Mortality – 1) the median age of the country's population; 2) population density; 3) number of hospital beds per thousand persons. Findings may be of assistance to public policy planners. Given the dominance of the age variable in the context of the COVID-19 pandemic, on the one hand, the allocation of resources for future pandemics should grow in countries with older population profiles (European countries). On the other hand, the emphasis in countries with younger populations (African countries) should be on better medical infrastructure in sparser regions.

Key words: COVID-19, Morbidity, Mortality, Population density, Median age Per-capita hospital beds

1 Introduction

The COVID-19 pandemic is an interesting subject matter for investigation in an effort to control the spread of the pandemic and to address future world pandemics. Three central risk factors associated with the spread of the COVID-19 pandemic and mortality from the SARS-COV2 virus are densely populated regions (an important issue in regional studies), older population distributions, and low per capita levels of beds in hospitals. The literature demonstrates the importance of these variables, where some findings are surprising. One would expect, for instance, that densely populated regions would encourage the spread of the COVID-19 pandemics. Yet, referring to denser vs. sparser regions, and based on 1,165 US metropolitan areas, after controlling for metropolitan size and other confounding variables, Hamidi et al. (2020) found significantly lower COVID-19 infection rates and lower death rates with higher county density. The authors explained this outcome on the grounds of two opposing forces, in which one overpowers the other. On the one hand, denser regions facilitate human interactions. This, in turn, *raises* anticipated infection rates and the scope of morbidity. On the other hand, the agglomeration forces associated with denser cities allow for, inter alia, better health infrastructure, associated medical literacy, and shorter response times in emergency cases.

Referring to the median age of a country's population (the second explanatory variable in our empirical model), Bauer et al. (2021) investigated the impact of the age variable in Europe and USA. The authors found stronger age dependency for COVID-19 compared to all-cause mortality. Pijls et al. (2021) provided meta-analysis of 59 studies comprising 36,470 patients. Findings showed that men and patients aged 70 and above have a higher risk for COVID-19 infection, severe disease, intensive care units (ICU) admission and death. Zhang et al. (2022) explored the impact of the age variable on COVID-19 morbidity and mortality in Wuhan City, China and found disproportionate age effect in clinical manifestations, risk factors, complications, and COVID-19 outcomes. Finally, referring to 48 European countries, Wang et al. (2020) suggest positive association between COVID-19 mortality and ageing population, median age, and life expectancy at birth. Lulbadda et al. (2021) suggest that the temperature, population size, and median age are positively associated with the spreading rate of COVID-19. There is no evidence supporting that case counts of COVID-19 could decline in countries with better health care facilities.

Referring to the number of hospital beds per thousand persons (the third explanatory variable in our empirical model), this variable provides a proxy for income level, vaccination rates and medical literacy. Brant et al., 2021 investigated the impact of the COVID-19 pandemic on all-causes hospitalization in Brazil. During the studied period, there were 54,722 hospitalizations by non-COVID-19 natural causes, representing a 28% decline compared to the previous five years. Presanis et al. (2021) examined the risk factors associated with hospital burden of COVID-19 and executed an observational cohort study, using data on all PCR-confirmed cases of COVID-19 in Regione Lombardia, Italy, during the first wave of infection from February-June 2020. The authors found decreased risks of severe outcomes such as Intensive Care Units (ICU) admission and mortality within a month of admission. This demonstrates a learning effect of the Italian health system.[1]

Following Arbel et al. (2020, 2021), the objective of the current study is to investigate the scope of morbidity and mortality from SARS-COV2 virus at a country-wide level based on three important risk factors: population density, median age, and the per capita hospital beds. The use of country-level rather than city-level datasets during the COVID-19 pandemic may be justified based on two important considerations: 1) COVID-19 regulation is typically formulated at the national level. 2) Compared to international migration, intra-national mobility among cities is much simpler. The approach employed in this study is the standard parametric procedure (OLS) where the incorporation of each explanatory variable should be justified. Another possible approach – machine learning – is implemented in Manousiadis, Gaki (2023). The authors investigated the resilience of US regions in terms of economic recovery from the pandemic.

The inherent problem associated with standard empirical regression (OLS) model is the different units of measurement of the independent variables. Consequently, in addition to the standard regression model, we estimate a model where all the variables are standardized to the normal distribution function (the beta coefficient model). This permits estimation in terms of one standard deviation of each of the independent variable, and thus the magnitude of effect on the dependent variable. The coefficients of this empirical model measure the change in the standard deviation of the dependent variable (either the scope or morbidity or mortality per 1 million persons) following a one standard deviation change of each independent variable.

Results show negative Pearson correlations among population densities (in line with Hamidi et al. 2020 – at a global level); number of hospital beds per thousand persons and

[1] See also Castagna et al. (2022), Fakih et al. (2022), and Hobohm et al. (2022).

the scope of morbidity and mortality (as anticipated – higher level of health investment yields better outcomes at a global level); and positive Pearson correlations between the median age of the country and the scope of morbidity and mortality (as anticipated and in line with the existing literature at a global level).

Referring to projected COVID-19 infection (mortality) rates, and following a one standard deviation increase, these independent variables may be ranked as follows: infection – 1) the median age of the country's population; 2) number of hospital beds per thousand persons; 3) population density, and mortality – 1) the median age of the country's population; 2) population density; 3) number of hospital beds per thousand persons).

Public policy repercussions of the study may be summarized as follows. Given the dominance of the age variable in the context of the COVID-19 pandemic, on the one hand, the allocation of resources for future pandemics should grow in countries with older population profiles (European countries). On the other hand, the emphasis in countries with younger populations (African countries) should be on better medical infrastructure in sparser regions. The latter finding is supported by Souris, Gonzalez (2020). The authors mostly found low hospitalization with high case-fatality rates in French districts with low population densities and attributed this phenomenon to the limitations of access to local healthcare services.

Our study has three relative advantages, which improve the limitations of previous studies. First, the study is at a global level and encompasses all the countries in the world. The conventional approach is to focus on one country only. Second, in previous studies standardized beta coefficients were not used. Consequently, each explanatory variable had different units of measurement and the magnitude of explanatory power could not be compared. Third, the results show that when the population density increases, the infection actually decreases. This finding is unique at the global level (existing at the municipal level in Hamidi et al. 2020 and partially in Arbel et al. 2022).

The remainder of this article is organized as follows. Section 2 gives the literature review. Section 3 describes the methodology and Section 4 provides the results. Finally, Section 5 concludes and summarizes.

2 Literature Review

COVID-19 is a global pandemic with multiple risk factors. The maps in Figure 1 and Figure 2 demonstrate the scope of morbidity and mortality on April 5, 2023. Globally, as of 10:14am CEST, April 5, 2023, there have been 762,201,169 confirmed cases of COVID-19, including 6,889,743 deaths, reported to WHO, a 0.09645% (less than 0.1%) of the world's population of 7.143 billion persons. Compared to other documented pandemics, such as, the 1918-1920 Spanish Influenza, the death toll is much smaller. According to Barro et al. (2020) the death toll of the Spanish flu is 2.1% of the world's population implying 150 million deaths when applied to current population. The decreased death toll may be attributed to better health infrastructure and technology. As of April 1, 2023, a total of 13,321,840,096 vaccine doses have been globally administered.

There is a significant correlation between COVID-19 and healthcare infrastructure and public health policies. Figure 3 demonstrates the negative correlation between the COVID-19 death rate and the number of hospital beds in the UK and the OECD countries (Figure 5). The authors conclude that: "Countries with higher capacity had fewer COVID-19 deaths, particularly for beds and surgical specialists." ESPON (2022, page 49).

The severity of the pandemic in different regions of the world has been influenced by the quality and capacity of healthcare infrastructure, as well as the effectiveness of public health policies implemented to control the spread of the virus.

In regions with strong healthcare systems and sufficient resources, such as advanced medical equipment, adequate numbers of healthcare workers, and available hospital beds, the impact of COVID-19 has generally been less severe than in regions with weaker healthcare infrastructure. Additionally, public health policies, such as lockdowns, mask mandates, and social distancing measures, have been effective in reducing the spread of

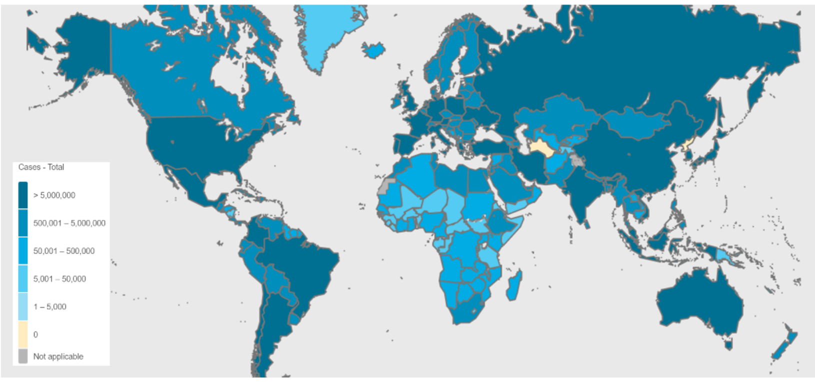


Figure 1: World Health Organization: World Map of COVID-19 Cases

Source: World Health Organization Dashboard. Available at: https://covid19.who.int/ (Last accessed on April 5, 2023).
Note: Globally, as of 10:14am CEST, 5 April 2023, there have been 762,201,169 confirmed cases of COVID-19, including 6,889,743 deaths, reported to WHO. As of 1 April 2023, a total of 13,321,840,096 vaccine doses have been administered.

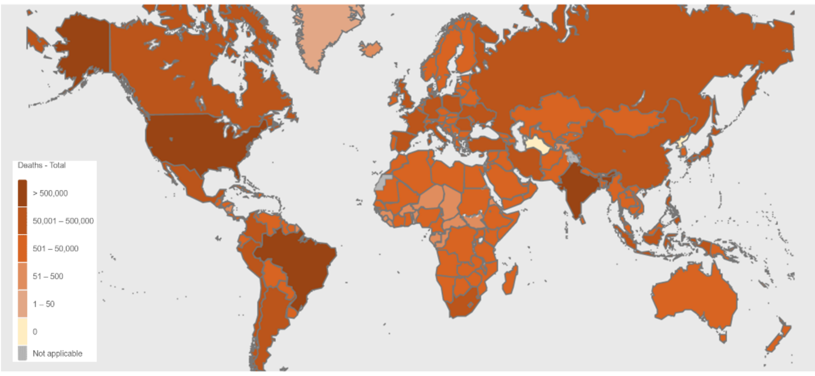


Figure 2: World Health Organization: World Map of COVID-19 Deaths

Source: World Health Organization Dashboard. Available at: https://covid19.who.int/ (Last accessed on April 5, 2023).
Note: Globally, as of 10:14am CEST, 5 April 2023, there have been 762,201,169 confirmed cases of COVID-19, including 6,889,743 deaths, reported to WHO. As of 1 April 2023, a total of 13,321,840,096 vaccine doses have been administered.

the virus in some areas.

On the other hand, in regions with weaker healthcare infrastructure, such as developing countries with limited resources, the impact of COVID-19 has been more severe due to a lack of medical equipment, healthcare workers, and hospital beds. Moreover, public health policies in these regions have been less effective due to various reasons such as lack of implementation or adherence by the population.

Overall, the correlation between COVID-19 and healthcare infrastructure and public health policies highlights the importance of investing in robust healthcare infrastructure and implementing effective public health policies to combat pandemics and protect public health.

There are several countries around the world where the impact of COVID-19 on morbidity and mortality has been closely linked to the strength of their healthcare infrastructure. For instance, the US has experienced one of the highest numbers of COVID-19 cases and deaths in the world. The quality of healthcare infrastructure has played a significant role in determining the impact of the pandemic in different regions of the country. Areas with more advanced healthcare systems, such as New York City, were better equipped to handle the surge in COVID-19 cases, while areas with weaker healthcare systems, such as rural areas, were more vulnerable to the virus. Figure 4 demonstrates that the United States has the highest global number of COVID-19 hospitalized patients – above 120,000

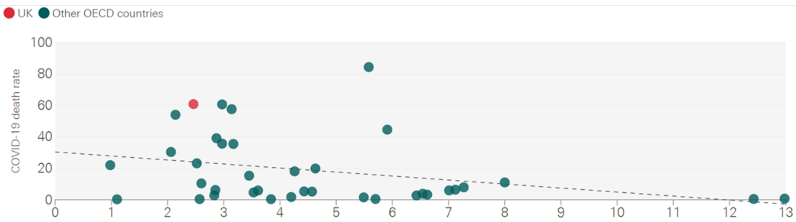


Figure 3: Hospital capacity compared to COVID-19 death rate, deaths as of 30 June 2020

Source: Rocks, Idriss (2020)

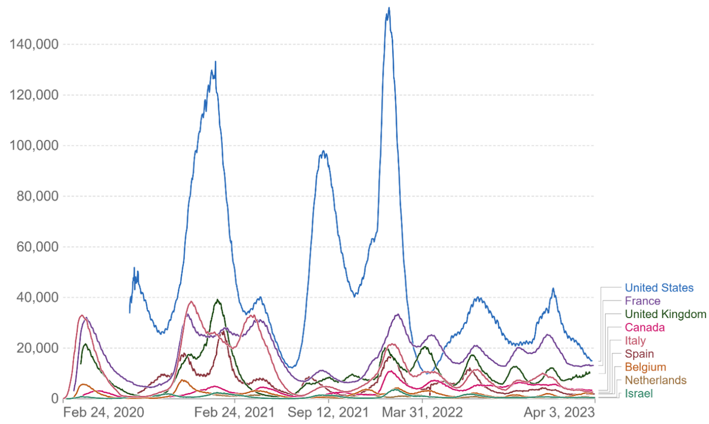


Figure 4: Number of COVID-19 Patients in Hospitals

Source: Our World in Data (2023)

persons – between December 28, 2021 - January 18, 2021 and above 140,000 persons between January 10, 2022 – January 26, 2022 (Our World in Data 2023). Referring to July 2020–July 2021, French et al. (2021) predicted that 100% full intensive care units bed capacity, would result in 80,000 excess deaths two weeks later. Janke et al. (2021) suggest that US geographic areas with fewer intensive care unit beds, nurses, and general medicine/surgical beds per COVID-19 case were statistically significantly associated with an increased incidence rate of death in April 2020. Italy was one of the first countries to experience a major outbreak of COVID-19 outside of China. The country's healthcare system was quickly overwhelmed, leading to high mortality rates. The Italian government was forced to implement strict lockdowns to slow the spread of the virus. Ferrara et al. (2022) suggest that the Italian regions with a lower number of general practitioners showed a higher number of deaths. India has also experienced a devastating impact from COVID-19, with a high number of cases and deaths. The country's healthcare infrastructure has been stretched to its limits, with shortages of medical oxygen, hospital beds, and other critical resources. The government has been working to increase capacity and resources, but the situation remains challenging. Brazil has also struggled with a high number of COVID-19 cases and deaths. The country's healthcare system has been strained due to a lack of resources and funding, leading to shortages of critical medical supplies and equipment. In France, the COVID-19 pandemic unevenly affected different regions of the country. Specifically, three regions in France were affected most, representing 75% of deaths due to the COVID-19 pandemic during the first wave. During the second wave, the highest death rates was recorded in previously low-impact regions. According to model 1 in Tchicaya et al. (2021), in the first wave, there was a statistically significant negative association between the number of resuscitation beds and the COVID-19 mortality rate. Yet this decrease comes at the expense of patients suffering from other pathologies for which care and surgical procedures have been postponed.

Overall, these examples demonstrate the critical importance of healthcare infrastruc-

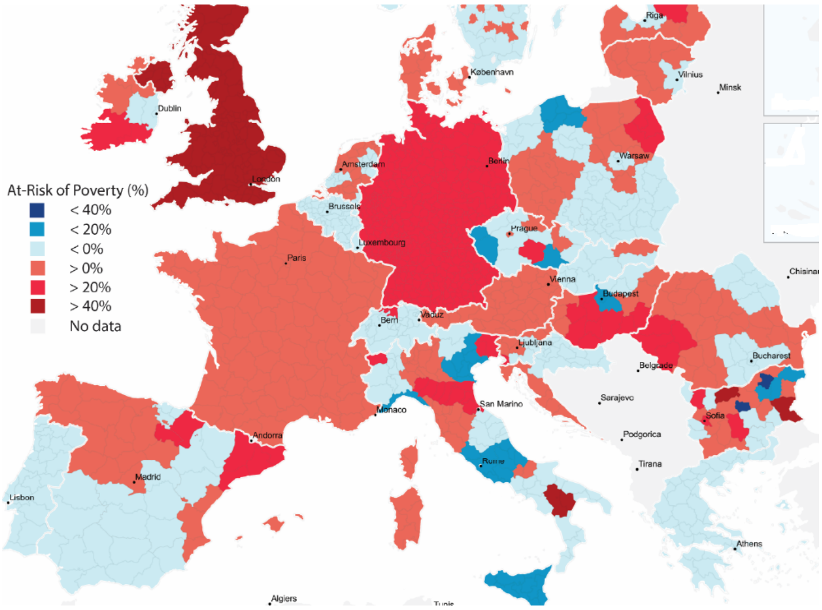


Figure 5: COVID-19 social consequences: Growth rates of At Risk of Poverty (%) from before (2019) and during the pandemic (2020) in European Countries

Source: ESPON (2022, page 49)

ture in responding to a pandemic like COVID-19. Countries with strong healthcare systems and sufficient resources have generally been better equipped to handle the pandemic and protect public health.

Another aspect of the COVID-19 is the growth of at-risk poverty following the pandemic. Figure 5 reports this change in the European countries. Overall, the evolution of people's at risk of poverty across the EU regions decreased by 1.21% on average compared to the pre-COVID-19 period. The UK had the highest change of people living in households with income below the risk-of-poverty threshold (with a growth rate estimated at 85.4%), followed by Iceland (32.6%), Germany (25%) and Latvia (9.9%). In these countries, the COVID-19 pandemic has led to an increase in poverty. On the other hand, about half of the EU member states do not show particular differences compared with 2019.

This can be explained by the fact that, in many countries, regions have the administrative competence to manage social aspects. Some regions have thus put in place specific regional and local policies to help the poorest households cushion the crisis, notably through direct financial aid to maintain or increase their purchasing power.

3 Methodology

Derived from this motivation, and particularly from beneficial public policy tools, we would like to investigate the extent to which hospital capacities, proxied by the number of hospital beds, influence COVID-19 cases and mortality around the world. Given that health investment is the only controlled public policy tool to promote future pandemics, the influence of this variable might prove to be important.

Given that countries around the world differ in population size, the dependent variables in our empirical models (the number of COVID-19 cases and deaths) have to be standardized. This is done by calculating the Cases-Population and Deaths-population ratio. The outcomes are multiplied by a factor of 1 million, so that the dependent variable would become cases/deaths per 1 million persons in the population. Our control variables are *Population_density* (persons per square kilometers) and *Median_age* (Median age of the country in years).

Table 1: Definition of variables

Variable	Description
Total_cases_p.mill.	The ratio between COVID-19 cases and the population of the country multiplied by 1 million
Total_deaths_p.mill.	The ratio between COVID-19 deaths and the population of the country multiplied by 1 million
Population_density	Population density measured as persons per square kilometers
Median_age	Median age of the country in years
Hospital_beds_p.th.	The ratio between the number of beds and the population of the country multiplied by 1,000

Table 2: Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max	99% CI
A. Total Cases per 1 Million Persons						
Total_cases_p.mill.	109,813	25,371.9	39,671.99	0.001	347,457.3	[25,063.53, 25,680.28]
Population_density	109,813	204.4703	674.1418	1.98	7,915.73	[199.23, 209.71]
Median_age	109,813	31.43817	8.869181	15.1	48.2	[31.37, 31.51]
Hospital_beds_p.th.	109,813	2.959307	2.355282	0.1	13.05	[2.94, 2.98]
B. Total Deaths per 1 Million Persons						
Total_deaths_p.mill.	102,399	491.422	766.664	0.001	6,115.04	[485.25, 497.59]
Population_density	102,399	204.875	671.5761	1.98	7,915.73	[199.462, 210.281]
Median_age	102,399	31.6389	8.90458	15.1	48.2	[31.57, 31.71]
Hospital_beds_p.th.	102,399	2.97657	2.368613	0.1	13.05	[2.958, 2.996]

Note: The data refer to information regarding 162 countries provided by the World Health Organization (WHO), and spans from January 22, 2020, to January 21, 2022.

3.1 Description of the Data

Information for this study was obtained from the World Health Organization (WHO). The data base encompasses 162 countries,[2] and spans five continents from January 22, 2020, to January 21, 2022. This yields 109,813 (109,322) observations with availability of information on the total COVID-19 cases (deaths) per 1 million persons. Yet only these two variables vary across both time and space. The other variables vary across space (from one country to another), but not across time.

3.2 Descriptive Statistics

Table 2 reports the descriptive statistics of the variables, which are subsequently incorporated in the empirical model. The table is divided into two parts. The upper (lower) part includes the descriptive statistics of observations for which information on total COVID-19 cases (deaths) per 1 million persons is available. The sample mean of COVID-19 cases (deaths) is 25,371.90 (491.42) per million persons and the 99% confidence interval is [25,063.53, 25,680.28] ([485.25, 497.59]). One standard deviation increase (decrease) equals 39,671.99 additional (less) COVID-19 cases and 766.664 additional (less) COVID-19 deaths per 1 million persons. The maximum scope of morbidity (mortality) is obtained in Seychelles Islands, Africa (Peru, South America) with 347,457.30 cases (6,115.035 deaths) per 1 million persons.

3.3 The Empirical Model

Consider the following empirical models:

$$\begin{aligned} Total\_cases\_per\_million \quad &= \quad \alpha_1 + \alpha_2 Population\_density + \alpha_3 Median\_age + \\ & \quad\ \alpha_4 Hospital\_beds\_per\_thousand + \mu_1 \end{aligned} \tag{1}$$

[2] A full list of countries may be provided upon request from the corresponding author.

$$Total\_deaths\_per\_million = \beta_1 + \beta_2 Population\_density + \beta_3 Median\_age + \beta_4 Hospital\_beds\_per\_thousand + \mu_2 \quad (2)$$

Where the dependent variables are *Total_cases_per_million* and *Total_deaths_per_million*; the independent variables are: *Population_density*, *Median_age* and *Hospital_beds_per_thousand*. $\alpha_1 \ldots \alpha_4$ and $\beta_1 \ldots \beta_4$ are parameters, μ_1 and μ_2 are the random disturbance terms, which satisfy all the classical assumptions of the regression model.

The inherent problem associated with this empirical model is the different units of measurement of the independent variables.[3] To address this problem, we re-estimate the following model:

$$Z(Total\_cases\_per\_million) = \alpha_1^{'} + \alpha_2^{'} Z(Population\_density) + \alpha_3^{'} Z(Median\_age) + \alpha_4^{'} Z(Hospital\_beds\_per\_thousand) + \mu_3^{'} \quad (3)$$

$$Z(Total\_deaths\_per\_million) = \beta_1^{'} + \beta_2^{'} Z(Population\_density) + \beta_3^{'} Z(Median\_age) + \beta_4^{'} Z(Hospital\_beds\_per\_thousand) + \mu_4^{'} \quad (4)$$

$Z(X_i) = \frac{X_i - \bar{X}}{\sigma_X}$ where $\bar{X}$ is the average and σ_X is the standard deviation of X_i. While the constant terms $\alpha_1^{'}$, $\beta_1^{'}$ are the normalized sample means (which equal zero under this formulation of the model), the parameters $\alpha_2^{'}$, $\alpha_3^{'}$, $\alpha_4^{'}$ and $\beta_2^{'}$, $\beta_3^{'}$, $\beta_4^{'}$ reflect the respective change in the dependent variable in standard deviation terms following a one standard deviation increase in the independent variable.

Another version of this model is given by the following equations:

$$Total\_cases\_per\_million = \alpha_1^{''} + \alpha_2^{''} Z(Population\_density) + \alpha_3^{''} Z(Median\_age) + \alpha_4^{''} Z(Hospital\_beds\_per\_thousand) + \mu_3^{''} \quad (5)$$

$$Total\_deaths\_per\_million = \beta_1^{''} + \beta_2^{''} Z(Population\_density) + \beta_3^{''} Z(Median\_age) + \beta_4^{''} Z(Hospital\_beds\_per\_thousand) + \mu_4^{''} \quad (6)$$

Once again, the constant terms $\alpha_1^{''}$, $\beta_1^{''}$ are the sample means, but in their original units of measurement (number of cases or deaths per 1 million persons). The parameters $\alpha_2^{''}$, $\alpha_3^{''}$, $\alpha_4^{''}$ and $\beta_2^{''}$, $\beta_3^{''}$, $\beta_4^{''}$ reflect the respective change in the dependent variable in the original units of measurements (number of cases or deaths per 1 million persons) following a one standard deviation increase in the independent variable.

4 Results

Table 3 reports the regression outcomes based on equations (1) and (3), where the dependent variable is *Total_cases_p.mill.*. Table 4 gives the corresponding results for equations (2) and (4) with *Total_deaths_p.mill.* as dependent variable. Table 5 gives the estimation outcomes of equations (5) and (6). Interestingly, in all tables, projected scope of

[3] According to Kmenta (1997, page 422): "The coefficients of a regression model – but not the tests or R^2 – are affected by the units in which the variables are measured. For this reason, a comparison of magnitudes of individual regression coefficients is not very revealing. To overcome this problem, applied statisticians have at time been using a transformation in the regression coefficients resulting in "standardized" or "beta" coefficients, which yield values whose comparison is supposed to be more meaningful. The idea behind the transformation is to measure all variables in terms of their respective sample standard deviations. The resulting "beta" coefficients then measure the change in the dependent variable corresponding to a unit change in the respective explanatory variable, holding other explanatory variables constant and measuring all changes in standard deviation units.".

Table 3: Regression Analysis Total Cases per 1 Million Persons with Normalized Variables

Variables	(1) Total_cases_p.mill.	Variables	(2) Z(Total_cases_p.mill.)
Constant	-32,307***	Constant	1.62×10^{-9}
	(437.9)		(0.00278)
Population density	-3.481***	Z(Population density)	-0.0592***
	(0.166)		(0.00282)
Median age	1,982***	Z(Median age)	0.443***
	(16.84)		(0.00377)
Hospital_beds_p.th.	-1,321***	Z(Hospital_beds_p.th.)	-0.0784***
	(62.86)		(0.00373)
Observations	109,813	Observations	109,813
R-squared	0.153	R-squared	0.153
F (3, 109,809)	6,607.78***	F (3, 109,809)	6,607.78***
1% Critical F	3.782	1% Critical F	3.782
H0: coef (Z(population density)) = coef		F (1,109,809)	19.23***
(Z(Hospital_beds_p.th.)); H1: Otherwise.		1% Critical F	6.635

Notes: Column (2) reports the regression outcomes where each variable (both dependent and independent) is standardized by $Z(X_i) = \frac{X_i - \bar{X}}{\sigma_X}$ where $\bar{X}$ is the average and σ_X is the standard deviation of X_i. The calculated F (3, 109,809) clearly rejects the joint null hypothesis that all $(k-1) = 3$ coefficients of the explanatory variables are equal to zero. The F-values and critical F-values at the bottom of the table refer to the null hypothesis that coef (Z(population_density)) = coef (Z(Hospital_beds_p.th)). Standard errors are given in parentheses. $*p < 0.1$, $**p < 0.05$, $***p < 0.01$.

morbidity (mortality) *drops* with higher population density by 3.481 cases (1.45×10^{-7} deaths) for each 1 unit *increase* in the population density of the country. This outcome is consistent with the results presented by Hamidi et al. (2020). Based on 1,165 US metropolitan areas, and after controlling for metropolitan size and other confounding variables, the authors found significantly lower infection rates and lower death rates with higher county density.

Referring to the explanatory variables *Median_age* and *Hospital_beds_p.th.*, the signs of their coefficients are as anticipated. Projected scope of morbidity (mortality) *rises* by 1,982 cases (3.72×10^{-5} deaths) per 1 million persons with a 1 unit increase in the median age of the country's population. Projected scope of morbidity (mortality) *drops* by 1,321 cases (2.98×10^{-5} deaths) per 1 million persons with 1 unit increase in the hospital beds per thousand persons in the country. Indeed, the literature defines age (e.g. Bauer et al. 2021, Pijls et al. 2021, Zhang et al. 2022) and hospital beds per thousand persons (e.g. Brant et al. 2021, Presanis et al. 2021, Castagna et al. 2022, Fakih et al. 2022, Hobohm et al. 2022) as risk factors for COVID-19 morbidity and mortality.[4]

Given that the units of measurements of the explanatory variables are not identical, columns (2) in Tables 3 and 4, we present the outcomes after standardization. This transformation permits ranking the contributions of the three variables following an identical change (one standard deviation of each independent variable). Figure 6 gives the relative contribution of each of the three variables, and Table 5 provides comparable contributions in terms of cases (deaths) per 1 million persons.

Referring to the scope of morbidity, the most influential explanatory variable is the median age of the country's population. A one standard deviation *increase* in the median age (by 8.9 years) is associated with a 0.443 rise in the anticipated standard deviation of COVID-19 cases per 1 million persons (17,576 cases per 1 million persons – see Table 5).[5] The second influential explanatory variable is the per capita rate of hospital beds. A one standard deviation *rise* in the number of hospital beds of the country (by 2.355

[4]In fact, referring to the latter variable, and like population density (e.g. Hamidi et al. 2020), one should consider two opposing forces. On the one hand, more hospital beds are associated with better medical infrastructure and increased prospects of COVID-19 recovery. On the other hand, congestion in hospitals and healthcare centers may be a source for elevated infection (Sampeth Jayaweera, Reyes 2019, Ngandu et al. 2022). This, in turn, might increase morbidity and mortality particularly during periods with high occupancy rates.

[5]This may also be demonstrated as follows. Based on Table 3, one standard deviation of *Total_cases_p.mill.* equals 39,671.99. Multiplication by 0.443 yields $39,671.99 \times 0.443 = 17,574.69$, which is approximately 17,576 cases per 1 million persons.

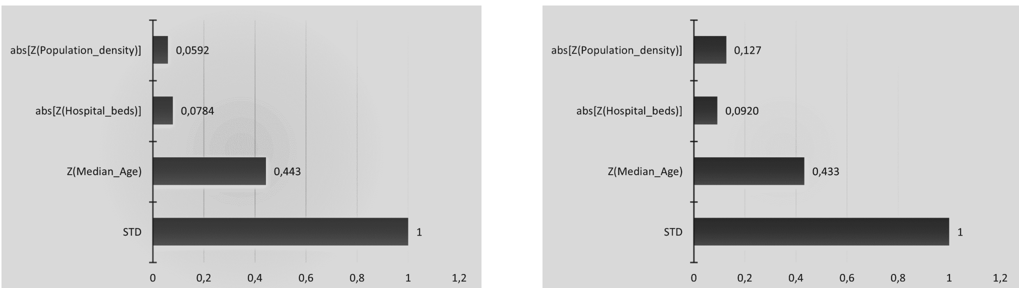
Table 4: Regression Analysis Total Deaths per 1 Million Persons with Normalized Variables

Variables	(1) Total_deaths_p.mill.	Variables	(2) Z(Total_deaths_p.mill.)
Constant	-0.000569***	Constant	1.06×10^{-10}
	(8.91×10^{-6})		(0.00289)
Population density	-1.45×10^{-7}***	Z(Population density)	-0.127***
	(3.35×10^{-9})		(0.00294)
Median age	3.72×10^{-5}***	Z(Median age)	0.433***
	(3.43×10^{-7})		(0.00398)
Hospital_beds_p.th.	-2.98×10^{-5}***	Z(Hospital_beds_p.th.)	-0.0920***
	(1.28×10^{-6})		(0.00395)
Observations	102,399	Observations	102,399
R-squared	0.144	R-squared	0.144
F (3, 102,395)	5,730.19***	F (3, 102,395)	5,730.19***
1% Critical F	3.782	1% Critical F	3.782
H0: coef (Z(population density)) = coef (Z(Hospital_beds_p.th.)); H1: Otherwise.		F (1,102,395)	56.05***
		1% Critical F	6.635

Notes: Column (2) reports the regression outcomes where each variable (both dependent and independent) is standardized by $Z(X_i) = \frac{X_i - \bar{X}}{\sigma_X}$ where $\bar{X}$ is the average and σ_X is the standard deviation of X_i. The calculated F (3, 109,809) clearly rejects the joint null hypothesis that all $(k-1) = 3$ coefficients of the explanatory variables are equal to zero. The F-values and critical F-values at the bottom of the table refer to the null hypothesis that coef (Z(population_density)) = coef (Z(Hospital_beds_p.th)). Standard errors are given in parentheses. $*p < 0.1$, $**p < 0.05$, $***p < 0.01$.

hospital beds per thousand persons) is associated with a 0.0784 *drop* in the anticipated standard deviation of COVID-19 cases per 1 million persons (3,112 cases per 1 million persons – see Table 5). Finally, the least influential explanatory variable is population density. A one standard deviation *rise* in the population density of the country (by 674.14 persons per square kilometer) is associated with a 0.0592 *drop* in the anticipated standard deviation of COVID-19 cases per 1 million persons (2,347 cases per 1 million persons – see Table 5). As the right side of Figure 6 demonstrates, to offset the positive contribution of the median age to morbidity scope, population density must grow by a factor of $\frac{0.4430307}{0.0591514} = 7.4898$ standard deviations with 99% confidence interval of (6.584, 8.396).

Referring to the scope of mortality, once again the most influential explanatory variable is the median age of the country's population. A one standard deviation *increase* in the median age (by 8.9 years) is associated with a 0.433 rise in the anticipated standard deviation of COVID-19 deaths per 1 million persons (331.6 deaths per 1 million persons



(a) Covid-19 Cases Per 1 Million Persons (b) Covid-19 Deaths Per 1 Million Persons

Figure 6: Beta Coefficients

Notes: $\text{abs}(x) = -x \,\forall\, x < 0$, $x \,\forall\, x \geq 0$. To offset the positive contribution of the median age to morbidity scope, population density must grow by a factor of 0.4430307/0.0591514 = 7.4898 standard deviations with 99% confidence interval of (6.584, 8.396). To offset the positive contribution of the median age to mortality scope, population density must grow by a factor of 0.425423/0.1266079 = 3.416 standard deviations with 99% confidence interval of (3.210, 3.622).

Table 5: Robustness Test

Variables	(1) Total_cases_p.mill.	(2) Total_deaths_p.mill.
Constant	25,372***	491.4***
	(110.2)	(2.217)
Z (Population density)	-2,347***	-97.07***
	(112.0)	(2.252)
Z (Median age)	17,576***	331.6***
	(149.4)	(3.052)
Z(Hospital_beds_p.th.)	-3,112***	-70.51***
	(148.1)	(3.027)
N	109,813	102,399
R-squared	0.153	0.144
F (3, $N-4$)	6,607.78***	5,730.19***

Notes: The table reports the regression outcomes where each independent variable is standardized by $Z(X_i) = \frac{X_i - \bar{X}}{\sigma_X}$ where $\bar{X}$ is the average and σ_X is the standard deviation of X_i. The constant term reflects the sample mean of the dependent variable, and the coefficients reflect the change in the total cases or deaths per 1 million persons following a one standard deviation increase. Standard errors are given in parentheses. $*p < 0.1$, $**p < 0.05$, $***p < 0.01$.

– see Table 5). Unlike the scope of morbidity, the second influential explanatory variable is the population density. A one standard deviation *rise* in the population density of the country (by 671.58 persons per square kilometer) is associated with a 0.127 *drop* in the anticipated standard deviation of COVID-19 deaths per 1 million persons (97.07 deaths per 1 million persons – see Table 5). Finally, the least influential explanatory variable is the per capita rate of hospital beds. A one standard deviation *rise* in the number of hospital beds of the country (by 2.37 hospital beds per thousand persons) is associated with a 0.0920 *drop* in the anticipated standard deviation of COVID-19 deaths per 1 million persons (70.51 deaths per 1 million persons – see Table 5). As the right part of Figure 6 demonstrates, to offset the positive contribution of the median age to mortality scope, population density must grow by a factor of $\frac{0.425423}{0.1266079} = 3.416$ standard deviations with 99% confidence interval of (3.210, 3.622).

5 Conclusions

The objective of the current study is to investigate the weight given to three risk factors associated with the scope of COVID-19 mortality and morbidity at a country level: population density, median age, and per capita rate of hospital beds per thousand persons. All of these variables have been identified in the literature as important risk factors (e.g., Hamidi et al. 2020 – population density; Bauer et al. 2021, Pijls et al. 2021, Zhang et al. 2022 – age; Brant et al. 2021, Presanis et al. 2021, Castagna et al. 2022, Fakih et al. 2022, Hobohm et al. 2022 – per capita hospital beds). Yet, their relative weights following a change in equal units of measurement have not been examined in a country level around the world. Consequently, we use empirical models with standardized coefficients, which measure the change in the standard deviation of the dependent variable (either the scope or morbidity or mortality per 1 million persons) following a one standard deviation change of each independent variable.

Referring to projected COVID-19 infection rates, and following a one standard deviation increase, these independent variables may be ranked as follows: 1) the median age of the country (a 0.443 standard deviation increase in the dependent variable); 2) per capita hospital beds (a 0.0784 standard deviation decrease in the dependent variable); 3) population density (a 0.0592 standard deviation decrease in the dependent variable).

A possible interpretation to the higher weight of the number of hospital beds compared to population density is the fact they proxy socioeconomic status and better medical literacy, which, in turn, may reduce the prospects of infection from SARS-COV2 virus. The implication of a better medical literacy is elevated awareness to the need to wash hands and wear masks. Combined with better water and sewerage infrastructure,[6] these

[6]In that context Tietenberg, Lewis (2012, p. 4) state that: "According to U.N. data, Africa and

factors might prove to be more important than population density in terms of the scope of COVID-19 morbidity.

Referring to projected COVID-19 mortality rates, and following a one standard deviation increase, these independent variables may be ranked as follows: 1) the median age of the country's population (a 0.433 standard deviation increase in the dependent variable); 2) population density (a 0.127 standard deviation decrease in the dependent variable). 3) per capita rate of hospital beds (a 0.0920 standard deviation decrease in the dependent variable).

A possible interpretation to the higher weight of the population density compared to the per capita rate of hospital beds is the fact that higher population density is associated with more human interactions, which, in turn, increase the infection rates of vulnerable population groups. The mortality prospects among these particular populations are higher (e.g., the delta compared to the omicron variants. The latter increased both infection and mortality rates).

Finally, note that for different dependent variables (i.e., scope of morbidity and mortality) one standard deviation of the independent variables are very similar. Yet, the impact of the same one standard deviation of population density on the scope of mortality is a higher *drop* compared to the scope of morbidity. This attenuation in the *drop* with higher population density may be explained on the grounds that while infection rates are direct derivatives of elevated human interactions proxied by population density, mortality rates are only indirect derivatives of population density. COVID-19 mortality follows infection. Other factors that may influence mortality are percent of vaccinated persons, and accessibility to medical services (intensive care hospital beds and equipment, anti-viral medicines, such as, Paxlovid). Other components, such as, vaccination rates or medical literacy are derivatives of the per capita rate of hospital beds. Consequently, the negative impact of population density on projected morbidity rate is attenuated compared to mortality rate.

Public policy repercussions of the study may be summarized as follows. Given the dominance of the age variable in the context of the COVID-19 pandemic, the allocation of resources for future pandemics should grow in countries with older population profiles (European countries). On the other hand, the emphasis in countries with younger populations (African countries) should be on better medical infrastructure in sparser regions. The latter finding is supported by Souris, Gonzalez (2020). The authors mostly found low hospitalization with high case-fatality rates in French districts with low population densities and attributed this phenomenon to the limitations of access to local healthcare services.

Our study is not without limitations. Every country in the world has its own regulations and in-depth research should be done with reference to each and every country. This article does not consider the scope of the health investment made (investment per inhabitant). For further investigation, we suggest doing follow-up studies on the division between men and women and by religion and by income.

Acknowledgements

The authors are greatful to Yifat Arbel for helpful comments.

Asia suffer the most from the lack of access to sufficient clean water. Up to 50 percent of Africa's urban residents and 75 percent of Asians lack adequate access to a safe water supply. The availability of potable water is further limited by human activities that contaminate the finite supplies. According to the United Nations, 90 percent of sewage and 70 percent of industrial wastes in developing countries are discharged without treatment."

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REGION
The Journal of ERSA
Powered by WU

Volume 10, Number 3, 2023, 45–57
DOI: 10.18335/region.v10i3.477

journal homepage: region.ersa.org
ISSN: 2409-5370

Relating Sustainable Development Goals in a Conceptual Integrated Model of Growth and Welfare

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Received: 19 January 2023/Accepted: 26 April 2023

Abstract. The United Nations Sustainable Development Goals (SDG) is one of the most relevant efforts aiming at the promotion of sustainable development around the world. Many indicators serve as a guide to evaluate the actual level of development and to identify the issues that need more attention. What is not clear yet is the association between the goals and their indicators. This can limit the information on effective political tools to reduce inequalities at the national and local levels. Based on that, the paper aims to explore the connections between SDGs. Its approach involves i) the proposal of a conceptual integrated model of sustainable development rooted in the literature and connectable with the SDGs; ii) based on World Bank (2019) data on sustainable indicators over two decades, the test of a two-stage econometric model, one to explain product per capita and a second one to explain lack of happiness, assessed by the suicide rate. From the results, it is possible to identify the factors that influence the level of wealth and happiness while integrating Sustainable Development Goals.

JEL classification: I3, Q01, C23

Key words: Sustainable Development Goals, Sustainable Growth Model, Happiness, SDG indicators

1 Introduction

The UN's Sustainable Development Goals (SDGs) (United Nations 2019) are the most significant global effort so far to advance global sustainable development. Achieving these goals should involve and influence sustainability (Kennedy et al. 2015). This comprises the revitalization of local economies, paying more attention to the rural areas, developing an ecological low-carbon economy (Liu et al. 2016), and safeguarding space for food production, ecosystem services, and biodiversity conservation (Thorne et al. 2017).

These are urgent issues in our times (Lafortezza, Sanesi 2019), smart quarters coexist with poor neighborhoods and slums, revealing unbearable social persisting inequities, accumulating environmental degradations, and perpetuating economic inefficiencies. The challenge is to react and think about valuable actions able to promote sustainability by learning from the successes and failures of policies and consultancies reported in the literature and revealed by the evidence (Shaker 2015, Xu et al. 2016, Shen et al. 2017).

Sustainable development involves "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). The challenge is to implement actions that are simultaneously ecologically viable, economically workable, socially desirable (Campbell, Heck 1999), and persisting over time (Adinyira et al. 2007).

From a spatial perspective, sustainable development should allow the "local population to attain and keep an acceptable, and not decreasing, level of welfare without endangering the opportunities of the inhabitants of adjacent areas" (Castro Bonaño 2003). In sum, a sustainable place can re-invent itself, to improve the lives of its inhabitants, promoting regeneration and respect for the environment, social cohesion, education for peace, and cultural integration (Ciudad del Saber 2012).

What matters and seems to make sense is to integrate sustainable development goals at different special levels knowing that people and places manage and optimize productive and creative capital (Fujita 1989). Many authors looked at the development of places with computable general equilibrium models (Kelley, Williamson 1984, Becker et al. 1986, Brueckner 1990). Others explored the concept of transitional dual economies (Lewis 1954), where rural areas provide the human and financial capital for urban growth (Fay, Opal 2000) in a typical core-periphery phenomenon (Krugman 1991). Henderson (2005) argues that development does not explain the dynamics of places, nor can these dynamics be the stimulus for development as it is possible to verify in many poor countries where urbanization did not lead to economic growth and development; the factors are resource usage (Henderson 1986), public transferences (Ades, Glaeser 1995) and institutions (Davis, Henderson 2003).

This paper aims to collect and systematize data on Sustainable Development Goals at the country level that can support the creation of frames of reference to integrate and interpret what appears to be detached disciplinary indicators. The assumption is that such indicators can only improve decision-making and promote sustainable development if integrated into knowledgeable mechanisms that can be useful to understand reality and suitable to identify and calibrate policy tools for different places.

What is the right tools level for each one of the sustainable development goals knowing that they interact with each other within specific contexts of space and time? The hypothesis is that there can be some instrumental association between SDGs to inform effective policy tools aimed to promote sustainable development.

To address that question and test this hypothesis, section 2 reviews the literature on UN Sustainability. Section 3 proposes a methodology to undertake an integrated analysis of the indicators of the UN Sustainability Goals. Section 4 provides a preliminary data analysis on World Bank Data (World Bank 2019) to perceive worldwide sustainability country profiles. Section 5 estimates a two stages econometric model that relates indicators of sustainable goals to growth and welfare and discusses the results and Section 6 concludes and proposes some future work for sustainable development knowledge and policy.

2 Literature Review in UN Sustainability Goals

Sensitive indicators of sustainability serve often to compare places (Quiroga Rayen 2001, Gallopín 2006). For instance, indicators that represent attributes of the urban system, public security, environment, culture, education, economy, funding, governance, migration, public participation, poverty, and the current development level. Resources such as the "Compendium of Sustainable Development Indicators Initiatives" and the "Community Indicators Consortium" currently allow places to access some comparable well-being data. The problem is that, on the one hand, global sustainability goals may not complement each other for each context and many trade-offs and interactions may arise between them. For instance, affordable and clean energy (Goal 7) goes with climate action (Goal 13), but the end of hunger (Goal 2) and sustainable landscapes (Goal 15) might be in contradiction with extensive land use for bio-energy (Goal 7) (Mika, Farkas 2017). For each space and time context, the priorities of the population differ according to their contextual needs which are different from the global priorities (Fuentes 2013).

The issue is whether sustainable development goals result from the global context, as often announced by international media, mirrored by the academic literature, stimulated by international institutions that support disciplinary-driven research; or if the concern is about sustainability in proximity contexts (Torre, Rallet 2005), without losing the framework of the spatially interconnected systems where place-based policies make sense (Neumark, Simpson 2015).

The assumption is that from the perspective of spatial and organizational proximity minimal wise investments in sustainability can reach marginal but cumulative benefits for regional sustainable development with demonstrative benefits for other places. At the local level, it is possible to attend to local geographic characteristics, committed economic capacity, responsible governance, managerial ability, adjusted policy tools, and face-to-face public participation; the dimensions for the deployment of sustainable investments (Shea et al. 2018). Given the significance of the SDGs for guiding development, rigorous accounting is essential for making them consistent with the goals of sustainable development (Wackernagel et al. 2017).

It is clear the need for some quantitative account of the SDGs for them to be a good guide for the development of regions and nations. However, as stated by Costanza et al. (2016), with 17 goals, 169 targets, and over 300 indicators proposed, the SDGs provide diluted guidance at best. Because of this, some attempts have been made to summarize the indexes and evaluate the correlation between the 17 SDGs. For instance, Costanza et al. (2016) proposed a Sustainable Wellbeing Index (SWI) and then linked it with SDGs; Anderson et al. (2022) created an SDG system model to observe the change in the influence of all targets on the official objective of the 2030 Agenda; Ament et al. (2020) and Pradhan et al. (2017) tried to identify the positive and negative correlations between the SDG indicators.

The contribution of this paper is the proposal and the test of a Circle of Development composed of seven vectors of development involving the 17 SDGs (Figure 1).

Territorial Capital is associated with making cities and human settlements inclusive, safe, resilient, and sustainable (G11), taking urgent action to combat climate change and its impacts (G13), conserving and sustainably using the oceans and seas for sustainable development (G14), protect, restore and promote sustainable use of terrestrial ecosystems, halt and reverse land degradation, and halt biodiversity loss (G15).

Productivity relates to ensuring access to affordable, reliable, sustainable, and modern energy for all (G7), promoting full and productive employment and decent work for all, and sustained, inclusive, and sustainable economic growth (G8); and ensuring sustainable consumption and production patterns (G12).

Income has to do with the end of poverty in all its forms everywhere (G1). Consumption, private and public links to end hunger and achieve food security everywhere (G3), ensure inclusive and fair quality education (G4), with achieving gender equality besides empowering all women and girls (G5), and in providing sustainable management of water and sanitation for all (G6). Financing involves strengthening the means of implementation and revitalizing the Global Partnership for Sustainable Development (G17) and, because of redistribution factors, reducing inequality within and among countries (G10). Investment contains building resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation (G9); promoting peaceful and inclusive societies for sustainable development, providing access to justice for all, and building effective, accountable, and inclusive institutions at all levels (G16). Well-being relates to ensuring healthy lives and promoting well-being for all at all ages (G3). The issue is if there are some relations between all these disciplinary goals, as it is pointed out in the question marks of Figure 1.

Although all goals are expressed as political actions, the question to address is: what political actions are more efficient to promote sustainable development, assuming means are scarce and that the different goals relate to each other and have different requirements in space and time?

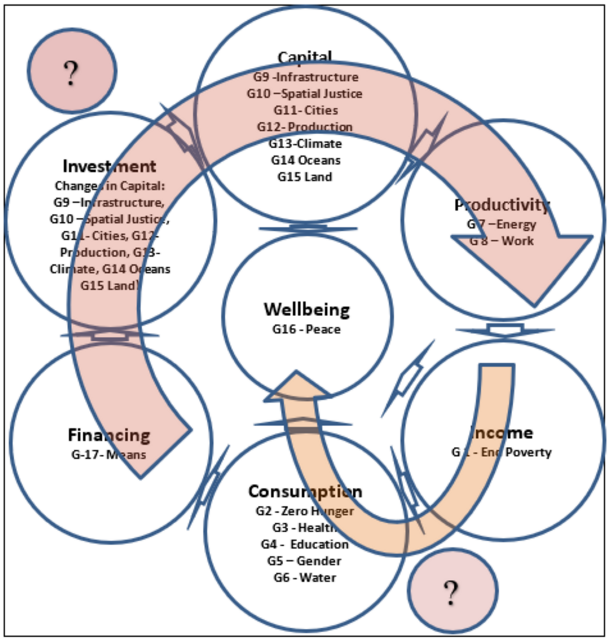


Figure 1: UN Sustainable Goals within the Circle of Development

3 Methodology

The paper aims to test if the Conceptual Model of UN Sustainable Goals within the Circle of Development presented in Figure 1 makes sense using indicators by country from the World Bank.

The scheme of Figure 1 guides a consistent aggregation of the 17 Goals materialized in two relatively robust regressions. The first one tries to explain income as a function of financing, investment, capital, and productivity. The dependent variable is Income per Capita (G1) and it is a function of the indicators for the goals G7, G8, G9, G10, G11, G12, G12 for low-income countries, G13, G14, and G17, and the urbanization rate. Equation (1) represents the model to be estimated.

$$\begin{aligned} \ln \mathrm{G1}_{it} = {} & \gamma_i \mathrm{urbanization} + \beta_1 \mathrm{G7}_{it} + \beta_2 \mathrm{G8}_{it} + \beta_3 \mathrm{G9}_{it} + \beta_4 \mathrm{G10}_{it} + \beta_5 \mathrm{G11}_{it} \\ & + \beta_6 \mathrm{G12}_{it} + \beta_7 \mathrm{G12\_low\_income}_{it} + \beta_8 \mathrm{G13}_{it} + \beta_9 \mathrm{G14}_{it} + \beta_{10} \mathrm{G15}_{it} \\ & + \beta_{11} \mathrm{G16}_{it} + \beta_{12} \mathrm{G17}_{it} + T + c_i + \epsilon_{it} \end{aligned} \tag{1}$$

The subscript i refers to country and t to year; T is the time-fixed effect; c_i is the country fixed effect and ε_{it} is the error term. To account for the multicollinearity in explanatory variables Principal Component Analysis (PCA) was used in variables with a higher degree of correlation (G7, G9, G10, and G11). The γ_i and the β are the coefficients to be estimated.

The second regression explains welfare as a function of income and consumption of private and public goods. It has Well-being (G16) assessed by the rate of suicide per 100,000 persons as the dependent variable and the social goals present in the Consumption Box of Figure 1 (G3, G4, G5, and G6) and the Income Box (lnG1, estimated in Equation 1) as explanatory variables. Equation (2) represents the proposed model. The δ are coefficients to be estimated.

$$\begin{aligned} \mathrm{G16}_{it} = {} & \delta_1 \ln \mathrm{G1}_{it} + \delta_2 \mathrm{G2}_{it} + \delta_3 \mathrm{G3}_{it} + \delta_4 \mathrm{G3}_{\mathrm{NAE}_{it}} + \delta_5 \mathrm{G4}_{it} + \delta_6 \mathrm{G5}_{it} \\ & + \delta_7 \mathrm{G6}_{it} + c_i + \epsilon_{it} \end{aligned} \tag{2}$$

Table 1 presents the list of indicators selected for each SDG. In the next section, there is a brief discussion about the evolution of each one. The equations were estimated using

Table 1: Selected indicators for each SDG

SDG	Indicator
G1	GNP per capita (constant 2010 US$)
G2	Mortality rate, under-5 (per 1,000 live births)
G3	Incidence of tuberculosis (per 100,000 people)
G4	Compulsory education, duration (years)
G5	Adolescent fertility rate (births per 1,000 women ages 15-19)
G6	People using at least basic drinking water services (% of the population)
G7	Renewable energy consumption (% of total final energy consumption)
G8	Unemployment, total (% of the total labor force) (modeled ILO estimate)
G9	Individuals using the Internet (% of the population)
G10	Exports of goods and services (% of GDP)
G11	People using at least basic sanitation services (% of population)
G12	Total natural resources rents (% of GDP)
G13	PM2.5 air pollution, population exposed to levels exceeding WHO guideline value (% of total)
G14	Agriculture, forestry, and fishing, value added per worker (constant 2010 US$)
G15	Forest area (% of land area)
G16	Suicide mortality rate (per 100,000 population)
G17	Personal remittances received (% of GDP)

data from World Bank (2019). The database contains information from 135 countries for the years 2000, 2005, 2010, and 2015. The equations were estimated using the fixed effects (within estimators) in STATA software.

4 Data on worldwide sustainability

The World Bank produced a specific database with indicators for the UN's SDGs (World Bank 2019). Based on this data (Figure 2) and selecting one available and adequate indicator per SDG, it is possible to estimate Equations (1) and (2) for the world and complement the analysis with the UN report of 2019.

SDG 1 is to end poverty in all its forms everywhere. The UN Report of 2019 says that the decline of extreme poverty continues, but projections of the proportion of people living below $1.90 a day show that in 2030 there will be still 6% of people in those conditions. This is associated with biased income creation and distribution not only between countries but, increasingly, within countries where rural detachment and urban exclusion persist. Sub-Saharan Africa deserves special attention on this issue (Wackernagel et al. 2017).

SDG 2 relates to the end of hunger, the achievement of food security, the improvement of nutrition, and the promotion of sustainable agriculture. The evolution of the mortality rate for those under 5 years old per 1,000 live births, available for many countries in the World Bank database, shows a clear improvement in the reduction of hunger around the world, mainly after 2010. Nevertheless, the number of people suffering from hunger has increased since 2014, associated with conflicts, environmental shocks, and economic slowdowns. Sub-Saharan Africa, Central and Southern Asia, and Oceania deserve special attention on this issue, not only related to hunger but also malnutrition.

Healthy lives and well-being for all ages is the aim of SDG 3. There have been major improvements in the world and even more in lower-developed regions in Sub-Saharan Africa and Central and Southern Asia. Notwithstanding this, in 2017, nearly 300,000 women died from complications relating to pregnancy and childbirth, and over 90 percent of them lived in low- and middle-income countries. The incidence of tuberculosis also decreased from 2000 to 2015, but that path is not steady in developing countries where, for some periods, there is an increase in the incidence. Regarding malaria, there were still, in 2017, about 219 million cases and 435,000 deaths from this disease, 90% in Sub-Saharan Africa.

UN Goal 4 aims to ensure inclusive and quality education and to promote lifelong learning opportunities for all. There is some improvement in the number of years of compulsory education but the percentage of children and adolescents not achieving the minimum proficiency in mathematics (56%) and reading (58%) is very low worldwide, as of 2015, and particularly alarming for Sub-Saharan Africa (84%, 85%), Central and Southern Asia (76%, 81%), and Northern Africa and Western Asia (57%, 57%).

To achieve gender equality and empower all women and girls is UN SDG 5. The indicator "Adolescent fertility rate (births per 1,000 women ages 15-19)" shows an interesting evolution for all the regions of the world, except Northern Africa and Western.. Nevertheless, the indicator is still higher in the least-developed regions of Central and Southern Asia and in Sub-Saharan Africa, where the proportion of women subjected to physical and sexual violence is above 20% of married women.

Goal 6 aims to ensure the availability and sustainability of water and sanitation for all. The indicator "People using at least basic drinking water services (% of the population)" in Figure 2 shows an evolution for most world regions except for Eastern Europe, where the water supply is deteriorating from 2000 to 2015. Furthermore, there are countries with high levels of water stress, mainly in Northern Africa, Western, Central and Southern Asia.

The world is improving towards ensuring access to affordable, reliable, sustainable, and modern energy (Goal 7) with only Sub-Saharan Africa still far behind in 2017. Nevertheless, the use of non-clean and unsafe cooking fuels is still common in many regions of the world in Central, Southern, Eastern and South-eastern Asia, Latin America and the Caribbean, Southern Africa, and Sub-Saharan Africa. The good news is, coming from Europe where clean and safe renewable energies are getting more share.

Goal 8 refers to the promotion of sustainable and inclusive economic growth based on full and productive employment and decent work for all. Although growth and employment are increasing in Asia, Europe, and North America, that is not the case in Sub-Saharan Africa, Latin America, and the Caribbean, which seemed trapped in a vicious circle of underdevelopment. Unemployment is decreasing all over (Figure 2) but it is very changeable in Europe and North America, where economic crises seem to have strong social and economic impacts. Notwithstanding this, the proportion of non-occupied young people is much higher for women, namely in Central and Southern Asia, Northern and Western Africa, Sub-Saharan Africa, and Eastern and South-eastern Asia.

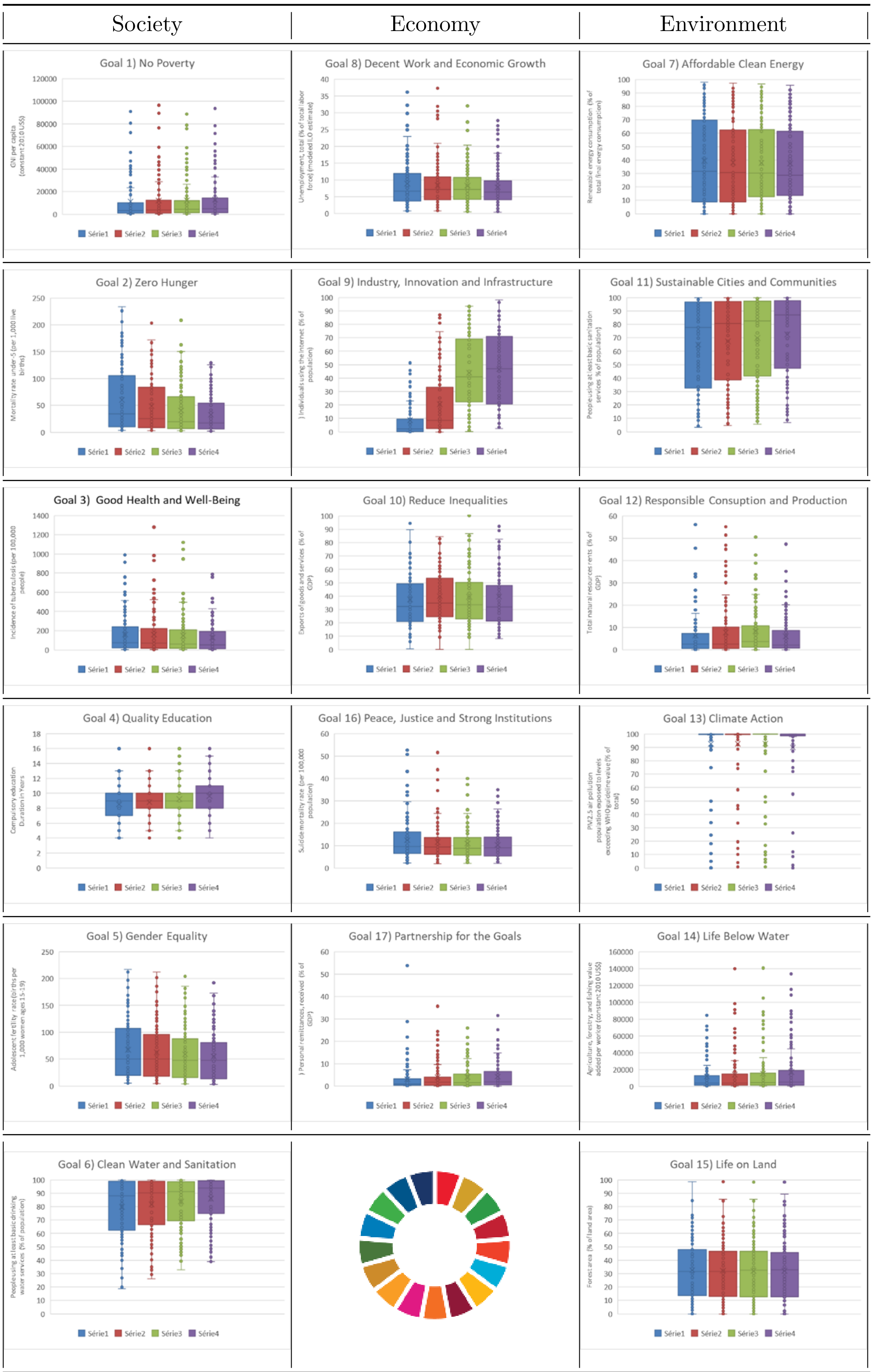
Goal 9 aims to build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation. Assuming that SD comes first from industrialization, investment in research and development and financing of small and medium enterprises would increase investment and productivity. The World Bank indicator of the percentage of individuals using the internet increased sharply until 2010 but stabilizes after the depression years. There are recent signs of industrial recovery in the developing world, after the shift from big public companies to private companies in the 1990s and after the great depression at the end of the first decade of the 21st century.

The reduction of spatial inequality within and among countries is the design of Goal 10. The growth of indebted countries strongly refrains and rural-urban migrations signal major inequalities within countries. Trade is a proxy indicator of inequality between countries and, looking at Figure 2, it can be seen a decrease in the percentage of exports in the product of the countries since 2010.

Goal 11 is the one more related to sustainable urbanization. The aim is to make cities and human settlements safe, inclusive, resilient, and sustainable. Looking at the indicator of the percentage of people using basic sanitation, there seems to be a clear improvement. The issue is that the average indicator per country does not report the tragic situation of many marginal slums associated with urbanization. Furthermore, urban waste is mounting; air pollution is unbearable in many large metropolises; traffic congestion seems unmanageable, and green spaces are short and degraded in many towns of the developing world.

Goal 12 tries to ensure sustainable consumption and production patterns, reducing the human footprint in the environment, improving the efficiency of resource use, and promoting healthy consumption patterns. The percentage of the rents from natural resources on the product might be an interesting indicator and looking at Figure 2, there are small positive signs globally.

Goal 13 refers to the urgency of actions to combat climate change and its impacts. There are many plans to reduce emissions and programs to adapt to the impacts. The



Note: Based on data from World Bank (2019).

Figure 2: Evolution of Indicators of Sustainable Development Goals in 2000 (Series 1), 2005 (Series 2), 2010 (Series 3), and 2015 (Series 4)

World Bank indicator was the number of particles in the air breathed by humans, but the signs of improvement were very low in the last few years.

Goal 14 proposes to conserve and sustainably use the oceans, seas, and marine resources for sustainable development. This involves the reduction of land-based pollutants, the decrease of acidification of the seas, and the sustainable management of fish stocks. The World Bank database does not provide a suitable indicator for the seas. The proxy indicator is the agriculture, fishing, and forestry value added per worker that, as Figure 2 shows, there is a small increase but still a long way to go to the benchmark of the best performers.

Goal 15 proposes to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and biodiversity loss. The number of species at risk of extinction are increasing, the proportion of degraded land is very high, mainly in developing countries, and the forest area is decreasing (Figure 2).

Goal 16 defends the promotion of peaceful and inclusive societies for sustainable development, access to justice for all, and the creation of effective, accountable, and inclusive institutions at all levels. The suicide rate is marginal but a strong indicator of this goal and shows some improvement exactly in countries with extreme values of suicides.

Finally, Goal 17 favors the strengthening of the means of implementation and revitalization of the Global Partnership for Sustainable Development. It rightly defends the mobilization of global and local funds, recognizing that personal remittances from migrant workers abroad are becoming the largest source of external financing in developing countries (Figure 2); although for extreme cases remittances decrease, there is an increase over the total average.

5 Results and discussion on the connection between UN Development Goals

Table 2 presents the estimative of regression 1. The variables and coefficients in bold are the ones statistically significant at the 0.05 level. The goals G8 (unemployment), G9 (use of the internet), G10 (exports), and G11 (basic sanitation) have the expected effect on per capita income. The higher the unemployment rate, the lower the income per capita; increases in exports and accessibility to the internet, and improvement in access to basic sanitation can lead to increases in a country's per capita income.

The results from Goals 7 (use of renewable energy) and 12 (natural resources rent) bring some interesting evidence. The percentage of renewable energy consumption has a negative correlation with the per capita income because most of it relates to the use of wood as the main source of energy. The rent from natural resources negatively affects income, but only in lower and middle-income countries, showing a lack of adequate governance in the management of natural resources in poor countries. This result finds support in other analyses. Ament et al. (2020) evidenced that economic growth is negatively associated with health and environment indicators and Pradhan et al. (2017) argued that Goal 12 is most commonly associated with trade-offs (negative correlations) regarding the other goals. Thus, potential conflicts between different agendas must be managed to pursue a sustainable development path, especially in low and middle-income countries.

The urbanization rate is statistically significant at 0.05 level only for countries in Central Asia (2) and Eastern Europe (6). In those countries, urbanization has been a good policy to increase the per-capita income. The year's specific coefficients are also statistically significant at 0.01 and have the expected positive sign.

Results of Table 3 show the factors that can affect the suicide rate, a proxy for non-happiness (Equation 2). There is a strong relationship between per-capita income (estimated in regression 1) and suicide rate: the richer a country, the lower its suicide rates. The coefficient of G3 (Incidence of tuberculosis per 100,000 people) is statistically significant and positive only for countries in Europe and North America. In such countries, the incidence of tuberculosis or the fear of catching it may affect well-being. The coefficient of G4 (compulsory education) is statistically significant at the 0.05 level and

Table 2: Goal 1 (per-capita income) explained by Economic and Environmental Goals

	Dependent variable: ln_G1 – Ln of GNP per capita (constant 2010 US$)		
Code	Variable	Coef.	Std. Err.
	Intercept	8.215*	0.412
G7	Renewable energy consumption	-0.293*	0.044
G8	Unemployment, total	-0.012*	0.003
G9	Individuals using the Internet	0.188*	0.030
G10	Exports of goods and services	0.073*	0.021
G11	People using at least basic sanitation services	0.266*	0.037
G12	Total natural resources rents	0.000	0.003
G12	Total natural resources rents – Lower and Middle Income Countries	-0.006*	0.003
G13	PM2.5 air pollution	0.000	0.002
G14	Agriculture, forestry, and fishing, value added per worker	0.000	0.000
G15	Forest area	0.005	0.004
G17	Personal remittances received	0.003	0.002
Urbanization			
1	Central America and Caribean	-0.005	0.005
2	Central Asia	0.359*	0.138
3	Eastern Africa	0.001	0.009
4	Eastern and South Eastern Asia	-0.001	0.011
5	Eastern Asia	0.010	0.008
6	Eastern Europe	0.040*	0.015
7	Middle Africa	-0.006	0.009
8	Northern Africa	-0.012	0.012
9	Northern America	-0.024	0.053
10	Northern Europe	-0.023	0.021
11	Oceania	-0.001	0.106
12	South America	0.002	0.014
13	South-Eastern Asia	0.006	0.006
14	Southern Africa	-0.018	0.010
15	Southern Asia	-0.007	0.009
16	Southern Europe	-0.001	0.007
17	Western Africa	-0.011	0.006
18	Western Asia	-0.010	0.009
19	Western Europe	-0.021	0.011
Year			
	2005	0.055*	0.020
	2010	0.127*	0.031
	2015	0.173*	0.042
	R-sq within= 0.6730		
	F(134, 362) = 51.00; Prob > F = 0.0000		
	Hausmann test (fixed x random effect): chi2(31)= 151.47; Prob>chi2 = 0.0000		

Note: * . . . significant at the 1% level.

has a positive sign, meaning the suicide rate increases with education level. This result may be different from what is expected, but there is some hypothesis that can explain it. The average suicide rate in Upper (14.586) and Upper Middle (12.215) income countries is much higher than the rate in Low (7.332) and Lower Middle (8.960) income countries. One of the reasons is because of the sub-notification of suicides in countries from the group of low and lower middle income. The other reason is that individuals with more years of study may be more prone to suicide when they face failures, public shame, and high premorbid function, as suggested by Pompili et al. (2013).

The country-fixed effects estimated in regression 1 are plotted in Figure 3 and represent the country-specific factor influencing per capita income. The higher the value (darkest colors) the more unobservable national factors are explaining the per capita income. As can be seen in developed and some developing countries like Argentina, Brazil, Chile, Mexico, South Africa, Turkey, and Uruguay, there are unobservable factors influencing positively the growth rates. In other countries, like Russia, India, and some in the African continent, the unobservable effects are pushing down the per-capita income.

Figure 4 presents the country-fixed coefficients for Regression 2. Countries like Russia, China, India, The USA, and Canada have the highest positive values, which means they have factors not included in the regression that explain their suicide rate. On the

Table 3: Goal 16 explained by Economic and Environmental Goals

Code	Variable	Coef.	Std. Err.
	Dependent variable: G16 – Suicide mortality rate (per 100,000 population)		
	Intercept	46.345*	6.876
ln_G1	Ln of GNP per capita (estimated in regression 1)	-4.915*	0.867
G2	Mortality rate, under 5	0.012	0.007
G3	Incidence of tuberculosis	-0.001	0.002
G3	Incidence of tuberculosis, Europe and North America	0.209*	0.020
G4	Compulsory education, duration	0.191*	0.090
G5	Adolescent fertility rate	-0.013	0.015
G6	People using at least basic drinking water services	0.043	0.030
	R-sq within = 0.3723		
	F(7,388) = 32.87; Prob > F = 0.0000		
	Hausmann test (fixed x random effect): chi2(7)= 50.02; Prob>chi2 = 0.0000		

Note: * ... significant at the 1% level.

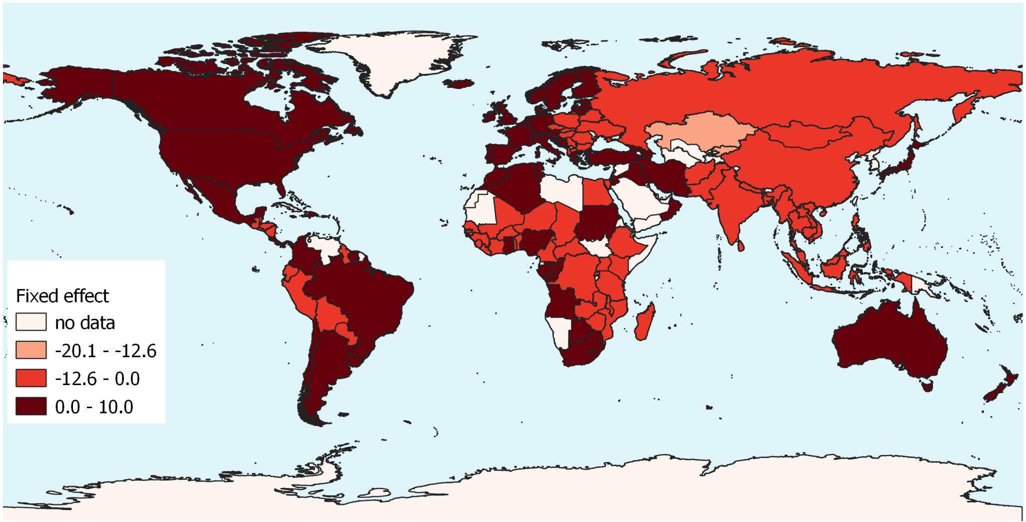


Figure 3: Countries' fixed effects, per-capita income (regression 1)

other side, in countries like Brazil, Colombia, Peru, Ecuador, Mexico, and some African countries unobservable factors are reducing the suicide rate.

Our interpretation of the evidence on the maps is that the quantitative indicators used in the regressions are not enough to explain the level of wealth and happiness of a country. Especially in the case of the suicide rate. Cultural, religious, and institutional factors not easily measure are affection positively and negatively the observable national rates. The challenge is how to measure them and analyze their influence on the achievement of the SDGs.

6 Conclusions

The paper aims to systematize data on SDGs, proposing a conceptual integrated model of sustainable development and estimating it econometrically with World Bank indicators. In summary, it is possible to observe that economic factors seem to be the most important determinant of the wealth of a nation. On the other hand, the model did not suggest that environmental factors can increase the income level. The rents of natural resources are bad for low and middle-income countries, indicating the need for improved governance in the management of natural resources in such countries.

To some extent, there is the confirmation of the hypothesis that there is some instrumental association between indicators of SDGs, as shown by the two interrelated models. Instead of targeting all the sustainable development goals with specific policies, it may be wise to look at the governance of natural resources in poor countries, question overall

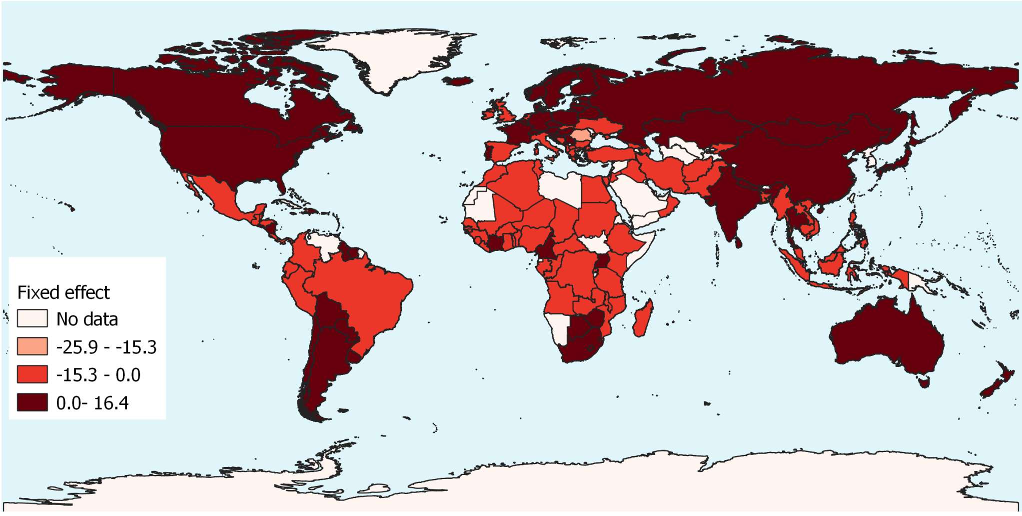


Figure 4: Countries' fixed effects, suicide rate (Regression 2)

urbanization policies and trends, look carefully at the education systems, and go further in explaining the country-fixed effects: why the Andes, most of Africa, and most of Asia do not grow as much as expected? And why do tropical countries seem to be happier than others?

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REGION
The Journal of ERSA
Powered by WU

Volume 10, Number 3, 2023, 59–81
DOI: 10.18335/region.v10i3.474
journal homepage: region.ersa.org
ISSN: 2409-5370

Bridging the evidence gap in spatial planning: Lessons from assessing the impact of new transport infrastructure

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Received: 7 January 2023/Accepted: 9 October 2023

Abstract. The article focuses on how the use of evidence in spatial planning could bridge the gap between vision and reality through the continuous evaluation of the spatial impacts of the proposed interventions. The introduction sets the theoretical, institutional, and practical context on how evidence is used to assess these impacts in relation to both the expected outcomes and the pursued policy priorities. The research section addresses these issues based on the empirical and methodological background derived from a series of successive studies carried out between 1999 and 2014. These studies are related to the establishment and operation of the spatial impact observatory of the Egnatia motorway, a major European transport infrastructure project in northern Greece. The results section introduces a methodological approach, succinctly referred to as the IRIS model in which spatial planning is conceived as an adaptive process, and the use of evidence aims to enhance its flexibility and preparedness in dealing with the uncertainties that arise from dynamic conditions, rather than relying solely on predetermined solutions. It comprises three key components: a theoretical model that simulates the relationship between transport infrastructure and spatial development, an intermediate data model in which raw data were constructed as evidence indicators, and a combination of inductive and deductive paths in which evidence is used to assess the anticipated impact of spatial plans and to evaluate the actual spatial outcomes after their implementation. Finally, the conclusions underline the value added of the IRIS approach as a comprehensive and integrative methodology that aims to improve the efficacy of spatial planning by establishing a link between theoretical models, policy objectives, and evidence-based decision-making.

Key words: spatial planning, transport infrastructure, impact assessment, adaptive process, evidence-based planning, data-models

1 Introduction: spatial planning and the quest for evidence

The field of spatial planning has a long tradition marked by diverse approaches and significant shifts in the prevailing points of view. Despite these variations, there is a noticeable consensus that the central aim of spatial planning revolves around the establishment of sustainable human habitats. To achieve this, the development of spatial plans combines creativity and rationality, relying on evidence both as a source of inspiration and as a means of documentation. To extract this evidence, empirical data must be processed, which, in turn, requires a proper understanding of the spatial elements to be observed. This understanding helps to explain, predict, and regulate their evolving state (Davoudi 2006, Faludi, Waterhout 2006, Kaw et al. 2020, Lord, Hincks 2010). Without a fundamental theoretical foundation, it becomes challenging to decide what data are relevant to collect and how to use them effectively to address complex spatial issues that challenge the capacity of spatial planning and underscore its need for reliable evidence. This evidence serves as an indispensable input for both the initial formulation and the evaluation of the anticipated impacts of spatial plans (Intezari, Pauleen 2019, Rittel, Webber 1973). Spatial planning is a complex process that deals with dynamic parameters, value judgments, and a wide array of unpredictable factors, such as political changes, technological advances, and natural disasters. Therefore, the search for evidence becomes crucial in substantiating the scientific rationality and technical expertise of spatial plans and in justifying the scale and cost of proposed interventions. Evidence plays also a vital role in acquiring the necessary political support, social acceptance, and legitimacy for the plans (ESPON DIGIPLAN 2021, Helming et al. 2011, Msila, Setlhako 2013, Weiss 1998).

The standard scientific approach is to rely on our senses for the observation of empirical data and on our reason to derive the evidence needed to describe, explain, and possibly predict and manage the real world. In this context, there is a tendency to view data as a source of objective information waiting to be discovered and used as evidence. This optimism about the existence of truth hidden in raw data is a misleading simplification because for the data to become accessible for use it must first be collected, measured, and classified into categories, datasets, series, and indicators, and then stored in files and databases in physical and/or digital form (Elgendy, Elragal 2016, Giest 2017, Günther et al. 2017, Leonelli, Tempini 2020). None of the above steps is simple or self-evident, but instead includes choices, for example, which data should be collected, which measuring instruments are appropriate, or whether and which sampling methods should be used. Additional complications arise from the need to ensure compatibility between quantitative and qualitative aspects of the data and between similar data referring to different time periods. Choices in all these issues have critical consequences for the type and reliability of the evidence extracted from raw data, and hence on the reliability of the produced scientific knowledge.

The production of reliable scientific knowledge follows either a top-down deductive method that starts from some theoretical hypotheses using evidence to check whether they are true or false, or a bottom-up inductive method that starts from the selection and processing of data using evidence to make theoretical generalisations. Leonelli, after thoroughly examining the relationship between scientific research and data and the ability to draw evidence and formulate reliable conclusions, argues that theories should first be linked to data using 'data models' as an intermediate device representing the phenomena under consideration and only then to extract evidence compatible with theory and capable of supporting scientifically valid conclusions. In this sense, according to Leonelli, 'data models' can be placed in a representational continuum between theory and reality, with data closer to reality and 'data models' closer to theory (Leonelli 2019, 2020a,b).

Increasingly in recent years, the quest for evidence relies on the processing of big data with algorithmic methods that reinforce the inductive approach that does not need theoretical hypotheses – a situation described by some as "the end of theory" (Succi, Coveney 2019, Voghera, La Riccia 2019). This trend is aggravated by methods that allow algorithms to be transformed by themselves through machine learning processes without the intervention of human intelligence (Gandomi, Haider 2015). However, the risks posed by the algorithmic inductive findings of artificial intelligence, to the extent that they do not require external verification, may reach a point that is not accessible or understood by human intelligence. This makes it possible to produce knowledge that may seem formally correct, but without any understanding of its hidden causality and real significance (Leonelli 2020a). In addition, the selective processing of loosely defined datasets without a specific theoretical model to guide the extraction of evidence increases the likelihood of substituting valid scientific knowledge with random observations that may serve specific political or other interests. Therefore, without a sufficiently or explicitly formulated justification for sources, representativeness, and frame of reference, the structure and content of the data acquire an arbitrarily decisive role in the type of knowledge produced (Davoudi 2012, Ekbia et al. 2015, Komninos, Kakderi 2019).

Acceptance of the need to support spatial planning with evidence to meaningfully assess the impact of a spatial plan as a basic condition for its implementation also implies its comparison with the expectations and projections of the original plan. In this sense, it is important to consider conceptual and methodological aspects concerning the monitoring and assessment of the impact of specific projects and plans in relation to the objectives and priorities pursued (ESPON DIGIPLAN 2021, Helming et al. 2011, Msila, Setlhako 2013, Owens et al. 2004, Rogers 2008, Weiss 1998). The current practise of national and international organisations reflects the above needs and considerations by promoting the impact assessment of plans and major projects as a necessary step before taking final decisions (EEAC 2006, ESPON 2012). Due to more general concerns and practical difficulties, most of the above efforts narrow their scope to specific sectors. The European Commission, for example, views the impact assessment as a set of logical steps to be followed to document the feasibility of a particular project/policy. At the same time, it also considers that only the environmental impact assessment should be mandatory, although it encourages the optional impact assessment of other sectoral dimensions without proposing a comprehensive framework to integrate the findings. In response to the commitment of Gothenburg to implement a sustainable development strategy, the European Commission started in 2002 the systematic development of an impact assessment framework including the circulation of a series of guidelines with the reservation that impact assessment should remain an aid to decision-making and not become a substitute for political judgment (EC 2002, 2005, 2009).

Spatial impact assessment procedures can be made in an ex-ante perspective or in an ex-post perspective. The 'ex ante' option is crucial in supporting decision makers on a project or policy under consideration by evaluating its possible impacts. In fact, this option depends on theoretical models for projection and on the previous experience of ex post assessment of similar projects. The ex-post option is an important part of evaluating the effectiveness of a project or policy, multiplying positive and counterbalancing any negative consequences, and providing input for the ex-ante evaluation of similar projects or policies in the future. It might also be possible to include ongoing assessment of circumstantial and/or preliminary impacts of projects/policies aiming to detect possible weaknesses and propose alternative solutions during implementation. Perhaps, as has emerged in a comparative examination of the relevant methods, several of the above issues can be addressed more effectively if territorial impact integration is adopted so that all individual sectoral impacts affecting a particular territorial unit are addressed in a uniform manner, including issues of spatial governance and spatial planning (Dunlop, Radaelli 2015, ESPON 2012, Medeiros 2014, 2020).

What is certain is the need for a monitoring mechanism to collect data and extract evidence that can respond in advance to the specific characteristics of a wide range of projects and plans, the real effects of which manifest themselves only when they take a concrete form and when they have been implemented and are operating in real-world conditions. According to White (2009), the theory-based approach of impact assessment, which examines the assumptions on which the causal chain from inputs to deliverables and their results, implies that the theoretical arguments supporting an intervention must be placed in the relevant social, political, and cultural context and developed in a flexible way, ready to adapt to changing circumstances considering alternative interpretations, but also any collateral consequences. In addition, there should be methodological rigour when analysing the relevant facts and events and when examining counterfactuals using the available methodological tools. Most studies of this kind rely on quantitative 'data models' to determine whether an intervention works effectively, without always shedding light on the causes of that success. To the extent that these studies do not fulfil the promise of the theory-based approach for empirically verifiable explanations, they resort to speculation about the reasons for deviations from the theoretically expected impacts, a fact that limits their contribution to the formulation of the relevant plans and policies.

In response to the problem of how to use evidence in spatial planning the rest of the article comprises three sections.

First, the research section of the article presents the most relevant aspects of the theoretical, methodological, and empirical background of a series of four successive studies conducted over a 15-year period, from 1999 to 2014, on the conception, establishment, and operation of a spatial impact observatory of the Egnatia Motorway, a major European transport infrastructure project in northern Greece. The aim is to reconstruct the main stages of the learning process that supports the basic argumentation of the article on the role of evidence in the adaptive capacity of spatial planning. Although the presentation follows chronological order, it also has the advantage of whatever wisdom has been acquired at the end of this journey.

Second, the results section introduces an adaptive approach to spatial planning, called the IRIS approach, which emphasises the importance of evidence in formulating plans and evaluating their impact. The approach acknowledges the uncertainty and emergence of unknown situations in the future and advocates flexible spatial planning frameworks that can adapt to changing conditions. Instead of relying on preconceived one-size-fits-all solutions, the IRIS approach suggests using evidence to enhance the flexibility and readiness of spatial planning.

Finally, the conclusion highlights the critical role of evidence in spatial planning and emphasises the value added of the IRIS approach in the integration of theoretical models, data models, and policy objectives. It underlines that spatial planning is a complex process where decisions require justification based on evidence, although there is no simple answer to what kind and amount of evidence is necessary to formulate good plans. By combining deductive and inductive paths, the proposed approach facilitates the assessment of impacts and the adaptation of plans.

2 Research: the spatial impact observatory of the Egnatia Motorway

The Egnatia Motorway is a major European transport infrastructure project in northern Greece, that was among the first round of the fourteen priority projects of the Trans-European Transport Network (TEN-T), a significant European policy created with the foundation of the European Union and fixed in the Treaty of Maastricht in 1992 (Bottcher 2006). The authors coordinated a series of four successive studies conducted during a 15-year period, from 1999 to 2014, on the conception, establishment, and operation of the spatial impact observatory of the Egnatia Motorway.

The first study was a feasibility study that examined the main elements required to establish the observatory, including the European experience of spatial planning and transport observatories, the role of accessibility in location decisions, spatial impact categories and monitoring indicators (Kafkalas et al. 1999). The observatory aims, on the one hand, to assess and monitor the spatial effects of the Egnatia motorway and, on the other hand, to provide data and analyses to support spatial development and planning in affected areas.

The second study was a pilot application designed to test and elaborate the different categories of indicators, such as socioeconomic, environmental, and transport indicators (Kafkalas, Pitsiava 2001). The aim was to develop the necessary know-how and to provide a comprehensive guide and an adequate sample of the procedures and results that would form the initial core of the observatory to start its operation immediately.

The third study was the application of the system of indicators intended to provide a report of the initial or zero state of the zones of influence of the Egnatia motorway as a model for the annual reports of the observatory and more generally to develop and finalise the instructions for its normal operation (Kafkalas, Pitsiava 2004). Selected aspects of the study of the initial state are presented to demonstrate how the appropriate groups of indicators mediate between the steps of the theoretical model and the pursued policy priorities.

Finally, the fourth study was an evaluation study to assess the contribution and prospects of the spatial impact observatory after ten years of continuous operation at the time of the official completion of the construction of the Egnatia motorway (Moutsiakis et al. 2014). The objective of the evaluation was to assess the contribution of the observatory in promoting territorial cohesion and sustainable development in the wider geographical area along the motorway and to assess the prospects of its future viability.

The accumulated research experience from the above-mentioned four studies constitutes a learning process on how to use theoretical concepts to extract the kind of evidence needed to assess the impact of planned interventions. While the Egnatia Observatory example is referenced as a case study, the broader focus is on the extraction of evidence from data and its use as a knowledge base for formulating plans and evaluating their impact, rather than solely evaluating the observatory's effectiveness in collecting and explaining post-construction data.

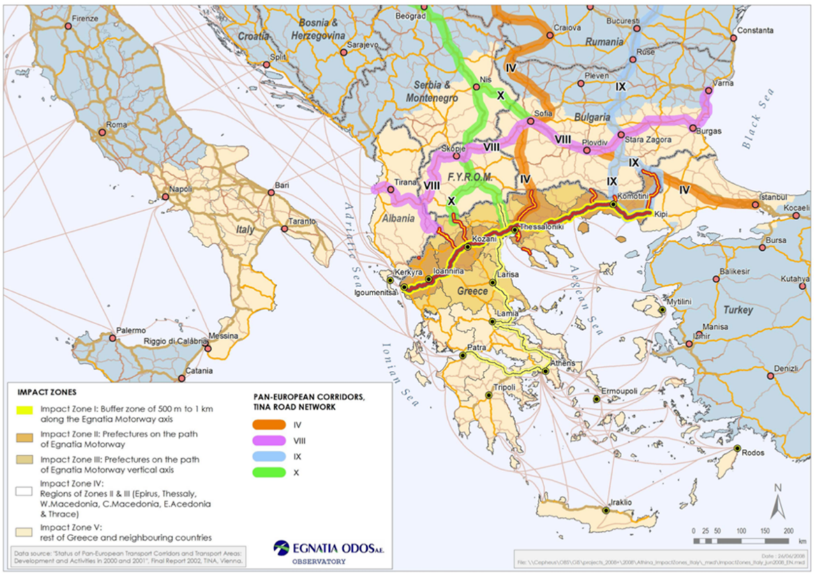
2.1 Inception: the main elements

The feasibility study was commissioned by Egnatia Odos S.A., the company responsible for the design, construction, operation, and maintenance of the entire Egnatia highway network, to examine the main elements for the establishment of a spatial impact observatory of the new transport infrastructure (Kafkalas et al. 1999). The highway is a major transport infrastructure project that crosses northern Greece with a total length of 670 km, including 40 km of 177 bridges and 50 km of 73 tunnels (Egnatia Odos S.A. 2022). The road axis, whose construction began in 1994 and was completed formally in 2014, connects the eastern border between Greece and Turkey with the port of Igoumenitsa in the west. On its route, it meets 11 important cities including Thessaloniki, the second largest city in Greece, and connects four important ports and six airports. An integral part of the project were also the vertical axes that connect the motorway with the Balkan countries and, more broadly, the system of pan-European transport corridors.

The importance of the axis and the size of the investment, which reached EUR 6 billion, underline the scale of expectations and made it necessary to promote actions complementary to its construction and operation to multiply the benefits and mitigate any negative side effects. Thus, the main objective of the observatory was the collection and processing of data with the aim of monitoring the developmental, spatial, environmental and transport impacts of the construction and operation of the axis and the provision of information and support to development planning policies and programs. It was also considered that the effective operation of the observatory would depend on the determination of the appropriate data and on the methods of their collection, measurement, and visualization.

In order to respond to the above, the feasibility study covered a wide range of issues including: (a) the European experience of spatial planning and transport observatories, (b) the current scientific debate on the role of accessibility in the choice of location of economic activities, (c) the spatial impact categories and the motorway operation system as well as the corresponding monitoring indicators with reference to European policies and guidelines, (d) the criteria for determining the geographical areas of influence of the road axis, and (e) the alternative scenarios for the organization and operation of the observatory. Of the above, the issues related to points (a) and (e) do not concern the central argumentation of the article, and thus they will not be discussed in the rest of Section 2.1, while for point (c) there will be an introductory description of the system of indicators, which will be discussed in depth in Section 2.2 presenting the pilot implementation during which the system of indicators was finalized.

The role of accessibility in shaping the patterns of uneven spatial development is reflected by the fact that in the European Union territory the differences in transport infrastructure follow, at least approximately, a similar geographical distribution to that of GDP per capita (EC 1994, Vickerman et al. 1999). Although levels of accessibility seem to be related with the location decisions of enterprises and households, this relationship is not rectilinear: different forms of accessibility affect different types of businesses in a variety of ways (McQuaid et al. 1996). The spatial behaviour of enterprises and households, in turn, has an impact on land values, natural resources, and the environment of urban areas and their rural hinterland. The most appropriate theoretical framework for the analysis of the above is the generic land-use transport interaction (LUTI) model according to which the spatial impacts of transport infrastructure consist of:



Source: http://observatory.egnatia.gr/maps/maps2008/impact_zones_2008_en.pdf
Notes: The observatory website was accessible to the public until the beginning of 2023 but is now under reconstruction as shown at the new Egnatia website https://egnatia.eu/en/homeen/. See also Fourkas, Yiannakou (2015). Furthermore, the new Egnatia website hosts a geoportal https://egnatiaodos.maps.arcgis.com/home/index.html with useful information.

Figure 1: Impact zones of the Egnatia Motorway

- The direct effects of transport, which are related with the changes in accessibility in terms of generalized transport cost, travel time, benefited population.
- The indirect socioeconomic effects which are related with the behavior of households and enterprises due to improved accessibility in terms of growth in productivity and changes in the allocation of activity and population resulting to changes in GDP, market size, population density, hierarchy at urban centers, land use patterns, etc. and
- The effects of diffusion (environmental impacts) arising from the above two types.

The theoretical and practical problems associated with the geographical range and the territorial reference base of the impact observatory of the Egnatia motorway were treated as the question of how to define its zone of influence. Due to the scale and importance of the transport axis, its influence was treated as a dynamic system of successive zones that participates in the kind, scale, and time horizon of its own impacts.

At the feasibility stage, the definition of these zones was based on two criteria linked to the key theoretical term of accessibility: (a) the spatial position of the axis, i.e., what is the geographical area that is directly or indirectly affected in terms of accessibility, and (b) its intended range of influence, i.e., what is the wider area where the optimization of accessibility is sought. Consequently, five impact zones were identified as follows: (a) zone I, the axis of the Egnatia motorway itself at a depth of 500-1,000 meters, (b) zone II, the geographical area of the prefectures through which the Egnatia motorway passes, (c) zone III, the geographical area of the prefectures through which the vertical axes pass, (d) zone IV the geographical area of the regions through which both the Egnatia motorway and its vertical axes pass, and (e) zone V, the wider area of the Greek and Balkan territory affected as a result of the changes brought about by the network of the Egnatia motorway axis and its vertical axes in the organization of the transport system as a whole (Figure 1).

Concerning the system of impact indicators, this was constructed taking into account the scientific debate on the theoretical models of land use and transport interaction, the available previous experience of transport observatories, and the relevant official guidelines of international organizations (EEA 1998, 2000, EUNET 2001, Medeiros 2014, TRIMIS 2022, Wegener, Bökemann 1998). To ensure the reliability and comparability of data, indicators had to be selected that, on the one hand, are in line with commonly accepted indicators at the national and European level and, on the other hand, adequately reflect the state of the economic, social and environmental characteristics of the areas of influence. Thus, the initial indicator system included three categories of about 50 indicators: socio-economic indicators (including spatial planning), environmental indicators, and transport function indicators.

2.2 Beginning: the pilot application

After the completion of the feasibility study, Egnatia Odos S.A. decided to proceed with the creation of the observatory of the spatial impact of the motorway. To this end, a pilot study was commissioned to complete and test the indicator system with real data (Kafkalas, Pitsiava 2001). Different indicators have different time frames and spatial impact scales. For example, indicators related to changes in land use, air pollution, and road safety are limited to the road axis and its adjacent area, while indicators related to socio-economic impacts extend to wider geographical areas. Therefore, it is important that the observatory's operation is continuous, as monitoring the effect of the motorway requires updating the data over time. In this context, 20 indicators were selected from all categories of indicators proposed by the feasibility report, and after examining several critical parameters and some alternatives, a 10 km section of the Egnatia motorway was selected as the scope of the pilot study.

In addition to calculating the 20 indicators selected for this section of the motorway, the pilot study included a detailed description of all indicators in a standard format that included all information and clarifications needed to accurately determine and calculate each indicator under real conditions. Each indicator is essentially a data model for the phenomenon to which it refers and should not be treated as a formal and self-evident process of raw data collection. In this respect, a theoretical rationale compatible with the overall approach has been formulated for each indicator and specific measurement techniques and procedures have been proposed, which may include specific theoretical models, as well as how the results should be recorded, interpreted, and presented.

Based on the results of the feasibility study and after the necessary adaptation and rationalization following the pilot application, the Egnatia Motorway Observatory monitors the indicators shown in Table 1.

Table 1: The system of the Egnatia Motorway Observatory indicators

1A. Social-Economic and & Spatial Planning Indicators
Benefited population
Market size (GDP)
Work force
Growth and prosperity level (Gross Domestic Product - GDP per head)
Unemployment rate
Accessibility of transport modes
Accessibility of industrial areas
Accessibility of sites of cultural & tourist interest
Population change
Urban population changes
Hierarchy of urban centres
Population density
Composition of production by industry sector (Gross Value Added - GVA)
Composition of employment by industry sector
Foreign trade
Urban land use changes
Industrial and commercial land use changes
Real estate changes

Table 1: The system of the Egnatia Motorway Observatory indicators (continued)

Business location
Entrepreneurship
1B. Environmental Indicators
Population exposed to traffic noise
Air pollution
Cohesion-fragmentation of settlements
Tunnel air quality
Landscape restoration
Fragmentation of natural areas
Land use changes
Proximity to protected areas
Crossings with surface waters
Water quality
1C. Transportation Indicators
Traffic volume (Annual Average Daily Traffic - AADT)
Traffic composition
Person Movements
Travel-time
Time-distance
Freight (transport of goods)
Annual Vehicle kilometres
Road safety
Level of service
Road network density
Traffic volume on National Road
Trans-border movements
Intermodal transport
Characteristics of Vehicle Movements
Passenger Journeys by alternative transport modes

Source: http://observatory.egnatia.gr/indicators_en.htm
Note: the observatory website was accessible to the public until the beginning of 2023 but is now under reconstruction as shown at the new Egnatia website (https://egnatia.eu/en/homeen/). For the initial version of the system of indicators see Fourkas (2005).

It is also worth noting here that the system of indicators developed for the first time is the basic core that can be enriched with additional complementary indicators as well as complex indicators, generated through the combination of individual indicators, depending on the phenomenon being investigated. Some examples of complex indicators are the density of road/rail network per surface and population, intermodal transport as the combination of several indicators such as the density of road/rail network, the number of terminals (railway/seaport/airports), accessible terminals and the total volume (passenger/freight) handled by terminals.

The operation of the highway is a continuous process, and the monitoring of the generated effects implies that for most indicators, the calculation procedures must be repeated to update the data according to a set time frame depending on the phenomena being studied. For example, the measurable effects of land use change can take more than three years to emerge, while the volume of travel between different cities along the axis can change at a much faster rate. In addition to differences in relation to time, the indicators differ significantly in relation to the geographical scale or zone of impact in which the phenomena considered produce a measurable impact. Thus, indicators relating to changes in land use and real estate, landscape restoration, fragmentation of natural areas, passage through surface water, population exposed to noise, air pollution, volume and composition of traffic, level of service, travel time and road safety are geographically limited to the road axis itself or to the adjacent area of impact zone I. Similarly, indicators

Table 2: Example of technical sheet: the beneficiary population indicator

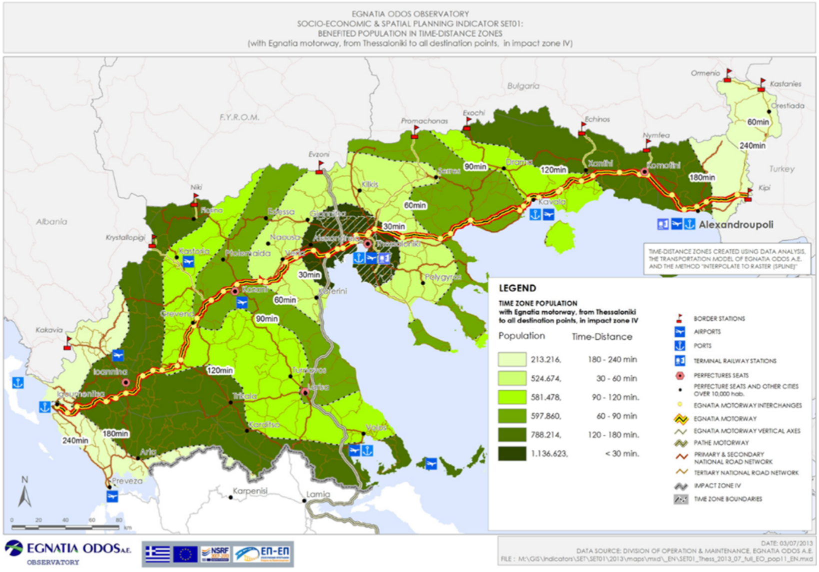
Definition	The indicator identifies the population potentially benefiting from the axis and which is defined as the population that is at a distance and/or time distance of (a) daily travel and (b) frequent travel from the seats of the prefectures and regions through which the axis passes		
Standard Format	The number of inhabitants of the area is determined based on the (time-) distance from the seats of the prefectures and regions in the existing road network		
	Table: beneficiary population by centre and (time-) distance		Map: beneficiary population by centre and (time-) distance
Units of Measurement	Population: Number of inhabitants	Distance (km): 50, 150, 300	Time distance: 45min., 60min., 90min., 3h
Spatial Reference	Zones II, III, IV $\kappa\alpha\iota$ V		
Measurement Frequency	Medium term: 5 Years		Long term: 10 Years
Feasibility	Estimation of the population accessible from an urban centre of the axis catchment area through the national road network and investigation of the prospects for functional interconnection between the various urban centres and different regions.		
Policy Objectives	Mobility - Accessibility		
Specifications	Comparative figures: Accessible population from TEN-T Accessible population from other motorways		
Data	Population of NSSG censuses at settlement level Settlements Road network Time-distance data of OD-B-8		
Sources	NSSG EGNATIA ODOS S.A.: Observatory (same measurements) EGNATIA ODOS S.A., Operation & Maintenance Division, Operation Directorate, Traffic Department EGNATIA ODOS S.A.: Observatory spatial database		
Problems	The time distance is a size that is not easily available for routes off Egnatia motorway. These paths require an assessment using GIS		
Comments	The distance and time distance are taken to study the following trends (a) the area of daily commuting around the county headquarters, which is a potentially a spatial functional unit, (b) the area of frequent travel mainly around the regional urban centres and (c) the area of wider functional interconnections around the regional urban centres. The indicator is also estimated using models such as the SASI model (Wegener, Bökemann 1998).		

Source: Adapted from Egnatia Observatory (2008)

related to socio-economic impacts, such as the beneficiary population, GDP growth and well-being levels, unemployment rate, urban population changes, urban hierarchy, accessibility of transport modes, accessibility to specific locations, coherence-fragmentation of settlements and intermodal transport, refer to a geographically wider area extending to zones of impact II, III and IV.

An example of how an indicator operates as a data model linking the real world with theory is the potentially benefited population, assessed first in relation to the distance on the road network and second in relation to the time/distance factor. The technical bulletin with the basic metadata of the indicator is given in Table 2.

Essentially, the factsheets accompanying each indicator include the necessary information and explanations to systematically extract the appropriate evidence and to ensure the reliability and comparability of measurements and results over the long term. Indicators refer to specific phenomena in a structured way and their role as 'data models' is to translate relevant empirical data into evidence to be used in the description, interpretation, and conclusions on the spatial impact of the Egnatia motorway. Results can be analysed and presented either for each indicator separately or in clusters of indicators



Source: Fourkas, Yiannakou (2015)
Notes: A full presentation of the results and visualization in tables, diagrams, and maps was provided at the website of the Egnatia Observatory that was available to the public until the beginning of 2023 and is currently under reconstruction as shown at the new Egnatia website https://egnatia.eu/en/homeen/. Furthermore, the new Egnatia website hosts a geoportal https://egnatiaodos.maps.arcgis.com/home/index.html with useful information.

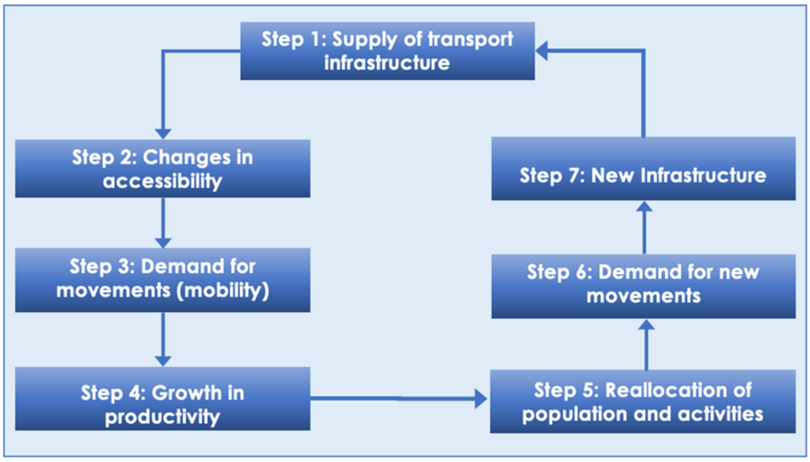
Figure 2: Egnatia motorway beneficiary population: time zones from Thessaloniki

which are constructed as new 'data models' of higher order to represent interconnected and complex phenomena according to the adopted theoretical framework. As an example, Figure 2 refers to the beneficiary population based on the distance from Thessaloniki, the main urban area along the axis.

2.3 Operation: the initial state

Following the completion of the pilot study, Egnatia Odos S.A. commissioned a study aiming to apply the system of indicators to assess the initial state of the zones of influence of the motorway (Kafkalas, Pitsiava 2004). This study was intended to become the model of the annual reports to be prepared by the observatory and for this purpose it was conducted in close cooperation with its staff. The object of the study was to develop and finalize the proposals, guidelines, and instructions originally formulated in the two previous studies, the feasibility study, and the pilot application so that the observatory would acquire a solid baseline before it began its full and normal operation. Some aspects of the study of the initial state are presented, with reference to key theoretical and methodological issues, including specifically how the appropriate groups of indicators mediate between the steps of the theoretical model on the one hand and with the pursued policy priorities on the other.

From an evolutionary perspective, the relationship between transport infrastructure and spatial structure depends on many agents, including public and private institutions and organizations, as well as collective and individual actors, the interplay of which exercise significant influence on how, when, and whether a potential impact will occur. These elements make it very difficult to find the correspondence between different kinds of territorial impact and specific characteristics of the transport infrastructure. However, it is possible to incorporate critical elements into theoretical models of the relationship between land use and transport change. There is a great variety of integrated land use transport models that contain a series of interlinked equations for predicting key variables related to economic activity, transport change, and land use patterns (Geurs, van Wee 2004). Figure 3 shows a seven-step (cyclical) model that satisfies the above criteria. This



Source: Adapted from Bruinsma et al. (1997)

Figure 3: A seven-step cyclical model of land use and transport interaction

is a simplified adapted version of a conceptual model on the relation between transport infrastructure and the spatial pattern of economic activities proposed by Bruinsma et al. (1997). A basic difference is that the transport cost is incorporated in Step 2, where accessibility expresses the generalized cost of travel.

As shown in Figure 3, transport infrastructure first and foremost affects accessibility and hence increases the economic potential of regions, producing a series of territorial impacts upon economic growth, the state of the environment, and land use patterns (Vickerman et al. 1999). This process is systematised according to the adopted model as follows: the supply of transport infrastructure (step 1) reduces the cost of transport and leads to an improvement in accessibility (step 2) that increases the demand for movement (step 3) and improves the productivity in the areas of its influence (step 4) triggering the reallocation of households and activities (step 5) and the generation of demand for new movements (step 6) which create pressures for the supply of new transport infrastructure (step 7).

In addition to the choice of an appropriate theoretical model, the elaboration of an evidence-based framework for the assessment of the territorial impacts of transport infrastructure upon spatial development presupposes the identification of relevant policy objectives and priorities. The adoption and formulation of policies is a dynamic process that has both territory-specific and time-specific components. In the case of the Egnatia Motorway, the spatial development and transport policy priorities were those stated in the official EU documents during the corresponding programming periods 2000-2006 and 2007-2013: the European Spatial Development Perspective (EC 1999), the Territorial Agenda of the European Union (Territorial Agenda 2007), the Green Paper on Territorial Cohesion (EC 2008), and the White Paper of European Transport Policy for 2010 (EC 2001). In summary, these policy priorities are:

- Parity of access means that policies should aim to close the accessibility gap between the different areas. This could be pursued through the allocation of new investment for the construction of new or the improvement of existing transport infrastructure.

- Territorial cohesion aims to confront socio-economic polarization and strengthen territorial cohesion through integrated multimodal and intermodal transport networks promoting polycentricity and a balanced system of settlements.

- The prudent management and protection of natural and cultural resources reflects the concern for the protection and improvement of the quality of the environment, addressing the environmental pressures that are generated by socio-economic conditions and the operation of the transport system

- The pursuit of social and economic cohesion is the aim of all sectoral policies. The assessment of progress towards this aim is reflected in policies aiming to close the gap in regional disparities as they are expressed by economic and social variables

After the formulation of the theoretical model and the identification of the main policy priorities, a critical task is to assess and possibly quantify the relationships between transport infrastructure and spatial development. Towards this aim, it becomes necessary to use clusters of indicators, which could operate as a mediating device linking the steps of the theoretical model with key policy objectives. In many projects, which focus on the territorial impact of transport system, different indicators have been tested (Andrikopoulou, Kafkalas 2000, Egnatia Observatory 2005, ESPON 2005, ESPON 2012, Fourkas 2006, Kafkalas, Pitsiava 2007, 2010). These efforts have been considered in the framework of the present approach to identify the kind of indicators that are appropriate to measure actual policy priorities according to the steps of the theoretical model. Based on the above considerations, the territorial impact assessment framework of the Egnatia Motorway Observatory is summarized in Table 3.

2.4 *Assessment: the first ten years*

At the end of ten years of continuous operation at the time of the official completion of the construction of the Egnatia motorway, Egnatia Odos S.A. commissioned an evaluation study to assess the contribution and prospects of the spatial impact observatory (Moutsiakis et al. 2014). More specifically, the aim is to determine how to assess the progress of implementation and the content of the Observatory's activities both in terms of the effectiveness of the resources it has and in terms of its contribution in promoting territorial cohesion and sustainable development in the wider geographical area along the road axis and vertical axes. In addition, the Observatory's prospects in the changing institutional and economic environment are examined, with the main orientation being to ensure its future viability. The development of the Egnatia Motorway Observatory and its integration into the administrative framework of the Egnatia Odos S.A. have been linked to the construction and development process of the motorway. Respectively, the spatial reference and the activities of the Observatory have focused on the system of the Egnatia Motorway and its vertical axes, supporting its operation and management and, in certain cases, the implementation of spatial planning at the local or/and regional level.

Despite the capacity of the Observatory to provide the evidence necessary for the evaluation of the socioeconomic and environmental conditions of the affected areas and to enable the improvement of spatial development planning, this potential was not fully realized. The main reason was problems of cooperation and/or compatibility with the involved decision-making authorities that either lack adequate expertise or rely on alternative sources for the collection and organization of information. The inability of the administration to use the Observatory as a source of reliable evidence and as a consulting service limits its potential contribution to the development of the regions affected by the Egnatia Motorway. However, the accumulated know-how and expertise have led to the creation of a data collection and impact assessment system with significant added value. Therefore, the Observatory has been established as a 'landmark' in the field of spatial analysis primarily for Northern Greece but also for the national territory (ESPON 2007, REGIO-MOB 2018).This fact constitutes the main feature of the new strategic orientation of the Observatory, which aims at the formulation and validation of its future potential as a tool to monitor the development trends in Northern Greece and the whole country in relation to the infrastructure and operation of the transportation system.

During the first ten years of operation, the Egnatia Observatory has accumulated a substantial amount of information, calculating several indicators on the socioeconomic and environmental impact of the Egnatia Motorway (Fourkas 2005, 2006, Giannakou et al. 2010). The results concerning socioeconomic impacts in terms of productivity, growth, and redistribution of activities and population, such as changes in GDP, market size, population density, urban hierarchy, and land use, were compatible with the theoretically expected impact due to the improvement of accessibility (Bröcker et al. 2002,

Table 3: Territorial impact assessment framework: theoretical model, policy priorities and impact indicators matrix

Steps/Objectives	Objective 1 Parity of access	Objective 2 Balanced development	Objective 3 Environmental protection	Objective 4 Social and economic cohesion
Step 1 Supply of Transport Infrastructure	supply indicators (i.e., length and density of road/rail network per surface and population)	composite indicators reflecting the potential use level of transport infrastructure (i.e., road density per surface in relation to the number of inhabitants per unit of road network)	Indicators expressing land changes and settlements' fragmentation due to transport development (i.e., land taken by transport development)	
Step 2 Changes in accessibility	indicators expressing accessibility levels (i.e., beneficiary population, travel time or the generalized cost of transport)			
Step 3 Demand for mobility	demand indicators (i.e., traffic volume --vehicle, passenger, and freight)		Indicators expressing the population exposed to potential annoyance (traffic noise/air pollution) due to new mobility patterns.	
Step 4 Growth of productivity				Indicators measuring economic variables (i.e., GDP per capita and activity rates, employment by sector of production, and unemployment rates)
Step 5 Reallocation of activities		socioeconomic characteristics of the various areas (i.e., employment per sector, GDP per capita, unemployment rates)	Indicators expressing the population exposed to potential annoyance due to changes in population and activity allocation.	Indicators measuring changes in population and activity allocation (i.e., population density and land use patterns)
Step 6 New demand for mobility	As in step 3		As in step 3	
Step 7 New transport infrastructure	As in step 1	As in step 1	As in step 1	

Source: Adapted from Kafkalas, Pitsiava (2010, 2013)

Bruinsma et al. 1997) as well as with the results of the ex post evaluations of similar projects (CSIL 2012). Some negative environmental impacts refer to the increase in air pollutant emissions and noise related to the generation of new traffic due to the increase in productivity in the vicinity areas mentioned above, as well as the negative externalities usually associated with the construction of large infrastructures. However, the overall environmental impact of the motorway is assessed as positive as the construction, in its largest part, led to the bypass of existing settlements and their statutory borders, a fact that resulted in a reduction of the percentage of population exposed to traffic noise and air pollutants, thus improving the quality of life in residential areas.

2.5 An example of value-added by the observatory: the SIMCODE-IGT project

The SIMCODE-IGT project (Spatial Impacts of Multimodal Corridor Development in Gateway Areas: Italy-Greece-Turkey) is a testimony to the value added of the Egnatia Observatory. The project aims to provide conceptual tools and an information base for evaluating the spatial impact of transport along the multimodal corridor linking South Italy, Northern Greece, and northwest Turkey in the broader context of European spatial development and transport policies (Kafkalas, Pitsiava 2007). Furthermore, the project aims to improve spatial cohesion and sustainability by allowing integration of transport policy priorities with spatial planning and spatial development efforts along the corridor and at the main gateways. To achieve this, the SIMCODE-IGT project uses spatial impact assessment to inform the formulation of policies promoting synergy between the priorities of transport infrastructure with those of spatial development and spatial planning.

In this context, the Egnatia Observatory with its system of indicators provides reliable data and updated information on many key aspects of spatial impacts. An example is the decoupling of freight transport demand, a composite indicator used to describe the relationship between economic growth (GDP) and total freight volume as the main factor responsible for freight-related externalities. This indicator is also related to the objective of the environmental protection policy (Objective 3, Table 3) and the increase in mobility and productivity (Steps 3 and 4 of the model Figure 3). When the GDP of a region increases at a much higher rate than the freight transport demand, the considered region appears to get a clear advantage from the expansion of its transportation task, indicating that it is becoming more efficient in utilising its existing transportation infrastructure and resources (Rodrigue 2020, Wang et al. 2021). This favourable condition prompts the consideration of strategic policy priorities that focus on improving efficiency in freight transport and promoting intermodality to optimise the movement of goods, thus leading to a more sustainable outcome (Kafkalas, Pitsiava 2010). However, before taking any decision, it is important to recognise the potential long-term implications considering the specificities of each region, because neglecting investment needed to promote efficient freight transport systems can hinder economic development and limit the competitiveness of the region in the long run (Kveiborg, Fosgerau 2007, Yang 2021).

3 Results: a methodological approach for adaptive spatial planning

Based on the lessons obtained and the insights inspired from the example of the Egnatia motorway spatial impact observatory, the extraction of evidence from data and its use as a knowledge base for the formulation of plans and the evaluation of their impact could be viewed as an adaptive process of basic relations linking theoretical models and planned interventions. A key insight is that in conditions where the emergence of unknown situations in the future is the most likely outcome, it is necessary to rely on flexible spatial planning frameworks that allow the recombination of the various elements and the adaptation of the respective plans (Getimis, Kafkalas 2002). The adaptive aspect of the approach implies that evidence should be used to enhance the flexibility and readiness of spatial planning to respond to unknown future conditions instead of pre-empting the future with pseudo-objective holistic solutions (Pitsiava, Kafkalas 2017). The proposed approach, which explores the path from data to plan, aims to strengthen the integrative and consensus building character inherent in spatial planning. The approach was given the symbolic name of IRIS, drawing parallels with the ocular diaphragm that regulates light intake and evoking the mythological connection to Styx water, known for testing truth, within Greek mythology, thus capturing the tension between raw facts and the extraction of evidence to accommodate multifaceted truths in the formulation of spatial plans.

The IRIS approach consists of several elements. It begins with the selection of a theoretical model that simulates the phenomena under study, such as the relationship between transport infrastructure and spatial development. The model represents a sequence of steps connecting these phenomena. On the other end of the process, there is the planned intervention, which aims to solve specific problems and align with policy priorities. The intermediate part of the process involves a data model that includes indicators that bridge the gap between the theoretical model and the plan. These indicators are selected to correspond with the steps of the theoretical model and provide the necessary evidence to formulate and evaluate planned interventions. The data model should remain flexible to accommodate a wide range of relevant phenomena and allow for selective use and addition of indicators based on the specific case.

Figure 4 visually delineates the fundamental elements of the IRIS approach, establishing a comprehensive framework capable of accommodating specific analytical components tailored to the unique context of each case. Within the context of the Egnatia motorway's spatial impact observatory, these specific elements have already been introduced in the research section and further elaborated upon in the subsequent discussion of the IRIS approach. This example serves as a demonstration of the key strength of the IRIS approach, which lies in its adaptability. It can be customised to suit various cases which may exhibit significant variations. This inherent flexibility makes the IRIS approach highly valuable for a broad spectrum of scenarios, as it can effectively address the inherent complexities and nuanced characteristics inherent to each distinct context. It should be noted that the initial idea of the bidirectional deductive/inductive path introduced by the IRIS model as the way to use evidence in spatial planning to bridge the gap between data and plans originates in the distinction made by Davoudi between the enlightening and the instrumental place of evidence (Davoudi 2012, 2015). She makes the distinction between a technical rational view of planning which perceives an instrumental place for evidence in the policy process that begins with the collection of often descriptive data and ends with a blueprint on the one hand and an enlightening rather than determining role of evidence in which policy is being informed by rather than being based on evidence.

At one end of the process is the choice of the theoretical model that simulates the real phenomena under study. For example, if the focus is on the relation between transport infrastructure and spatial development, the model should map the sequence of steps connecting these two sets of phenomena. Such a model, as the one used in the case of the Egnatia Motorway Observatory, can be presented as a series of steps as shown in Figure 3. At the other end of the process is the planned intervention aimed at the solution of specific problems and the pursuit of objectives corresponding to policy priorities. These are not always explicit and detailed but can be expressed in broad and generic terms and often refer to a long-term perspective of spatial development, such as the Europe 2020 strategy for smart, sustainable, and inclusive growth. For example, in the case of transport infrastructure, examined in the case of the Egnatia motorway, the above strategy is translated into guidelines to lay the foundation for how the EU transport system can achieve its green and digital transformation and become more resilient to future crises.

The intermediate part of the process is the data model needed to extract evidence from the data and bridge the gap between the theoretical model and the plan. This part consists of a system of indicators which are selected to correspond with the steps of the theoretical model, as was done in the case of the observatory of the Egnatia motorway. This system of indicators acts as a monitoring device which is used to collect and organise the appropriate data and extract the evidence needed for the formulation of planned interventions and the assessment of their impact in relation to both alternative plans and the pursuit of specific policy priorities. Given the complexity of the phenomena considered, the data model, as expressed by the indicator system, should remain flexible

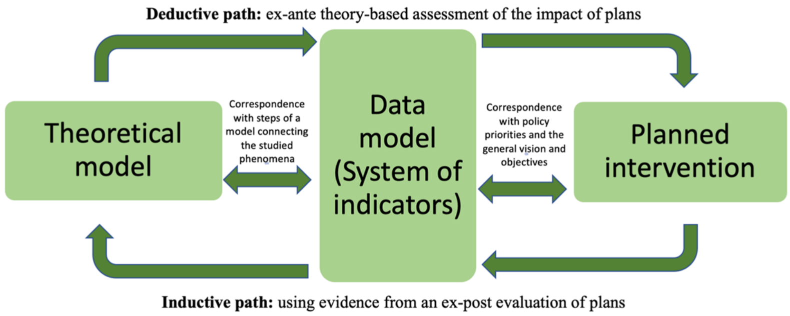


Figure 4: A generic scheme of the IRIS approach of adaptive spatial planning

for monitoring a wide range of relevant phenomena and should leave room for selective use and/or addition of indicators depending on the particular focus of interest on a case-by-case basis.

Theoretical models provide the background for insight and ideas on what indicators corresponding to the steps of the model should be included in the data model of the system of indicators to provide relevant evidence. Planned interventions provide the basis for the selection of the data model, i.e., those indicators that provide the appropriate evidence to measure the effectiveness of plans in promoting policy priorities. An example of this double correspondence is provided in Table 3 that presents the territorial impact assessment framework of the Egnatia motorway. The steps of the theoretical model for the phenomena studied are in the first column and the policies pursued through the plan are in the first row. The cells of the table were filled with the appropriate indicators that come from the intermediate data model of the indicator system that bridges the gap between the theoretical model and the planned intervention. What indicators are appropriate for the monitoring of a step, or a policy is a challenging issue that needs separate argumentation depending on each case examined.

The upper half of the process is the deductive path in the sense that it uses evidence for an ex-ante theory-based assessment of the impact of plans by providing insight into which parts of them and why they are expected to work or fail. This knowledge is crucial to enable the consensus required for the acceptance and implementation of the plans. When applied to projects already implemented, this path could help design and implement compensatory and complementary interventions aimed at minimizing unwanted effects. Given the fact that the deductive path depends on the adopted theoretical model simulating the real phenomena, there is always a danger to be used as a binding self-fulfilling prophecy instead of a flexible provisional solution to be tested. The bottom half of the process is the inductive path in the sense that it uses evidence from ex post evaluation of the spatial impacts of already implemented plans to test their effectiveness in the promotion of policy priorities. This knowledge of whether and in what way certain parts of the plan worked is potentially useful for subsequent plan-making of similar new projects or compensatory and complementary interventions to minimize any negative consequences. Given the fact that the inductive path does not depend on a theoretical model, simulating the real phenomena is susceptible to manipulation for the ex-post justification of the plans by presenting only the kind of evidence that proves their effectiveness.

The knowledge of what works and how effectively provides crucial insights that may be used to validate and/or adapt accordingly the initial theoretical model, the intermediate data model, as well as the policy priorities pursued by the plan. In this respect, the system of indicators in its capacity as a data model may be viewed as sensory organs which record changes in the environment and regulate the (re)organization of human activities within a territorial entity. This interaction has different outcomes which emerge in different time scales from the immediate to the very long term. An example of an immediate adaptive response is the diversion of traffic due to a bottleneck, while the increase in public green space or the expansion of city boundaries are examples of medium- and/or long-term adaptive responses. The inevitable inertia that accompanies the fixed assets associated with many planned interventions also plays a decisive role that orients spatial planning towards compensatory measures or regulatory mechanisms rather than to the destruction of existing and the building of new infrastructure.

It is important to note that while the IRIS approach provides a methodology and framework for adaptive spatial planning, its application and effectiveness may vary depending on the specific context and characteristics of each project. The general idea and principles behind the IRIS approach can be applicable to spatial planning projects that may differ in terms of their goals, geographical location, stakeholders involved, and available data. However, the specific implementation and the selection of indicators and data collection methods would require careful consideration and adjustment based on the specific project's requirements and context. Therefore, while the IRIS approach offers a valuable approach to enhance the flexibility and adaptability of spatial planning, it may need to be tailored and customised to suit the unique circumstances of each project.

4 Conclusion: adaptive spatial planning and the critical role of evidence

In the contemporary landscape of spatial planning, particularly in the wake of the digital era and the proliferation of big data, the use of evidence has become a crucial factor in the decision-making process. However, the complexity of determining the nature and extent of evidence required to devise a good plan remains an intricate challenge with no straightforward answer. Studies on what spatial planners do in this regard show that depending on each case, different data are collected, interpreted, and used as evidence, including qualitative characteristics such as views and expressed concerns of the local community and the interests of other stakeholders. Furthermore, these studies highlight a fundamental reality: The impartiality of decisions can become a subject of contention, irrespective of the volume and nature of the evidence employed. This arises from the absence of a distinct methodology that systematically justifies the hierarchy of priorities in the formulation of proposals. (Davoudi 2006, ESPON DIGIPLAN 2021, Lord, Hincks 2010). This intricate interplay between evidence, objectivity, and prioritisation unveils the multifaceted nature of contemporary spatial planning endeavours, inviting the exploration of new paradigms to balance data-driven insights with theoretical understanding and social consensus.

In this context, the IRIS approach introduces a comprehensive and integrative methodology that improves the efficacy of spatial planning processes. By establishing a link between theoretical models, policy objectives, and evidence-based decision-making, the IRIS approach addresses the complexities inherent in spatial planning. Using a system of indicators, this approach bridges the gap between theoretical models and planned interventions, ensuring a more informed and adaptable planning process. This integration of inductive and deductive paths empowers planners to make well-founded decisions by assessing the impact of plans before and after implementation. By tracking the correspondence between clusters of indicators, theoretical models, and policy objectives, the IRIS approach offers a methodical means to validate and refine plans. Its specific value-added lies in its capacity to combine scientific insight with political will, thus facilitating a more informed and consensual approach to spatial planning challenges. Furthermore, the IRIS approach can contribute to the development of adaptive governance frameworks in spatial planning. By continuously assessing impacts and incorporating feedback into the planning process, adaptive governance can enhance the resilience and responsiveness of spatial plans to changing circumstances.

The completion of the circular path ensures that both the deductive part and the inductive part contribute to the knowledge that enables the bridging of the evidence gap between data and plans. This is crucial for the critical relationship between scientific advice and political will that has been analysed elsewhere as the tension between an enlightening path that takes science into account in the formulation of plans and an instrumental path that uses science to effectively implement political decisions (Davoudi 2012, 2015, Kafkalas, Pitsiava 2010, Pitsiava, Kafkalas 2017). A more pessimistic view is that whenever there is a question of a confrontation between science and politics, the former is usually de facto reduced to the role of rationalising political decisions or switches to a pragmatic rationalism that allows the transition from knowledge to vision in terms of the real limitations and possibilities set by politics (Flyvbjerg 2003). The proposed IRIS approach resolves these issues through mediation of the indicator system, which acts as a data model that connects the steps of the theoretical model with the policy priorities pursued by the plan. In this way, the policy priority pursued by the plan is linked to the causality of the steps assumed by the theoretical model. However, it should be noted that the completion of the circular path could not happen simultaneously for the same plan. This becomes possible in the medium and long run by successive rounds of assessment of impacts and by comparison of many similar parts of many planned interventions.

In the context of the previous discussion, it is underlined that to bridge the distance from the present to the reality envisioned by the plan, the available data should be organised as evidence through theoretically informed 'data models' compatible with the dominant theoretical narrative of spatial planning. To the extent that spatial planning concerns an unknown future, the above adaptive approach does not guarantee the correctness of the decisions (Assche et al. 2017). The reason is that spatial organisation is a system of organised complexity, the future state of which, that is, the object of spatial planning, is formed through an evolutionary dynamic of functional and organisational differentiation and adaptation to constantly changing conditions (de Roo et al. 2020, Komninos 2018, Mehaffy, Salingaros 2014). However, what the IRIS approach can do is to improve the adaptability of the spatial planning process by providing the evidence necessary to improve the relevance and effectiveness of the plans. But, as we have seen, the identification of evidence presupposes both a practical interest to solve a problem and a theoretical approach to guide the attempt for its solution.

Thus, the question of the appropriate plan depends on the question of what should be considered as appropriate evidence to assess its relevance and effectiveness. Accordingly, the evolution of the main narratives of spatial planning, which can be seen as an evolutionary adaptation of spatial planning itself, reflects changes in the way reality is approached and how data are selected and interpreted to become evidence in the formulation of plans. An example offers the current situation where new digital technologies and applications dominate and, through generalised digital connectivity, provide new possibilities for data collection and processing in real time. The search for evidence takes advantage of access to data that allow the assessment of citizens' opinions and needs in the formulation of plans. Algorithmic techniques and the dematerialisation of many activities create expectations for better spatial governance and spatial organisation but are also accompanied by risks of increased surveillance and restriction of rights as they allow the collection and processing of big data beyond the limits of voluntary participation and consent of citizens. These trends create new expectations and risks that seem to be at the core of the future evolution of spatial planning.

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REGION
The Journal of ERSA
Powered by WU

Volume 10, Number 3, 2023, 83–104
DOI: 10.18335/region.v10i3.468

journal homepage: region.ersa.org
ISSN: 2409-5370

The Rise of Bitcoin, Economic Inequality and the Ecology

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Received: 8 December 2022/Accepted: 9 October 2023

Abstract. What do we know about the interrelations between economic inequality, ecology and the increased use of Bitcoin? The aim of the paper was to empirically test the relationship between economic and ecological effects related to the increase in Bitcoin's network hashrate in a selection of countries that have the highest influx of crypto-mining. To test these three hypotheses, I collected a dataset concerning Bitcoin indicators, economic indicators and ecological indicators that were obtained from multiple trustworthy sources: OECD, World Bank, Fred Data, World Inequality Database (WID). Handling the data challenges, I used this unique panel dataset to explore the relationship between Bitcoin's hashrate and two types of outcomes: (i) economic outcomes where inequalities may emerge or direct measures of inequality (such as the GDP, income inequality (GINI) and the share of people with top 1% of income and 1% of wealth), and (ii) ecological outcomes (such as carbon emissions, carbon footprint and electronic waste). I found that the Bitcoin currency is associated with a certain redistribution of wealth but, it itself remains concentrated in the wealth of the top 1%. Also, there is evidence for certain nonlinearities in the relationships with the ecological degradation, echoing the concept of the Kuznets curve.

Key words: bitcoin, ecology, hashrate, inequality, productivity

1 Introduction

The advancement of digital currencies over the last decade has contributed to a huge increase in the popularity of trading and mining them in the crypto space all around the world. Cryptocurrencies are digital currencies that can be exchanged between people without the need of any third-party intervention from an organisation such as a central bank. The rise of cryptocurrencies became prominent in recent years due to the accessibility of the blockchain and its anonymity. The rise of the cryptocurrency market came along over a decade ago with the creation of Bitcoin in 2009, with many more following in its footsteps, creating what is now a huge platform of digital currencies which can be created, traded and used to purchase valuables. But how much do we know about the interrelations between economic inequality, ecology and the increased use of Bitcoin?

What we know is that the Bitcoin network alongside most other cryptocurrencies operates via the 'proof of work' mechanism, which was created as a way to secure the network and does so in a very effective manner. This mechanism is used to protect the network from attacks and fraudulent users, by users needing to complete proof of work to validate transactions to be added to the blockchain for all to see. In doing this some users, called miners, are rewarded a portion of the digital currency, and thus generate the coins, but at a cost, because to do this effectively the miner requires a very powerful computer system. Since Bitcoins popularity spiked, the network saw a huge influx of users, which raised questions about Bitcoin's sustainability due to its current mechanism being highly energy intensive (Di Febo et al. 2021).

So, the crypto space operates with an incredibly high demand for electrical energy, due to its current operational mechanism. This intense need for a lot of energy is a very relevant topic, from the perspective of ecological degradation, which has been a growing concern over the last decades. This is particularly concerning as not all the energy to be supplied is from renewable sources, but instead from scarce and incredibly damaging fossil fuels, which emit an unsustainable amount of greenhouse gases into the environment. In 2015, the Paris Agreement was signed by several countries in strive to avoid climate change by pushing global warming below 2°C, but the rise of the digital currency era could prevent this from happening. There is also a great amount of electronic waste being disposed of in relation to Bitcoin mining, which again has a damaging effect on the environment that the world is striving to eliminate (Di Febo et al. 2021).

Another very relevant area within this topic, which is discussed in this study, is whether or not these cryptocurrencies will help with wealth and income inequality. Many sources suggest that the crypto space has helped with the world's income inequality, I will explore whether the blockchain is actually run by the wealthiest and whether it is not just a new method of driving the wealth of the already wealthy up, whilst the poorer will not enjoy much benefit in the long run. This is very relevant today as world inequality is still very high and there are many efforts to push for equality, but this new digital age could help worsen the current economic situation around the world.

The aim of this paper is to assess which are the different factors that affect the digital currency world with focus on Bitcoin, in order to shed light on how and why they operate and to disentangle the possible economic and ecological outcomes of their use. To achieve this, the current paper compiles a unique panel dataset, informed about the Bitcoin networks, their main determinants with economic and social nature, as well as information about the ecological degradation in the countries included in the dataset. This information allows us to explore the trends in Bitcoin usage and the ecological damage in a country and the relationship between them.

The rest of this paper is structured as follows. Section 2 will offer the literature review on how Bitcoin was developed and how it works, the economic outcomes in relation to Bitcoin's development, the ecological impacts from its development and finally a dive into the non-linearities in these relationships, in line with what we know about the economic and statistical meaning of the Kuznets curve. Section 3 will present the empirical part of this study, this will include the description of data and estimation strategy, followed by the results and their analysis. Section 4 will offer some concluding remarks, with discussion on the importance of the findings presented here and some ideas for further research.

2 Literature review

2.1 The history of the blockchain technology

During the 2008 financial crisis, a paper was released called 'Bitcoin: A Peer-to-Peer Electronic Cash System', by a pseudonymous individual named Satoshi Nakamoto. This paper illustrated that the current financial system had some major weaknesses, which stemmed from the trust model (Nakamoto 2008). The current financial model we are familiar with is almost completely reliant on a third-party, this third party is a financial institute such as a central bank or governing body. Nakamoto goes on elaborates that the current system "cannot avoid mediating disputes" (Nakamoto 2008, p. 1) and that there no way to currently have "completely non-reversible transactions" (Nakamoto 2008, p. 1), this is mainly due to trust between the individual parties. This trust factor can lead to fraud and is very common and thus creates an unwanted hostility between a merchant and a buyer (Vranken 2017).

This hostility seems to stem from the system being able to reverse transactions and at the time there was no way of protecting a seller from being vulnerable to fraud. However, this uncertainty in payments and costs of mediation can be avoided by a buyer using physical payments such as cash but this isn't sufficient in the growing digital age. So, Nakamoto proposed a computational system to make payments without the need of involvement from a financial system, so peer to peer transactions can occur directly without trust needing to be placed on the third party (Chohan 2021). This would be done by having a system where there is a timestamp of proof of transactions in a chronological order, to create a safe space to buy and sell via a digital currency without the worry of a fraudulent individual attempting to 'double spend' (Nakamoto 2008).

Although Satoshi Nakamoto put the blockchain technology on the map it wasn't him who first established this technology, in fact this technology wasn't initially created for cryptocurrencies. David Lee Chaum, a cryptographer who published a dissertation in 1982 named 'Computer Systems Established, Maintained and Trusted by Mutually Suspicious Groups', describes the first instance of a blockchain system. The blockchain is a simply a distributed, decentralised ledger that records and stores data such as transactions. As the name suggests the data is first recorded and stored in blocks and then the block is added to a chain thus creating a long chain of information which is all stored in a cryptographical sequence. These transactions are verified through a consensus mechanism, this information is stored for all participants to see and cannot be deleted, so every transaction can be seen and traced back to its origin (Crosby et al. 2016).

2.2 How the Blockchain works

The blockchain operates with three fundamental attributes, the first attribute is to be 'decentralised', meaning that the control of the network is not held by a singular organisation or governing body. In fact, its control is distributed among all its participants/nodes so even if one individual is corrupt the network won't fail. The second of these traits is that there is direct peer to peer transactions which entails trust between two unknown parties to interact directly to form a transaction, but this trust is built upon both users having access to proof and history of transactions. The last of these fundamental traits is that the ledger is distributed among all nodes so again if one element of data is tampered with it will not compromise the system (Chohan 2021). The data is stored on many hardware devices from many multiple nodes that are within the system. This is favourable to many people when compared to a centralised system that most are familiar with such as central banks, which can be completely compromised If the main node is corrupt or tampered with. Which can make it less safe as not everyone can or will see the corruption take place within the system, such as hackers or fraudsters as the centralised system runs on a cloud network which is very vulnerable to attacks.

In Nakamoto's paper he defines an electronic/digital coin as "a chain of digital signatures" (Nakamoto 2008, p. 2), this is done in practice when a transfer happens between two nodes on the blockchain platform. In this transaction the initial owner of the electronic coin digitally signs a hash, which is a function that meets the required inscribed demand that is needed to solve the complex blockchain calculation (Begum et al. 2020). This verification system allows for a node to see the history of ownership of the coin. However, in doing this method the second owner will not know if the first owner had double spent and this is an issue. Traditionally the financial institute will check each transaction and each payment has to go through this central authority (central bank) to be validated as not double spent.

Double spending is where a cryptocurrency is used twice or more and can occur when the transaction information within the blockchain is changed, if these modified blocks make their way into the blockchain then the person can reacquire their already spent crypto. The job of proof of work is to prevent this happening. However, unlike a centralised system where it would be easy to spot an error like this, the blockchain operates differently because it has millions of users with their own records. Double spending is very bad for a network as it can reduce the value of the coins and make it worthless.

In blockchain technology there is no mint or central authority to do this, so the method created was to make these transactions publicly known and an over consensus agreement on where the coin has been and where it arrived first. So, a proof system showing the exact time each transaction was made, with a positive number of nodes agreeing on its legitimacy. To do this there was proposed a timestamp server, which is where the hash of a block of items is and publicly announcing the hash, in doing this it shows all nodes that at that exact time the data existed (Nakamoto 2008).

2.3 The proof of work mechanism & Hashrates as a Measure for Bitcoin Use

The proof of work was the first and still is currently the leading consensus mechanism for the cryptocurrency network which was also proposed by Satoshi Nakamoto in 2008. Unlike other database systems, that would be controlled by an individual and would require them to update the system on their own, like a school or hospital database systems. The blockchain is self-governing meaning there isn't one person that can control or change the system, in fact contributions from over 60 million users worldwide that participate in the network to allow it to function accordingly. This means that people trying to commit fraud can be easily spotted, this is a huge benefit that this consensus model has. This is because instead of one person having control of the database, everyone has access to it via their own logs which are recorded and public. Proof of work is a special algorithm that uses a huge amount of effort to locate and eliminate counterfeit uses of computing power (William et al. 2022).

The proof of work mechanism is completed by users of the network called miners, these miners perform proof of work on new block to then be added to the blockchain, this works by the miner finding the winning proof of work in order to validate the transactions. In other words, the miners are running very energy demanding programs on their computer to solve these very complicated mathematical problems to be the one to guess the correct 'password' to validate the transaction and thus add the transaction to the blockchain. This method of validation is actually a hash function (Crosby et al. 2016). Upon validation the user receives a portion of the cryptocurrency as a reward for their work. So, the proof of work mechanism works similarly to Adam Back's hashcash, as it involves the scanning for a value that when hashed, with hash function SHA-256. This is a secure hash algorithm and is cryptographic, the hash algorithm creates unique hashes, and the number begins with a number of zero bits, the work required is exponential and is verified by executing a single hash. This is done by finding a nonce value that satisfies the cryptographic hash function, which means that the node has found the value that gives the block's hash the zero bits that is required (Küfeoğlu, Özkuran 2019).

So, a new block was proposed which for the Bitcoin network this set to be every 10 minutes, when this happens every active miner will have their computers continuously guessing a random nonce value, if the hash (H) with the guessed nonce (N) value is higher than the target value (T) then the computer will have to restart and guess a new nonce value until the nonce value satisfies equation 1 below (O'Dwyer, Malone 2014).

$$H(B.N) > T \quad (1)$$

When the first miner has found the correct nonce value so that the hash function is less that the target value, the block can then be added to the Bitcoin blockchain and in doing this validation the miner receives a portion of Bitcoin.

So, a Bitcoin miner goes through a process to solve the complex mathematical problem to find the nonce value so that the hash of the block containing the transaction information is smaller than the target (Kroll et al. 2013). This computational process requires an incredible amount of computational power as the CPU, GPU or ASIC devices will be constantly guessing random values. However, the more computational power the miner has the greater the amount of guesses their computer system can make per second and thus the greater the reward for that miner is. This value is called the hashrate and can be described as the computational power being used to mine and process transaction via the proof of work mechanism, so the higher the hashrate would indicate a larger number of nodes participating and thus a greater energy use overall. This is where speculations on the energy consumption of the Bitcoin network come from, as this process clearly requires a lot of energy. Due to the reward scheme integrated into the mining process, many people saw this as an opportunity to make money and the regular home computer setup was ditched for many to invest in mining rigs/farms. The more valuable Bitcoin or any other digital coin using the proof of work mechanism is, the greater the incentive for the miners to have better and more equipment (Qin et al. 2018).

Initially when Bitcoin was first released and several years after the hashrate was low, meaning that less computational power was needed for the computer to solve the problem and earn the reward. However, as the popularity of Bitcoin grew, so did its value and thus attracting more miners. As the number of miners grew, the number of attempts to validate the blocks to be added to the blockchain increased exponentially, meaning there was a greater chance of the correct hash value to be found. In the case of this technology becoming used popularly world-wide, Nakamoto had precautions put in place to make the difficulty to mine increase. Bitcoin's difficulty algorithm which was put in place to stabilise the system and maintain a 10-minute duration of finding new blocks to be validated. So, the difficulty of mining changes depending on the number of miners that are actively trying to crack the code, this difficulty is changed by increasing or decreasing the zeros in front of the target hash (O'Dwyer, Malone 2014). So, the higher the hashrate is, the more difficult the proof of work becomes. This difficulty in completing the proof of work on a block was also introduced to compensate for the expected increase in the speed for the hardware used to mine. This difficulty is what drives the energy use of Bitcoin up, as the harder it is to solve, the greater the energy needed to run these supercomputers. So intrinsically the proof of work mechanism is built to be very energy demanding as popularity increases.

The reason for this energy intensive design of the proof of work mechanism is necessary for the network's security against an attack. The most talked about is called a 51% attack, this is where attackers are able to control more of the network's hashrate than honest nodes (Ye et al. 2018). The proof of work mechanism helps to prevent this sort of attack by making it very energy demanding to control this much of the network so it wouldn't be sustainable or profitable for someone to do so (Shi 2016, Courtois et al. 2013).

2.4 Bitcoin and Economic Outcomes

Bitcoin and the blockchain technology have become very mainstream over the recent years with its value increasing significantly over the recent year. In 2018 Bitcoin's total market capitalisation was over $200,000,000,000 which is greater than the GDP of many countries in the world (Wealth 2018). Gross domestic product (GDP) is the total monetary value of all goods and services in a country, this value is usually calculated annually and can be referred to as the size of a country's economy. There are many factors and methods that go into calculating a country's GDP such as money spent, money earned or the value added to the economy, so when looking at Bitcoin's contribution it comes with great difficulty. For example, a Bitcoin miners contribution comes from the labour and capital output but for investors in Bitcoin their contribution comes from the profit made on the asset and for the regular user of the Bitcoin network it is the actual currency itself (Wealth 2018).

In a paper called "Role of Bitcoin on Economy", it can be seen that in Dubai the GDP increased by nearly 10% from 2009 to 2011, which was expressed to be due to the Bitcoin technology helping online trading and retail industries to boom. The Bitcoin technology allows for faster transactions in a more efficient way that there has been before. Bitcoin is also universal, meaning that there is no need for exchange rates which would be necessary in the conventional use of money (Singhal, Rafiuddin 2014). Another study that has shown Bitcoin's effect on GDP, showed that Bitcoin has a very significant effect on GDP, with each unit change of Bitcoin having an effect of increasing or decreasing GDP by a coefficient of 2924749 with a negative relationship (Utomo 2016). It has also been found that an increase in the use of crypto trading with Bitcoin being the dominant currency has led to enhanced GDP and globalisation (Miśkiewicz et al. 2022).

In the recent years of the uprising of the Bitcoin network, many speculations on the wealth distribution of the currency have risen. In theory a new currency that allows for anonymity with free and easy access, could help drive down wealth and income inequality.

However, many argue that Bitcoin's circulation has landed with the wealthiest, and the average user will not reap the benefits of the network compared to a user who was wealthy previous to Bitcoin's creation. In the light of the Bitcoin network, inequality can be increased by many individuals and organisations who can't compete with miners in countries where the electrical energy cost is high. We see a movement of their mining facilities to areas of the world where the cost of electricity is much less, meaning the profits for the miners are higher in countries where this energy cost is low. This means the poorer areas being exposed to more ecological pollution which is a great downfall of the current system (Dilek, Furuncu 2019).

It has been estimated by Credit Suisse, a large financial company in America, that a large sum of Bitcoins wealth is only distributed to a small minority of addresses, with the top 4% of users owning 97% of its wealth (Novak 2019). Another paper calculated that approximately in 2015 12 million Bitcoin was in circulation with 47 users holding over 28% of this value showing an incredible amount of inequality in the distribution of the Bitcoin network (Wolfson 2015).

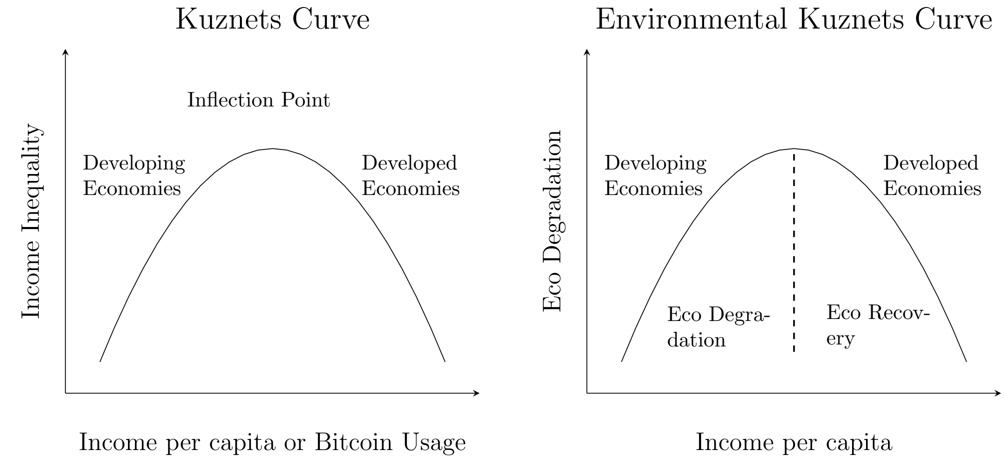
Another way to look at the wealth inequality of the Bitcoin network is to use the Gini index. The Gini index is a coefficient used as a measure of inequality across a certain population of people. The value of this coefficient is between 0-100 or 0-1, with a higher value indicating that the distribution of wealth is very low hence a higher inequality. Yet a lower value would indicate a more equal distribution of the wealth within the population. For Bitcoin this value started very low but by late 2009 early 2010 the value of this coefficient shot up to nearly 0.9 (or 90). However, this value was estimated to have reduced to 0.67 when looking at the top 10000 network addresses (Weymans 2022).

As we can see from the graph above the Gini coefficient has been declining for Bitcoin which shows the inequality of its wealth distribution is getting better over time. However, using the Gini coefficient has its limitations where a few users on either of the extreme ends of the wealth can change the statistic in a significant way.

The Kuznets Curve proposed and developed by Russian American economist Simon Kuznets uses this Gini index to show how income inequality behaves for a developing economy. An inverted 'U' shaped relationship exists between the income inequality and the growth of an economy represented as income per capita. The relationship that Kuznets discovered is very interesting as it shows that as an economy begins to develop, we see an increase in the income inequality that is measured by the Gini coefficient. In between the origin of the graph and the point labelled 'Developing economies' describes an economy at low levels of development, where the majority of the population will have a low income, and at this level the income inequality is relatively low. However, as the economy becomes more developed a minority of the population will gain higher income which then widens the income gap in the population which can be seen on the first graph from the point labelled 'Developing economies' to the point labelled 'Turning Point Income', in this region the income inequality is very high and is related to these few members experiencing a greater reward from the growing economy. As the economy keeps developing, we see a drop in the income inequality which the area between the peak of the graph and the point labelled 'Developed Economies', in this region appears the middle class. This is due a higher income experiencing a larger tax on their income which is used as investment on public goods and social welfare (Kuznets 1955).

The Kuznets curve was also developed to show how the development of an economy can also display the same shape for environmental degradation. This is to do with a developing economy having increased industrialisation, with a continuous increase in the capital stock, which means pollution increases and damages the environment. This can be shown on the second graph on Figure 1 which displays the environmental Kuznets curve, and once again we see that the pollution of a developing country increase initially and worsens the environment but again there is a turning point where the economy has developed and this environmental degradation begins to decrease and the environment will head towards its fruitfulness which was displayed before the development of the economy (Grossman, Krueger 1993, Dasgupta et al. 2002).

As discussed before Bitcoin's inequality coefficient, Gini, started at a very low value and then had a dramatic rise and now this value is declining as the wealth distribution



Notes: The above presented image is a well-known relationship. It is quoted in many studies, see for example Matthews (2018)

Figure 1: Economic and Environmental Kuznets Curve

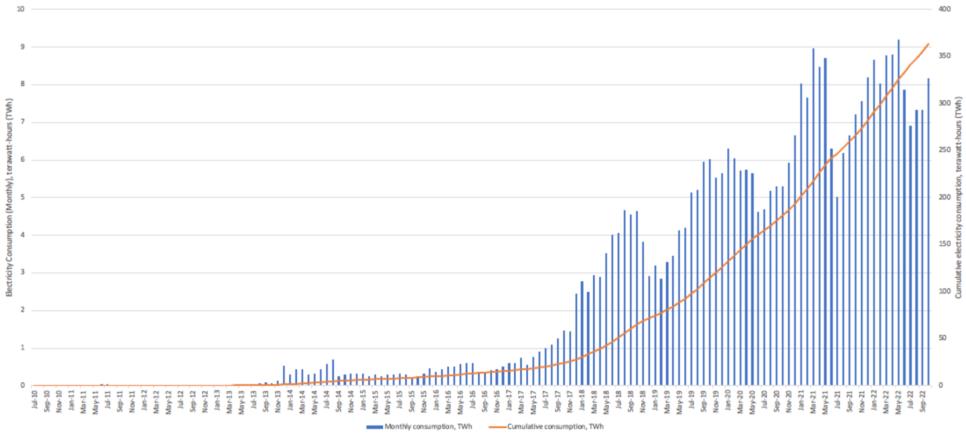
is being more spread out. This could be interpreted that Bitcoin is also experiencing a Kuznets curve due to its quick economic growth. However, the pollution caused by Bitcoin is still rising but this is due to it being in its development stage, and there is curiosity on whether or not it will also be subject to an environmental Kuznets curve, so once it has fully developed could we see a decrease in the environmental degradation. This will be explored throughout this paper as rich literature on its nature is not yet available.

2.5 Bitcoin and Ecological Outcome

Although there are many positive attributes of cryptocurrencies and the blockchain upon their creation, that initially gave rise to many people and organisations around the world seeing this new decentralised ledger as positive change away from a government-controlled economy. However, as of recent years many studies about the platform have unfolded the major negative impacts on the climate that this platform is causing due to its overwhelming energy use, which is purposefully built into its design (Truby 2018). This energy use links to an ever-increasing amount of carbon dioxide being released into the atmosphere which many experts have stated is not sustainable. Sustainability is essential for this digital platform in this day and age, as the world is currently suffering from a lack of care towards the environment. If these issues are left undealt with, it could not only cause a collapse to the digital currency platform itself but also cause permanent negative damage to the environment which this sector does not want on their hands.

As stated previously Bitcoin and other cryptocurrencies have a very energy intensive mechanism that becomes more energy demanding with time, which results in the network having an exponentially increasing energy consumption. In order for the current mechanism to work there needs to be miners. As discussed before miners use their computational power to solve a complex mathematical problem which finds a specific hash value to validate a block and then the block can be added to the blockchain (Egiyi, Ofoegbu 2020). The incentive to do this is because on completing this task the miner is rewarded an amount of that coin. However, this is where the extreme power usage comes from, as many people around the world saw this as a means to earn a lot of money.

Initially when cryptocurrencies first came into popularity there weren't many new transactions being added to the ledger and the currencies weren't worth a lot, so the steaks weren't very high. This meant the computer power and associated energy needed to mine wasn't that intensive, which meant most crypto miners were able to work from their own computers at home. Due to the difficulty increase of Bitcoin mining discussed in section 2.3, meant that the average miner was upgrading from their home computer to



Source: Data is obtained from Cambridge Bitcoin Electricity Consumption Index (CBECI) Database

Figure 2: Total Bitcoin Electricity Consumption

mining warehouses which is where the most financially successful mining operations are held. These mining warehouses are huge facilities that are running thousands of power intensive computers. This meant that there was a switch from CPU's and GPU's to mine the Bitcoin to ASIC's (Application-Specific Integrated Circuit) (Taylor 2017). These ASIC rigs are running constantly throughout the day attempting to find the right hash value, ASIC's can also produce more guesses of the hash value every second resulting in a greater competition among miners (Sutherland 2019). ASICs are purely mining devices and they serve little other purpose meaning as soon as their used until their no longer as fast as they were originally, they become electronic waste (De Vries 2019). Along with the power to run these computers there also needs to be cooling devices such as huge industrial fans which are also running at all times and thus requiring even more power is needed to keep this huge number of computers cooled and running (Stoll et al. 2019).

The power consumption gets worse with the increased incentive that the miner could have the potential to be very profitable with the ever-increasing value of Bitcoin. The value of Bitcoin was recorded to be $0.07 in 2010, at this time not many were invested into the network. However, this value rose quickly, with its value reaching $960 at the start of 2017 but this value quickly rose near the end of 2017 where it was recorded at highs of $20000 per coin and exceed a value of over $40000 in 2021 (Dilek, Furuncu 2019, De Vries 2021).

This increasing price created a huge increase in the number of miners on the network and caused the demand for energy to supply these mining facilities to increase drastically. Digiconomist have estimated that Bitcoin alone will use more that 120 terawatt-hours of electricity annually, which in comparison is a greater energy consumption that the whole of Norway annually (Digiconomist 2022). This is more than a 40% increase in electrical energy consumption when compared to last year's energy consumption. In an even more recent study, we saw the estimated energy consumption of Bitcoin increase to over 130 TWh, which was based on the consumption in July 2022 and means that per transaction the network will require 1455.8 kWh of electricity, which means for every transaction enough energy is used to power the home of an average American household for nearly 50 days (Reiff 2021).

Over the years Bitcoin's energy consumption has been compared to the energy consumption of many countries annually and has been reported to have exceeded the annual energy consumption of over 150 countries in 2017 (Dilek, Furuncu 2019).

As we can see from Figure 2, Bitcoin's total electricity consumption is constantly rising, there are dips in the monthly data (Grey bars) however this is due to the unpredictability of the network, but as a general trend we see that over the year's Bitcoin is consuming more and more electricity. The issue behind this energy use is where this electrical energy is coming from, in a recent study by the University of Cambridge it found that 40% of the mining power comes from coal (Smith 2022). The use of fossil fuels in such a large amount is not great for the environment as the CO2 that is produced is unprecedented with latest data showing that Bitcoin produces 22 million metric tons of carbon dioxide emissions in just a year, which is roughly the same amount produced by over 2.7 million homes (Smith 2022). Although the Bitcoin network is using renewables, it is not enough for their continuous system, as renewables aren't as reliable as a steady flow of electricity from a coal mine (Digiconomist 2022, Onat et al. 2021).

The growing energy consumption has led many to believe if nothing is done in the near future, we could see cataclysmic climate events that could cause devastating effects on the human population and the planet. Another study on the pollution emissions of Bitcoin mining from the University of Hawaii Manoa, estimated that the carbon dioxide emissions in 2017 was upwards of 69 million metric tonnes (Egiyi, Ofoegbu 2020). It was also calculated that due to the difficulty increase that the Bitcoin network intrinsically has as discussed in the end of section 2, we saw that per transaction the energy requirement increased from 6.09 kWh to 493.77 kWh and the associated carbon emissions from 4.53 kg of emissions to 430.92 kg of emissions in just 6 years from 2015 to 2021. This value is set to keep rising at a spectacular rate due to the increased popularity, and complexity of the Bitcoin network (Onat et al. 2021).

There is also a selection of non-renewable sources being used to power the Bitcoin network mining procedures, however there is still a large portion of energy being supplied from fossil fuels. Many are concerned that this continuous use of fossil fuels could push global warming over the 2°C limit (Goodkind et al. 2020). These increasing air pollutants can cause major issues to human health alongside damaging the planet (Clark, Greenley 2019). In a study in 2018 looking at the Bitcoin mining network it was reported that Bitcoin mining was receiving 77.6% of its energy from renewable sources (Bendiksen, Gibbons 2018), however in another study in 2018 it estimated this value to be closer to 28% (Rauchs et al. 2018). This uncorrelation in the value of Bitcoin's use of renewables is concerning but with the studies discussed on the carbon emissions it suggests the value is lower than estimated by many.

In an article by Christian Stoll called 'The Carbon Footprint of Bitcoin' he discusses that Bitcoin mining would produce nearly 500 grams of carbon dioxide emissions per kWh of energy consumed (Stoll et al. 2019). If we assume this value to stay constant for Bitcoin, and using the yearly energy estimated previously of 120TWh, we could see Bitcoin carbon emissions to be upwards of 60 million metric tonnes. Due to the disparity of what energy sources Bitcoin uses, this value could be less, however, many mining operations have moved to many fossil fuel reliant countries such as Iran and China which would mean this value could be rising (De Vries 2021).

Alongside Bitcoin's energy consumption leading to carbon dioxide emissions that are harming the environment there is also the issue of electronic waste (E-waste). This electronic waste is due to the intensive nature of the proof of work mechanism and with these ASIC mining rigs constantly running, there leads to malware of the devices. This is an often occurrence and replacement of these devices is done regularly. However, the number of people doing this leads to a heap of electronic devices being thrown away and they end up as e-waste that doesn't get recycled. In China which hosts a majority of the big Bitcoin mining operations, only 16% of all electronic waste is collected and in other countries like Iran, Malaysia and Kazakhstan there are even fewer e-waste regulations as these countries are all comparatively low-income countries. This clear lack of attention towards the growing e-waste problem can cause devastating effects to both human and ecological health (De Vries, Stoll 2021, Jana et al. 2021).

Electronic waste from Bitcoin mining has also shown evidence of bacteria growth in soil with bio-remediation properties. This increase in electronic waste can be very hazardous to the environment if nothing is done (Jana et al. 2022). The amount of electronic waste created by Bitcoin mining in 2019 was nearly the same amount of waste produced in Luxemburg annually and is only set to rise as more users join the growing network (Lang et al. 2019).

The literature on Bitcoin focuses enthusiastically on its benefits and ability to affect inequality in a positive manner. However, the economic literature knows about important nonlinearities in the relationship between productivity and ecology and income, known generally under the Kuznets curve and environmental Kuznets curve labels. Hence, I think a gap exists in terms of the lack of details around the relationship between Bitcoin, inequality and ecology in terms of nuances of the measurement of the main notions and in terms of non-linearities in their dependencies. I will try to shed some light on this gap with the further explorations below.

3 Empirical Analysis

3.1 Data

In this research on the economic and environmental effects of Bitcoin I collected data from multiple sources (see Appendix A). This data was over various years and for multiple countries, although not all data was in the same scale. I found data on the monthly hashrate for Bitcoin from Cambridge Bitcoin Electricity consumption index (CBECI), the hashrate data was for 9 countries (China, Russian Federation, U.S.A, Canada, Malaysia, Kazakhstan, Iran Islamic Republic, Ireland and Germany), this hashrate was in two parts, the average monthly hashrate percentage and the average absolute hashrate over the year 2019-2022. Hashrate is described as the computational power used by a Proof of Work (PoW) cryptocurrency network, it can also relate to the number of active miners that are attempting to solve hash puzzles (CCAF 2023), it is measured in Exahashes per second (Eh/s) and can give us a direct assumption on the energy consumption as a higher hashrate links to a greater energy consumption and a lower hashrate is linked to a lower energy consumption (Financial 2022).

The next set of data I collected was the GDP for all the same countries as mentioned above. GDP is the Gross domestic product and is essentially a monetary measure of the size and health of the economy of a country over a certain period of time, for the research I am conducting, it is each year. I found this value via multiple sources such as OECD, Statista and the Federal Reserve Bank of St. Louis (FRED database). The GDP can be used to estimate the size and growth rate of an economy and was measured in billion dollars. The values I found were for the year 2019-2022.

I then found the Gini index/coefficient for the same countries, this value as well as the GDP was a yearly value. I gathered the data for the Gini index again from multiple sources, such as OECD, FRED data and Statista. The Gini index is a measure of the distribution of income and related to the wealth inequality of a country. A high Gini index represents a high level of wealth inequality and a low Gini value means the wealth is more evenly distributed, the scale for the Gini I have used is from 0-100, other scales may be from 0-1 but both serve the same purpose (Hayes 2022).

The last of the economic variables were income inequality and wealth inequality of the top 1%. I use the renowned Piketty's database – World Inequality Database (WID) to inform these indicators. These indicators are two alternative proxies for economic inequality, but the literature suggests that wealth would be more significant than income in the context of this research (Novak 2019).

Alongside the economic variables I also collected 3 ecological variables. These 3 variables are the carbon emissions, electronic waste and carbon footprint for the top 10% of carbon emitters. I found this data using the OECD database, e-waste monitor, ITU, Statista and world inequality database. Carbon emissions were measured in Megatons (Mt) and is the amount of Co2 that is emitted into the environment from each country, each year. The electronic waste is the number of electronic devices thrown away to landfill each year as waste and was collected in million tonnes. The carbon footprint is the total amount of all greenhouse gases produced by our actions this variable was for the top 10%

Descriptive statistics for all variables in the dataset used for this analysis are available in Appendix B.

3.2 Methodology

For the variables I have collected, I have panel data as it is observing how the different parameters behave over a period of time in different places. Within this time component, I had months and years and I used an OLS regression with the years and countries employing fixed effects for time and location, as these variables were constant across all the data and I had months detrending. Yet the results with and without month detrending did not differ too much because some of the values were already available only on yearly level. Yet, I preserved the monthly level of the observations to gain degrees of freedom for the estimations.

H01: The economic factors affect the level of Bitcoin's network hashrate.

H02: The ecological factors are affected by the level of Bitcoin network hashrate.

H03: Bitcoin's network hashrate is associated with a non-linearity in the economic factor, in line with an-inequality-Kuznets-curve tendency.

3.3 Operational Models

To operationalize this **H01**, I use the following operational model:

$$\text{Bitcoin Hashrate} = \text{Economic variables} + \text{Error} \tag{2}$$

To operationalize this **H02**, I rely on the following operational model:

$$\text{Ecological variables} = \text{Bitcoin Hashrate} + \text{Error} \tag{3}$$

To operationalize this **H03**, I will use operational model:

$$\text{Bitcoin hashrate} = \text{Kuznets curve} + \text{Error} \tag{4}$$

I will test the operational models using different proxies, to show and compare the results across the different specifications. The proxies for Bitcoin are the hashrate percentage and the hashrate absolute. The proxies for economic factor are the GDP productivity, GINI, income inequality for top 1% and wealth inequality for top 1%. The proxies for the ecology are the carbon emissions, the electronic waste and the carbon footprint. I will do this to test these hypotheses with the different proxies of the main components of the hypotheses in this study in order to make sure I have consistency across the different specifications. Put differently, this is a way to triangulate these results within the econometric methodology.

4 Results and Analysis

Table 1 shows the estimations for the association between Bitcoin and the economic factor. When GDP increases, we have a strong correlation that hashrate decreases, this holds true both for hashrate percentage and absolute hashrate. It could be interesting to see which of the determinants of GDP are most responsible for this association between GDP and Bitcoin as this will further extend our understanding of this relationship. However, it is still a very interesting result as it shows that Bitcoin was redistributed towards less wealthy countries. Yet, it is also true that an increase in the use of Bitcoin would in theory create more circulation of money thus increasing GDP for a country. So, this might seem as very positive news about Bitcoin and its propensity to decrease the economic inequality in the world. If we take a look at the next economic variable, this positive news seems to be further confirmed, as we see that the lower the Gini coefficient is, the higher the hashrate tends to be. As the Gini is a direct measure of inequality, this finding means that the wealth of Bitcoin is getting more distributed and this would mean more wealth distribution outside of the network. The Gini value association is only detectable for the hashrate percentage and not the absolute hashrate. However, looking at the last two variables we start to see some complexities, previously

Table 1: Economic variables effect on Bitcoin Hashrate

	hashrate_perc				hashrate_absolute			
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
gdp_productivity	-0.008***				-0.005***			
	(0.001)				(0.001)			
GINI		-1.621***				-0.383		
		(0.491)				(0.605)		
Income_1perc_ppl			-1,567.067				1,618.109	
			(5,146.791)				(6,069.827)	
Wealth_1perc_ppl				-1,182.202***				-1,031.962***
				(188.539)				(230.809)
country FE	YES	YES	YES	YES	YES	YES	YES	YES
year FE	YES	YES	YES	YES	YES	YES	YES	YES
month_detrended	YES	YES	YES	YES	YES	YES	YES	YES
Constant	171.666***	123.084***	270.767	408.437***	139.545***	74.573***	-169.285	369.189***
	(14.222)	(21.923)	(720.999)	(57.046)	(18.830)	(27.008)	(850.305)	(69.836)
Observations	261	216	252	252	261	216	252	252
R-squared	0.795	0.749	0.745	0.782	0.762	0.747	0.759	0.778

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; OLS with fixed effects for country and year, month detrended data; Specification (1) to (4) use outcome variable: hashrate, and Specifications from (5) to (8) regard outcome variable hashrate_aboslute.

Table 2: Ecological effects due to Bitcoin's Hashrate

Variables	(1) carbon_-emissions	(2) carbon_-footprint	(3) e_waste	(4) carbon_-emissions	(5) carbon_-footprint	(6) e_waste
hashrate_perc	134.510***	-0.000	0.005***			
	(8.506)	(0.000)	(0.001)			
hashrate_absolute				87.776***	-0.000	0.004***
				(8.981)	(0.000)	(0.001)
country FE	YES	YES	YES	YES	YES	YES
year FE	YES	YES	YES	YES	YES	YES
month_detrended	YES	YES	YES	YES	YES	YES
Constant	-503.091	36.000	9.515***	1,474.036*	36.000	9.545***
	(632.310)	(0.000)	(0.101)	(764.699)	(0.000)	(0.099)
Observations	204	252	183	204	252	183
R-squared	0.850	1.000	0.998	0.766	1.000	0.998

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; OLS with fixed effects for country and year, month detrended data; Specification (1) and (4) use outcome variables: Carbon emissions, Specifications (2) and (5) regard outcome variable Carbon footprint and Specifications (3) and (6) regard outcome variable e-waste.

not known. Namely, the income for the top 1% is not correlated with Bitcoin hashrate, but the wealth of the top 1% is significantly associated. The wealth of the top 1% seems here to be decreasing with an increase in hashrate. This means that the top 1% are getting worse off. This however is strangely juxtaposed to the existing literature that finds that the top 1% are profiting off an increased use of the Bitcoin network and the 'Bitcoin inequality' where the wealth distribution although getting more distributed is still heavily located with the more wealthy (Wolfson 2015, Weymans 2022). But in a way, it is logical that if re-distribution increases, then those who were previously dominant in the inequality will appear to be losing. Hence, actually there is consistency here between us and the literature, but it needs to look at the economic meaning of the statistical sign more closely.

In Table 2, we have the ecological pollution as an outcome (measured through alternative proxies), and we explore its relationship with the Bitcoin use as a determinant factor. Looking at the carbon emissions we see that there is a strong association between the carbon emissions increases and the increasing use of Bitcoin (both when measured with hashrate percentage or absolute hashrate). This finding is completely consistent with the literature. An increase in the hashrate tells us that there is an influx of users undergoing the proof of work mechanism which increases the energy use, and this is directly correlated to an increase in the carbon emissions. The carbon footprint has no correlation with the hashrate in this model which could be as a result of lack of controls for this variable as it takes into account more than just the carbon emissions (such as cars and other modes of transport). For the electronic waste variable, we see that there is also a strong association with an increased hashrate. This also is a convincing finding, as the higher the hashrate is, the more computers are being used to mine data, which in turn would lead to more computers being used up and replaced, in the replacement process these computers are disposed of as electronic waste.

In Table 3, we can see that the hashrate percentage and hashrate absolute do have a non-linear relationship with economic prosperity, which can be called a Bitcoin-Kuznets curve, in line with previous literature labelling nonlinear relationship with economic wealth in this manner (Weymans 2022). As seen from Table 3, the impact from wealth on Bitcoin is first positive but then declines with the further increase in wealth. The same occurs for the carbon emissions as it starts off increasing then a decreasing relationship appears, and the carbon footprint is not significant in this table. However, something quite interesting happens with regard to what the data reports about inequality increases in terms of wealth concentration and the nonlinear relationship of this indicator with GDP. For this variable we see in the table that the opposite occurs, at first it is decreasing and then increasing, so as the wealth of the top 1% is increasing. But this also occurs

Table 3: Bitcoin Kuznets Curve in Wealth Inequality

Variables	(1) gdp_productivity	(2) carbon_emissions	(3) carbon_footprint	(4) e_waste	(5) hashrate_perc	(6) hashrate_absolute
Wealth_1perc_ppl	-848,682***	2,820,585***	0.0	-122**	8,789***	7,070***
	(113,842)	(376,207)	(0.0)	(48)	(1,818)	(2,307)
Wealth_1perc_sq	1,501,659***	-5,386,515***	-0.0	175**	-17,136***	-13,923***
	(194,708)	(635,261)	(0.0)	(83)	(3,111)	(3,947)
Constant	134,930***	-353,690***	36.0	30.8***	-1,039***	-807**
	(16,788)	(56,069)	(0.0)	(7.1)	(268)	(340)
country FE	YES	YES	YES	YES	YES	YES
year FE	YES	YES	YES	YES	YES	YES
month_detrended	YES	YES	YES	YES	YES	YES
Observations	252	204	252	183	252	252
R-squared	0.996	0.833	1.000	0.998	0.807	0.789

Note: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; OLS with fixed effects for country and year, month detrended data; Specification (1) uses outcome variable: GDP, Specification (2) regards outcome variable: Carbon emissions, Specifications (3) regards outcome variable: Carbon footprint, Specification (4) uses outcome variable: e-waste, Specification (5) regards outcome variable: Hashrate and Specification (6) regards outcome variable: Absolute Hashrate.

Table 4: Bitcoin Kuznets Curve in GDP

Variables	(1) GINI	(2) carbon_emissions	(3) carbon_footprint	(4) e_waste	(5) hashrate_perc	(6) hashrate_absolute
gdp_productivity	0.001	-7.9***	-0.0	-0.001***	-0.033***	-0.037***
	(0.001)	(0.5)	(0.0)	(0.000)	(0.003)	(0.004)
gdp_sq	0.0	0.0***	0.0	0.0***	0.0***	0.0***
	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Constant	32.8***	90,644***	36.0	16.8***	395.876***	414.7***
	(5.9)	(4,187)	(0.0)	(0.8)	(29.757)	(40.2)
Observations	216	204	252	183	261	261
R-squared	0.968	0.924	1.000	0.999	0.841	0.808

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; OLS with fixed effects for country and year, month detrended data; Specification (1) uses outcome variable: Gini, Specifications (2) regards outcome variable: Carbon emissions, Specifications (3) regards outcome variable: Carbon footprint, Specification (4) regards outcome variable: E-waste, Specification (5) regards outcome variable: Hashrate, Specification (6) regards outcome variable: Absolute Hashrate.

for the electronic waste variable as we can see on the graph initially is it decreasing and then increasing. Firstly, this means that when wealth concentrates in a few, it might bring more productivity, but will also associate it with more harmful behaviour to the environment. Second, in spite of the different signs and directions across specifications, it still is always evident that non-linearity exists in the relationship of this variables employed. This important to note because the relationship which is already known to exist between GDP productivity, inequality and carbon footprint has been destabilised and is now present in the relationship between inequality and the Bitcoin hashrate. Some path dependence but also some changes and complexities seem to have occurred and need better data and more attention.

In results Table 4, these results use different proxies for the economic wealth (GDP rather than the top 1% of wealth as it was in Table 3). The only difference is that specification 1 uses GINI as an outcome measure for the local inequality. And we see that GINI has a linear relationship with GDP that disappears when we add a square value of GDP, and it does not provide any useful information for us as well as carbon footprint again. Otherwise, our specifications are the same as in Table 3 and they report consistent results with Table 3.

5 Conclusion

The exploration in this study regards the extent of the economic and ecological effects associated with the rise of the Bitcoin network. To explore the relationship between these effects, I compiled a unique dataset with a wealth of economic and ecological variables (such as: GDP, Gini, income and wealth inequality of the top 1%, carbon emissions, electronic waste and carbon footprint). The literature review offered an overview of the descriptive facts known about Bitcoin, the economy and the ecology, and the empirical explorations help to shed some further light on this relationship, factoring in also some aspects of nonlinearity.

The empirical analysis in this study shows that GDP has an inverse effect on the use of Bitcoin, with a rising GDP being associated with a lower hashrate. The Gini coefficient has the same relationship, which is in line with the reviewed literature, that claims that over time the Bitcoin-wealth is getting more evenly distributed among all users (Weymans 2022). The relationship of Bitcoin-wealth with the income and wealth of the top 1% however differs. For the income of the top 1% it showed an inverse relationship, while the wealth of the top 1% shows a positive relationship with Bitcoin. The interpretation of these findings can be done (in line with the existing literature on the top 1%) that Bitcoin-wealth gets more evenly distributed, however Bitcoin is in the hands of the wealthier 1%. Put differently, the redistribution in Bitcoin doesn't really mean an improved objective economic inequality – the Bitcoin-wealth seems still to be enriching the rich.

For the ecological variables available in the dataset used for this study, I find a consistent trend with both carbon emissions and electronic waste. These two variables both increased with the increase of hashrate. Which makes complete intuitive sense and is consistent with the literature, as an increased hashrate would indicate more active miners. Thus, an increased energy consumption is expected. In addition, increased number of hashrates indicates that the miners are probably using the previously discussed most efficient ASIC devices for mining, and the higher rate of using these ASICs leads to the generation of more electronic waste in time, since they wear out in higher numbers within the same time in comparison to the old devices. For the carbon footprint variables, there were no significant values that would indicate a relationship with an increase or decrease in hashrate. This makes us reflect on the statistical and ecological meaning of the footprint variable as a good measure for ecological aftermaths. That's particularly relevant, and apparently rather alarming, since such aftermaths are consistently detectable with the measures of emissions and e-waste, but invisible with the footprint variable.

The results in this study are obtained, using a personally compiled panel database, which contains more information, efficiency and variability than both cross-section and time-series data could offer and allows me to extract more statistical meaning from the raw data. Using the panel data, I completed an OLS regression with fixed effects for time and location. This is motivated by the fact that while this dataset is unique and previously not addressed for empirical exploration, still part of the data needed to be computed or was available at different levels. Thus, the most sparing and simple OLS with fixed effects allows me to extract the most without over-reliance on what might be sensitive to the pitfalls due to data availability.

Regarding the first hypothesis, I found that it cannot be falsified, i.e. the economic variables did have an effect on the Bitcoin variable, although the relationship was not as expected. Across the different specifications, the results were generally consistent. I found a significant relationship between the economic factors and the Bitcoin hashrate. Yet, the use of different proxies helped to identify some nuances about this relationship. While the use of GINI showed results consistent with the existing literature, namely decreasing inequality with the increase of Bitcoin, the use of the other variables depicted the picture in further details, as follows. GDP reported a negative relationship with Bitcoin, which might agree with the assumption that poorer countries started to mine. Yet, when we focus on the richest 1% of the population, the relationship of Bitcoin with income is not at all present, and it seems that the presence of Bitcoin is strongly associated with the richest 1% of the populations across the world.

Regarding the second hypothesis, I also found that it cannot be rejected, namely, the change in the Bitcoin variable did have an effect on two out of the three specifications tested.

The final third hypothesis was that Bitcoin was associated with a Kuznets curve type of nonlinearity that is typical for economic and ecological inequality. To cross check this, I explored the relationship between economic productivity and its square term on the one side and on the other side I used three alternative outcomes: (i) the economic inequality (to operationalize the classical Kuznets curve), (ii) the ecological pollution (operationalizing the ecological Kuznets curve) and (iii) the Bitcoin hashrate, as an outcome variable. When I used GDP as a measure of economic productivity and its square, the results obtained differed in direction from the findings when I used the 1% of the wealthy population. However, in both cases the expected nonlinearity was present. The difference in direction is also consistent with my previous findings that Bitcoin spreads across less wealthy countries but remains locked within the wealthier 1% of the population. This, more generally, gives the general novel insight, that the nonlinearities from ecology and economic development seem to have transferred in the field of the use of Bitcoin. Yet, the Bitcoin world has replicated in some complex ways the existing inequalities previously known in the literature.

While the above results shed some light on complexities in the relationship of inequality and ecology, that might be of high importance, still this work has some limitations which stem from the data availability which makes the use of more robust methods inaccessible at this point. Therefore, this research paper's main contribution entails raising some important flags for where attention might be due when better data becomes available in the future. Namely, during the collection of this data, I faced the challenge that there were multiple missing values in many of the data sources. For this electronic waste data, it was very hard to find many values, as some countries hadn't had a specific statistic in place for the measurement. Thus, I gathered most of the data I could and for the data that was not available, I used a 10% increase each year which was in-line with the data assumption from previous studies about China that the electronic waste was increasing by 10% each year. The data I gathered for the Bitcoin variables was monthly data, however monthly data was not available at some cases, and this meant that I had to use the yearly value to fill in the missing points, yet this led to some loss of variability.

Despite the limitations of the data, which meant that I had to use also the most conservative methods, the results in this study are still important in two ways: (i) they are validated with external consistency with the literature and (ii) they offer novel insights that report internal consistency between the findings of the current study. Thus, even with the existing data challenges, I still managed to show some significant and complex relationships of the Bitcoin hashrate and the economic and ecological variables. My results indicate that further work is worth to be done in the same direction, especially in order to confirm and further disentangle how the complex transfer of the economic inequalities has happened in the world of Bitcoin, and to delve further in the differences in terms of country and individual redistribution of income and wealth.

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A Appendix: Data Sources

Country	Data Source Link
China	
	https://data.oecd.org/gdp/gross-domestic-product-gdp.htm
	https://fred.stlouisfed.org/series/MKTGDPCNA646NWDB
	https://wid.world/data/
	https://www.statista.com/statistics/263770/gross-domestic-product-gdp-of-china/#: :text=Gross domestic product (GDP) of China 1985-2028&text=In 2022, the gross domestic,in the world GDP ranking.
	https://data.oecd.org/inequality/income-inequality.htm
	https://ccaf.io/cbnsi/cbeci/mining_map
	https://www.statista.com/forecasts/1171540/gini-index-by-country
	https://data.oecd.org/air/air-and-ghg-emissions.htm
	https://www.statista.com/statistics/499891/projection-ewaste-generation-worldwide/
Russian Federation	
	https://data.oecd.org/gdp/gross-domestic-product-gdp.htm
	https://fred.stlouisfed.org/series/MKTGDPCNA646NWDB
	https://wid.world/data/
	https://www.statista.com/statistics/263772/gross-domestic-product-gdp-in-russia/#: :text=In 2021, the GDP in,around 1.84 trillion U.S. dollars.&text=The Russian economy is primarily,private sector and the state.
	https://data.oecd.org/inequality/income-inequality.htm
	https://ccaf.io/cbnsi/cbeci/mining_map
	https://www.statista.com/forecasts/1171540/gini-index-by-country
	https://data.oecd.org/air/air-and-ghg-emissions.htm
	https://stats.oecd.org/Index.aspx?DataSetCode=EWASTE
U.S.A	
	https://data.oecd.org/gdp/gross-domestic-product-gdp.htm
	https://fred.stlouisfed.org/series/GDP
	https://databank.worldbank.org/indicator/NY.GDP.MKTP.CD/1ff4a498/Popular-Indicators
	https://wid.world/data/
	https://www.statista.com/statistics/188105/annual-gdp-of-the-united-states-since-1990/
	https://data.oecd.org/inequality/income-inequality.htm
	https://ccaf.io/cbnsi/cbeci/mining_map
	https://www.statista.com/forecasts/1171540/gini-index-by-country
	https://data.oecd.org/air/air-and-ghg-emissions.htm
	https://stats.oecd.org/Index.aspx?DataSetCode=EWASTE
Canada	
	https://data.oecd.org/gdp/gross-domestic-product-gdp.htm
	https://fred.stlouisfed.org/series/NGDPRSAXDCCAQ
	https://databank.worldbank.org/indicator/NY.GDP.MKTP.CD/1ff4a498/Popular-Indicators
	https://wid.world/data/
	https://www.statista.com/statistics/650869/real-gdp-canada/
	https://data.oecd.org/inequality/income-inequality.htm
	https://ccaf.io/cbnsi/cbeci/mining˙map
	https://www.statista.com/forecasts/1171540/gini-index-by-country
	https://data.oecd.org/air/air-and-ghg-emissions.htm
	https://stats.oecd.org/Index.aspx?DataSetCode=EWASTE
Malaysia	
	https://fred.stlouisfed.org/series/MKTGDPMYA646NWDB
	https://databank.worldbank.org/indicator/NY.GDP.MKTP.CD/1ff4a498/Popular-Indicators
	https://wid.world/data/
	https://www.statista.com/statistics/319024/gross-domestic-product-gdp-in-malaysia/#: :text=The gross domestic product in,a new peak in 2028.
	https://ccaf.io/cbnsi/cbeci/mining_map
	https://www.statista.com/forecasts/1171540/gini-index-by-country
	https://data.oecd.org/air/air-and-ghg-emissions.htm
	https://www.statista.com/statistics/1394260/malaysia-co2-emissions-from-energy-use/#: :text=In 2022, the amount of,highest in that same year.
	https://www.statista.com/statistics/499891/projection-ewaste-generation-worldwide/
Kazakhstan	
	https://fred.stlouisfed.org/series/MKTGDPKZA646NWDB
	https://databank.worldbank.org/indicator/NY.GDP.MKTP.CD/1ff4a498/Popular-Indicators
	https://wid.world/data/
	https://www.statista.com/statistics/436130/gross-domestic-product-gdp-per-capita-in-kazakhstan/#: :text=Gross domestic product (GDP) per capita in Kazakhstan 2028&text=The gross domestic product per,U.S. dollars (+29.89 percent).
	https://ccaf.io/cbnsi/cbeci/mining_map

Continued on next page

Table A.1 – continued from previous page

Country	Data Source Link
	https://www.statista.com/forecasts/1171540/gini-index-by-country
	https://data.oecd.org/air/air-and-ghg-emissions.htm
	https://www.statista.com/statistics/1320969/energy-related-co-2-emissions-kazakhstan/
	https://www.statista.com/statistics/499891/projection-ewaste-generation-worldwide/
Iran Islamic Republic	
	https://fred.stlouisfed.org/series/MKTGDPIRA646NWDB
	https://databank.worldbank.org/indicator/NY.GDP.MKTP.CD/1ff4a498/Popular-Indicators
	https://wid.world/data/
	https://www.statista.com/statistics/294245/iran-gross-domestic-product-gdp-per-capita/#: :text=The gross domestic product per,year to 4,996.57 U.S. dollars.
	https://www.statista.com/forecasts/1171540/gini-index-by-country
	https://data.oecd.org/air/air-and-ghg-emissions.htm
	https://www.statista.com/statistics/1302695/iran-emissions-per-capita-from-electricity-generation/
	https://www.statista.com/statistics/499891/projection-ewaste-generation-worldwide/
Ireland	
	https://data.oecd.org/gdp/gross-domestic-product-gdp.htm
	https://fred.stlouisfed.org/series/CLVMNACSAB1GQIE
	https://databank.worldbank.org/indicator/NY.GDP.MKTP.CD/1ff4a498/Popular-Indicators
	https://wid.world/data/
	https://www.statista.com/statistics/377002/gross-domestic-product-gdp-per-capita-in-ireland/#: :text=The gross domestic product per,a new peak in 2028.
	https://data.oecd.org/inequality/income-inequality.htm
	https://ccaf.io/cbnsi/cbeci/mining_map
	https://www.statista.com/forecasts/1171540/gini-index-by-country
	https://data.oecd.org/air/air-and-ghg-emissions.htm
	https://stats.oecd.org/Index.aspx?DataSetCode=EWASTE
Germany	
	https://data.oecd.org/gdp/gross-domestic-product-gdp.htm
	https://fred.stlouisfed.org/series/CPMNACSCAB1GQDE
	https://databank.worldbank.org/indicator/NY.GDP.MKTP.CD/1ff4a498/Popular-Indicators
	https://wid.world/data/
	https://www.statista.com/statistics/295444/germany-gross-domestic-product/#: :text=GDP of Germany 2022&text=In 2022, Germany's gross domestic,in the world GDP ranking.
	https://data.oecd.org/inequality/income-inequality.htm
	https://ccaf.io/cbnsi/cbeci/mining_map
	https://www.statista.com/forecasts/1171540/gini-index-by-country
	https://data.oecd.org/air/air-and-ghg-emissions.htm
	https://stats.oecd.org/Index.aspx?DataSetCode=EWASTE

B Appendix: Main Variables and Their Descriptive Statistics

Variables	Definition	Source	Obs.	Mean	Std.Dev.	Min	Max
gdp_productivity	Gross Domestic Product	OECD, World Bank, Statista,FRED	261	5246.3	7581.7	171.1	22996.1
GINI	Income Inequaltiy Coefficient	OECD, World Bank, Statista	216	37.5	7.2	26.9	48.9
Income_1perc	Income of the Top 1%	World Inequality Database	252	0.2	0.0	0.1	0.2
Wealth_1perc	Wealth of the Top 1%	World Inequality Database	252	0.3	0.1	0.2	0.5
carbon_emissions	Co2 Emissions	OECD, World Bank, Statista	204	1865.9	2769.4	11.9	10081.3
carbon_footprint	Carbon Footprint	World Inequality Database	252	45.4	13.4	34.0	75.0
e_waste	Electronic Waste	OECD, World Bank, Statista	183	3.5	3.8	0.1	10.2
hashrate_perc	Bitcoin Network Hashrate % share	CBECI	261	10.4	17.1	0	75.5
hashrate_abs	Bitcoin Network Hashrate Absolute	CBECI	261	13.3	21.0	0	91.1

REGION
The Journal of ERSA
Powered by WU

Volume 10, Number 3, 2023, 105–136
DOI: 10.18335/region.v10i3.498

journal homepage: region.ersa.org
ISSN: 2409-5370

Quantifying the Circular Economy in European Regions: a Bridge towards Smart Specialisation?

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Received: 26 May 2023/Accepted: 24 October 2023

Abstract. Circular Economy (CE) aspects are becoming increasingly relevant for a sustainable transition and regional development. Still, a methodology to assess regional performance and interregional differences is exclaimed to be missing at least in the European context. This gap makes it difficult to assess policies and evaluate development patterns. The authors present a methodology to overcome this research gap by including several dimensions of social, environmental, and economic CE aspects. The methodology consists of 29 indicators grouped in six dimensions with data obtained from various data bases. A static and a trend index are calculated to compare European NUTS 2 regions in terms of their current CE status and its development over the last years. The new insights paint a more differentiated picture of regional CE transition highlighting that a segregation is observable not so much between North and South or East and West but more between urban and rural regions. Regarding the practical CE implementation in European regions, the instrument of smart specialisation is discussed.

JEL classification: O18, P48, R1, R11

Key words: Circular Economy, Smart Specialisation, Transformation, Assessment Methodology, Regional Development

Declaration of Interest: The authors report there are no competing interests to declare.

1 Introduction

The challenge of a sustainable transition has two sides. The first is related to the output side of production, namely the generation of greenhouse gas (GHG) emissions and their reduction. Whereby the policy focus is strongly concentrated on this aspect, the second side which is related to the material input of production, still leads a relative niche existence. However, the relevance of this neglected perspective is highlighted by facts such as the tripling of global extraction of materials between 1970 and 2017 (IPCC 2015, 2020, Oberle et al. 2019, United Nations 2021). At the same time, global population and global income levels tend to rise in parallel with changing consumption patterns following a Global Northern standard. This has placed additional pressure on material extraction and consumption.

As the majority of this material stream is not recycled, composted, or reused after it has served its primary objective, it is turned into waste. While raw materials become increasingly scarce and more expensive to extract, waste of unrecycled material accumulates in equal measure and leads to new problems such as the pollution of biospheres (Deus et al. 2017, Haas et al. 2020, Nikolaou, Tsagarakis 2021). One substantial approach to reduce extraction and waste generation is the decoupling of economic growth from environmental exploitation. One of the central levers to achieve this decoupling is the transformation towards a Circular Economy (CE). The concept of a CE is based on developing circular systems of material and energy that maintain the value of resources as long as possible to realign environmental boundaries with economic activity (Muñoz, Navia 2021). The idea of circularity is becoming increasingly popular and is promoted by national governments supranational organisations such as the EU, as well as many business organisations and business around the world (Korhonen, Honkasalo,, Seppälä 2018). Regarding the practical implementation of a CE, activities will not only involve the product level but also administrative levels, particularly regions. This is by reason that facilitating factors for a CE such as stakeholder cooperation or the establishment of closed cycles are positively related to proximity. Accordingly, many political strategies are implemented on a regional level (Vanhamäki et al. 2020). However, the role of regions in a CE is not covered as extensively in the scientific debate as its relevance would justify. Since the successful implementation of circular measures in regions needs to recognise regional characteristics rather than proposing a one-size-fits-all solution, the missing regional focus also constitutes a political problem. Addressing this apparent gap is even more urgent for Europe as the Green Deal sets a new development paradigm of climate-neutrality until 2050 that involves CE as a central building block for EU policy in the coming decade (European Commission 2019, 2021, McCann, Soete 2020, Arsova et al. 2022).

The article at hand fills a gap by addressing the topic of CE in European regions. One of the central weaknesses is the availability of a quantitative framework to measure the implementation and effects of CE at the regional level. Such an extensive framework is missing in Europe, thus we propose a multi-dimensional methodology that combines existing approaches and introduces new aspects to overcome shortcomings of earlier models (European Commission 2011, Elia et al. 2017, Mitrovic, Veselinov 2018, OECD 2020, Mazur-Wierzbicka 2021, Arsova et al. 2022). To do so, both a static and a trend index are calculated to assess the state and the recent development of CE in European NUTS 2 regions. This analysis answers which regions can serve as an example for others, which regional policies have been successful, and highlights how to shape the process in the future. These findings are then integrated into the framework of regional innovation policy in Europe, particularly the regional innovation strategies for smart specialisation (RIS3). This instrument has been promoted as the primary policy measure for regional policy in Europe and is increasingly discussed in terms of a green transition. Accordingly, article discusses how CE and smart specialisation are related and make a claim that their mutual relevance for regional development should be further analysed (Doranova et al. 2012, Gianelle, Kleibrink 2015, Montresor, Quatraro 2018, Gerlitz et al. 2020). Applying such a framework of regional CE measurement (1) allows policy makers and scientists to track progress of regional CE development, (2) highlights geographical patterns, (3) identifies target regions for further analysis, and (4) helps to focus support schemes to those regions that need support.

Against this background, the article is structured as follows: Section 2 provides an overview about the concept of CE and its relevance, particularly for Europe. Afterwards, the geographical dimension of CE is presented before the linkages between CE and smart specialisation are discussed. In Section 3, an overview of the state-of-the-art assessment of CE in regions is presented and research gaps are identified. Section 4 addresses these gaps and reveals the development of a multi-dimensional framework of CE assessment. The results are presented in Section 5 and discussed in Section 6. The article closes with a conclusion and a discussion of the policy relevance (Section 7).

2 The concept of CE

CE as a concept has emerged from integrating different scientific disciplines from economics to natural sciences and is anchored in the broader waste and resource debate (Blomsma, Brennan 2017). These diverse origins lead to a certain level of confusion regarding the definition of CE and its embedding in different research streams. The current discussion about CE in practice requires a solid foundation of the concept's intellectual roots which will be illustrated in the corresponding subsections.

2.1 Theoretical foundations

The origins of circularity considerations trace back to the 1960s with the recognition of planet Earth as a closed system of circular relationships (Boulding 1966, Haas et al. 2020, Nikolaou, Tsagarakis 2021). CE as a particular topic was first introduced by Pearce, Turner (1990), but a steady shift could be recognised over the previous decades when attention transferred to a greater industrial and societal focus regarding controlling pollution and resource treatment (e.g., Meadows et al. 1972). CE then gathered further pace in the 1990s with the emergence of several environmentally related research streams developing in parallel, merging, and then separating over time. Among these research streams were fields such as industrial ecology which is based on the idea to learn from material and energy flows in nature, industrial symbiosis focusing on actor networks, cradle-to-cradle design centring on adapting societal flows to natural flows and sharing economy approaches emphasising the role of individual behaviour (Korhonen et al. 2018, Domenech et al. 2019, Bourdin et al. 2022).

The concept which evolved from this melange of ideas and that later became known as CE has recently gained urgency in light of mitigation of climate change with a particular drive derived from policymakers such as the EU, individual countries such as China or Sweden, as well as business development bodies such as the Ellen MacArthur Foundation (Chizaryfard et al. 2021). CE as a concept was developed and led by practitioners with a scholarly position and is still emerging. This is one of the reasons of conceptual confusion about CE definitions (Korhonen et al. 2018). The multitude of CE variants in the scientific literature in terms of concept, approach, and scope underlines the development the concept has undergone (Kirchherr et al. 2017, Wilts 2017). The fact that CE is an evolving concept influenced by different scientific disciplines and shaped by different stakeholder groups provides an explanation why the process of developing a definition is not completed and probably never will be. Until now, there is no consensus on how to clearly define CE so that several definitions exist in parallel (Korhonen, Honkasalo,, Seppälä 2018, Kovacic et al. 2020, Chizaryfard et al. 2021). Even if one wanted to provide a single definition, this endeavour would be doomed to fail as it would always exclude some interests and could not recognise the dynamic and evolving discussion on CE (Korhonen et al. 2018). Accordingly, we do not claim to present a universal definition here. However, the development of a quantitative methodology requires an understanding of what a CE is and entails.

Generally, definitions are divided based on different assumptions. Korhonen et al. (2018) identify two lines of thought based on a business and a scientific perspective on CE. Opposing that, Hachaichi, Bourdin (2023) name two streams with one focusing on a product level of restorative design and another on an economic level of creating cycles along production, distribution, and consumption processes (Hachaichi, Bourdin 2023). Methodologically, a product-level oriented CE regards material flows inspired by biological cycles. This is done so that each cycle of material use is complemented by another cycle, rather than seeing the materials being disposed after use (Kiser 2016, Braungart et al. 2007, Braungart, McDonough 2009, Braungart 2011). To "design out" waste, the input side of production is adapted by focusing on biological ingredients or "nutrients" which should be at least non-toxic but possibly even beneficial when returned to the biosphere. The concepts of recycling (1) and reuse (2) are complemented by the third factor of reducing (3), thereby forming the "3R principles". These principles have recently been supplemented by recovering (4) to create the "4R principles" (Ellen MacArthur Foundation 2013, 2015, Heshmati 2015). A broader definition of CE, which is the one that will be applied in this article, combines the previous aspects, and embeds them into a multidimensional framework encompassing economic, environmental, and social aspects. From this perspective, CE is not only a production variant but a concept that also covers societal aspects and economy-level implications.

Accordingly, the benefits of CE can be divided into economic, social, and ecological aspects. From an economic point of view, CE promises potential net savings of material and energy costs, competitive advantages, and increased competitiveness for companies, as well as improvements in selection and product quality for consumers. Additionally, local industries, a category to which CE companies commonly belong, have proven to perform better in times of economic recession which might indicate a stronger resilience through circularity (Greenovate Europe 2012, Ellen MacArthur Foundation 2013, Ketels, Protsiv 2017). Niang et al. (2023) highlight that growth in employment in CE-related sectors was higher than the growth of total employment, indicating an economic benefit of CE. Moreover, the preservation of high-quality materials can reduce the demand and therefore the dependence on the import of raw materials and intermediate consumption. Regional cycles make value chains less vulnerable to price fluctuations and to the insecurity of supply potentially arising from resource scarcity or geopolitical factors (European Commission 2014, 2016, Ketels, Protsiv 2017, Wilts 2017, Bourdin, Torre 2020).

From an environmental point of view, CE reduces the pressure on the extraction of raw materials by increasing the supply of recyclates. Moreover, negative externalities of waste production and inappropriate disposal can be addressed by recycling, designing for repair, and extending the life-cycle of products. However, the concept of CE is limited by fundamental laws of thermodynamics stating that certain quantitative and qualitative losses are unavoidable. Moreover, maintaining the high quality of virgin materials is almost impossible since all processes of recycling involve a certain amount of quality loss and down-cycling. It is therefore required to notice that the promise of a CE will not solve the problem of an unsustainable economy on its own through technological innovation and new institutional frameworks. This is even more true as rebound effects are a well-known phenomenon and have in many cases, undermined the efficiency gains of CE (Georgescu et al. 2014, Gregson et al. 2015, Gonçalves Castro et al. 2022). It is this aspect that is primarily addressed in the social dimension of CE. While CE involves social benefits such as job creation, stronger societal cooperation, or lower expenditures for households, an exclusively technical or economic focus will fail to deliver behavioural changes and neglects governance and management challenges required for a successful CE implementation. Aspects of cooperation and multidimensional interactions between different stakeholders come into play. Cultural and social aspects such as stakeholder relations, institutions, and policies are inevitable building blocks for a holistic transition perspective (Korhonen et al. 2018, Beaurain et al. 2023, Chembessi et al. 2023). While a large part of CE literature deals with product or company perspectives, the geographical perspective, particularly the regional level must not be neglected as it will play a major role in the implementation of CE policy. Social factors of CE implementation are especially related to sub-national levels such as regions as they provide the conditions for stakeholder cooperation, the set-up of innovation systems of diverse actors, administrative capacity, as well as beneficial conditions for the development, widespread use, and diffusion of environmental innovations (Van den Heiligenberg et al. 2017, Losacker et al. 2021, Chembessi et al. 2021a, Arauzo-Carod et al. 2022). Accordingly, the neglect of the regional aspect in scientific articles and practical policy of CE underestimates the role played by governance structures, and institutional requirements to design appropriate CE policies (European Commission 2019, 2021, Vanhamäki et al. 2020, Dagilienė et al. 2021, Henrysson, Nuur 2021, Arsova et al. 2022, Morales, Dahlström 2022, Williams 2022, Rezaie et al. 2022). This research gap is one of the reasons why the potential to leverage green transition is so far not exploited. Leveraging regional development potential for the run-up of CE might benefit both. Moreover, the regional perspective allows for the identification of success factors and regional requirements for a successful CE implementation.

In this context, current research indicates that CE development is geographically highly diversified. For instance, the share of adoption of CE principles in high-income

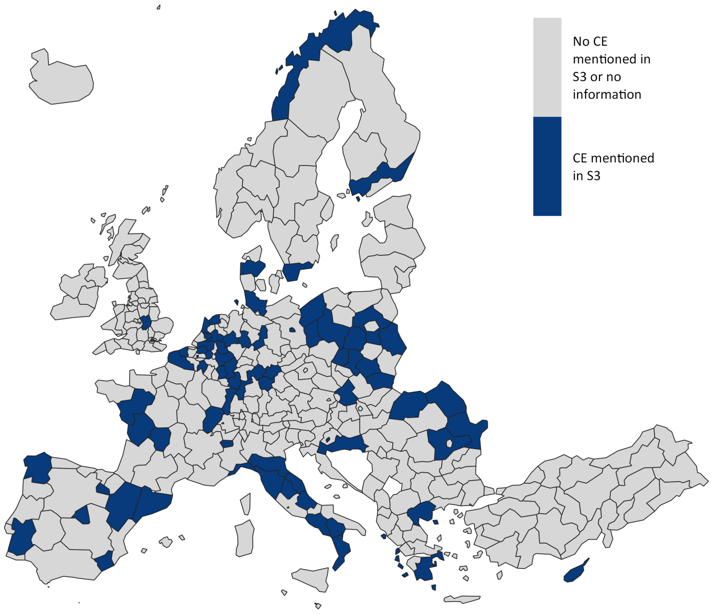
EU countries tends to be larger than in less developed EU countries (Mitrovic, Veselinov 2018). At the regional level, urban areas are particularly highlighted when it comes to CE transition. This is justified by the argument that these regions suffer more from typical urban downsides of waste generation and therefore benefit most from CE measures. These findings imply that spatial factors such as an urban structure shape the formation of CE. However, it remains unclear whether the divide between highly- and less-developed regions in terms of CE is an objective fact or a misunderstanding based on limited data availability (Bačová et al. 2016, Muñoz, Navia 2021, Mazur-Wierzbicka 2021). These questions will be further addressed below.

2.2 CE in Europe

Geographically, research on CE is strongly rooted in parts of Asia and Europe from where research has gradually spread (Hachaichi, Bourdin 2023). In particular, China has introduced CE measures on a large scale and promoted CE to an economic development strategy to mitigate the environmental challenges associated with strong economic growth (Heshmati 2015, Silvestri et al. 2020). The EU has also recognised the relevance of CE to align economic growth and sustainability. Stating that raw materials are *"the lifeblood of the EU economy"* (European Commission 2016, p. 3) and identifying a high import dependency when it comes to certain resources, a transformation towards a more regenerative and resource-sensitive growth model is required (Ragossnig, Schneider 2019, WEF 2014, European Commission 2010, 2020a, EEA 2016, 2020). Steps towards the integration of CE in European policy have been institutionalised since 2008 with relevant directives and strategy formulations (Avdiushchenko 2018, Mazur-Wierzbicka 2021). The adoption of a Circular Economy Action Plan in 2020 has officially promoted CE to a main building block of the sustainability agenda of the European Commission. This Action Plan is also embedded in the larger picture of establishing a new growth strategy, framed as the EU Green Deal, as well as the aspiration to improve resource efficiency and reduce European import dependence on raw materials (Wilts 2017, Salvatori et al. 2019, Domenech et al. 2019, Borett et al. 2020, European Commission 2011, 2019, 2020a). However, the EU economy is still considered too linear and certain policies have taken extended time until being pursued by European and national policies (European Commission 2019, Reike et al. 2018, Mazzanti, Zoboli 2009). Compared to the original idea of CE, certain aspects are regularly lost in transition towards practical policy. One of these is the social aspect of changing consumption and production patterns whereby CE is often reduced to an instrument of maintaining an unsustainable model of economic growth (e.g., Dunlap, Laratte 2022).

2.3 CE and smart specialisation

As indicated above, it is claimed that the regional aspect of CE is highly relevant for successful policy implementation (e.g., Gibbs, O'Neill 2017, Arsova et al. 2022) (e.g. Gibbs and O'Neill, 2017; Arsova et al., 2022). In this context, Fusillo et al. (2021) underline that trajectories of regional CE innovation systems resonate with regional capabilities. Thereby, the regional level has become a focal point of European policy over the last decade as a consequence of previous strategies being too generic and too removed from regional requirements and capacities (e.g., Fedeli et al. 2020). One of the central instruments is smart specialisation. This approach has risen to be the pivotal European policy instrument for cohesion and regional policy. The strategy behind the instrument is to guide regions in their process of identifying and developing their competitive advantages by concentrating regional resources accordingly. Identifying economic growth areas via bottom-up processes under the premise of structural renewal rather than structural conservation shall help to overcome interregional gaps in terms of productivity or research and development (R&D) in Europe by supporting less-developed regions. Theoretically, the concept is embedded in the frame of innovation systems and economic geography (Foray, Goenaga 2013, Foray et al. 2009, 2011, 2021, Isaksen, Trippl 2014, Asheim et al. 2016, D'Adda et al. 2018, Tödtling, Trippl 2018). By now, smart specialisation has become the central pillar for economic development and growth policy in Europe (McCann,



Source: Computations by the authors based on data from Joint Research Centre (2022).

Figure 1: CE focus in smart specialisation strategies (S3), 2022

Ortega-Argilés 2015, Lopes et al. 2019, Gómez Prieto et al. 2019).

In recent years, there is an ongoing discussion about updating smart specialisation after the instrument has existed for about a decade. One stream of discussion argues in favour of extending the original smart specialisation concept to better suit the requirements of a green transition. However, others call for a refocusing on the initial targets of smart specialisation (Foray et al. 2012, Doranova et al. 2012, Benner 2020, Tödtling et al. 2021, Isaksen et al. 2022). In relation to the current sustainability discussion, an extension of S3 has been discussed in order to combine sustainability and innovation policy (McCann, Soete 2020, Larosse et al. 2020, Arsova et al. 2021, Landabaso 2020, Kruse 2023). The latter stream of discussion is particularly interesting in terms of CE. When discussing CE at regional level, the question arises whether the existing European instruments recognise CE as a target, whether they represent appropriate delivery channels for CE implementation, or which adaptions might be required to combine both concepts.

In practice, several European regions have already combined their smart specialisation strategies (S3) with CE goals. For instance, exemplary regions from Spain and Slovenia present strategies on smart specialisation for addressing process and product innovations in the CE transition (Smart Specialisation Platform 2020a,b). Also, certain Finnish regions have identified CE as an important economic domain of activities in the priorities of industry, construction, and waste sectors (Council of Tampere Region 2021). In this context, Figure 1 provides an overview of European regions that already refer to CE topics as a focal point in their S3. The information was extracted from the database of regional S3 (Joint Research Centre 2022) by screening it for terms indicating the implementation or support of CE ("circular", "sustainable production", "recycling", "resource efficiency", "cradle to cradle"). The picture shows a relatively even distribution of regions that refer to CE in their S3 (dark grey) and highlights that the instrument of smart specialisation and the purpose of CE are increasingly merged in regional political strategies.

In current research, CE in S3 and European regional development are increasingly addressed in qualitative case studies. For instance, Harding et al. (2021) find that many European case studies on smart specialisation to foster a green transition have chosen a focus on CE. A perspective on renewable energy transition and the facilitating role of smart specialisation in this context is presented by Steen et al. (2018). Morales, Dahlström (2022) analyse smart specialisation for a green path renewal in Finnish and

Swedish regions. Apart from that, it is analysed how various regions have concretised S3 thematic priority areas related to the CE priorities within the regional context (Vanhamäki et al. 2021). Tsipouri et al. (2020) claim that the transformation towards a CE can be accelerated and become beneficial when CE is a strategic focal point for regional innovation strategies. Accordingly, Stanojev, Gustafsson (2021) suggest smart specialisation to strengthen innovation for CE, a claim that is also formulated by Hristozov, Chobanov (2020). However, the combination of the two EU priority strategies and policies, namely CE and smart specialisation, represents a challenge in terms of methodology, prioritisation, and coordination. Although the topic has been raised by several researchers and policy makers, a notable research gap remains when it comes to implementation on a larger scale.

3 Regional CE assessment in Europe

Studies have rated the existing monitoring and assessment tools for CE transition, particularly at the regional level, to be inadequate. While most methodologies were developed and applied in China, these remain geographically specialised and are hardly transferable to other world regions with different structural environments (Zhang et al. 2008, Quing et al. 2011, Geng et al. 2012, Su et al. 2013, Avdiushchenko, Zajac 2019, Ye et al. 2021). Therefore, the lack of tools to monitor and evaluate CE implementation in European regions remains *"one of the clearest gaps in the CE literature"* (Silvestri et al. 2020, p. 3). Although the need for an assessment methodology is highlighted (e.g., Blomsma, Brennan 2017, Virtanen et al. 2019, Borett et al. 2020), the number of publications on regional assessment has remained limited and frequently focused on single aspects of circularity rather than a broader notion. This fact hampers the transition towards a CE as crucial information is missing.

Current gaps of CE assessment involve, for instance, a lack of suitable indicators and data accessibility, particularly on sub-national levels. Thereby, the gap refers particularly to accessibility and transferability as the number of metrics and indicators is steadily increasing. Here, the absolute number of adequate metrics is not considered a weakness but rather the availability of data at the regional or local levels. For instance, the circular material use rate, an indicator measuring the share of material recovered and returned to the cycle, is available only for the national level (EASAC 2016, Saidani et al. 2019, 2022, Avdiushchenko, Zajac 2019, Arsova et al. 2022). Moreover, indicators on socio-institutional aspects such as consumption, governance, or political sensitivity are under-represented compared to more technological indicators. However, the quality and variety of indicators is less of a problem than the availability of data on lower aggregated levels. These data-related gaps have also been recognised by the European Commission, which has initiated a process of reviewing the existing indicators (Vercalsteren et al. 2018, European Commission 2018, 2020a).

Methodologies to assess CE in Europe have been developed but limitations remain. The following will provide/provides an overview of the most relevant papers and articles focusing on CE quantification in Europe whereby their weaknesses, when it comes to the construction of a new index, are identified and addressed in the next section. Until now, several circularity indices were developed on the country level, but these cannot be transferred to the regional level. This is due to the absence of regional data or country-specific indicators. Moreover, it is a common occurrence to neglect the social dimension of CE in favour of a more economic and technical focus (e.g., Hervey 2018, Mitrovic, Veselinov 2018, Avdiushchenko 2018, Mazur-Wierzbicka 2021, Banjerdpaiboon, Limleamthong 2023). Several other papers propose extensive methodologies without applying them practically, sometimes due to the identified data being unavailable on a larger scale (e.g., EASAC 2016, Saidani, Kim 2022). Work like this provides an overview of available indicators and potential calculation techniques but does not provide regional insights or raise political implications.

Other papers neglect certain aspects of CE. Among the neglected factors are those of a social, economic, or ecological nature (e.g., Ketels, Protsiv 2017, Taelman et al. 2020). Another sort of research articles offers a limited focus on individual aspects such as job creation (Niang et al. 2023) or technological patterns (Fusillo et al. 2021), while ignoring others. This research provides an additional academic value of CE in their specific niche. However, the CE as a complex and diverse concept is not adequately represented in that the findings are hardly robust when it comes to a comparative perspective. Additionally, several papers suffer from limitations such as non-transferability of regional indicator sets (e.g., Avdiushchenko, Zajac 2019, Virtanen et al. 2019, Heshmati, Rashidghalam 2021), a limited numbers of indicators (e.g., Silvestri et al. 2020, Skare et al. 2023), or a limited number of regions (e.g., Bianchi et al. 2022). In addition to the problem of missing comparability when only certain regions are analysed, the weakness is not so much the indicator design but the problem of non-transferability due to specific indicators that exist exclusively in certain countries.

The development of CE measurement methodologies at sub-regional levels such as cities is discussed and applied by Papageorgiou et al. (2021), Bote Alonso et al. (2022), and Henrysson et al. (2022), revealing the same limitations for the regional level, namely a lack of suitable indicators and data availability. However, it needs to be recognised that the existence of weakness does not understate the scientific value of the described articles. They simply do not suffice on their own for our purpose, so we pursued a synopsis of the state of research with individual complements.

4 Data and methods

4.1 Data

For this paper, the authors applied a broad definition of CE, meaning that environmental, social, and economic aspects are regarded as relevant for a CE (see Section 2.1). As a foundation, we conducted an extensive literature review that led to the identification of a set of dimensions including traditional dimensions of circularity such as waste and consumption as well as employment statistics, innovation, and political indicators associated to S3 (see Table 1). These dimensions cover environmental aspects (waste statistics), economic aspects (innovation, circular employment), behavioural patterns (consumption and production), and aspects of regional policy. The final set of 29 indicators in six dimensions is the result of a pragmatic approach to select consistent, harmonised, and standardised data adhering to three requirements: (1) The data must cover all of Europe rather than only certain countries, (2) the data must be available for a time span rather than only a point in time so that development is shown, and (3) the data must be available on a regional level.

It had to be decided whether to apply an analysis exclusively based on indicators with a broad data coverage, potentially leading to the same results as other papers, or to construct an analysis with new indicators that consist of data gaps but potentially reveal new insights. The authors decided to apply new indicators even when the data coverage was not optimal. However, certain databases and indicators were not included as they violated at least one of the three basic requirements, which mostly referred to data availability. The chosen administrative level for the analysis was NUTS 2, which refers to the regional level in Europe. This choice was motivated by data availability and relatively high coverage but does not come without disadvantages. The NUTS 2 level is responsible for the development of regional strategies for most European regions, but certain regions have allocated this responsibility to the more granular NUTS 3 level. Additionally, it needs to be remarked that an assessment on the national level (NUTS 1) would allow for the use of more detailed and targeted CE indicators that are not available on regional NUTS 2 level (see Appendix A).

Most indicators used for the analysis were obtained from the Eurostat (2022) database. Patent statistics were obtained from the PATSTAT database whereby a four-digit search strategy was applied to identify patents related to waste management and recycling (Eurostat 2023). The year 2018 was selected as the base year by reason of being the most recent year with the highest data availability for EU regions. Rather than choosing the most recent year for each indicator, it was decided to keep a common base year to provide a coherent CE analysis for that point in time. The selected base year to calculate the trend of CE development was 2012. This base year was also chosen by Banjerdpaiboon, Limleamthong (2023) for a comparison to 2018 values. 2012 stood out as the year with a relatively high data coverage for the relevant indicators. Moreover, no major crises were observed in the time frame that could have distorted the results. Finally, the time span of six years between 2012 and 2018 exceeds the duration of legislative periods in EU regions, ensuring a certain autonomy from political trends. However, the strict focus on 2012 and 2018 had to be softened in some cases. For instance, the statistics on waste production and treatment in European regions are based on a pilot project conducted in 2011 so data is limited to this time. Moreover, data regarding the regional generation of different kinds of waste from ESPON (2022) was included due toits high data quality. However, the time frames (2006 and 2014) did not fully correspond to the standard of the methodology.

The applied policy indicators reflect the fact that monitoring schemes often neglect more qualitative indicators such as circular strategies (Reich et al. 2023). However, an exclusive focus on traditional quantitative indicators such as recycling rates ignores important social and political aspects of CE and neglects aspects such as the leverage exerted by public authorities (Wijayasundara et al. 2022). These policy indicators are qualitative in their basic form and have been transformed to become quantitatively usable by applying a binary coding system (0: does not have a strategy, 1: does have a strategy). This kind of transformation is accompanied by the danger of a selection bias resulting from a non-random selection of cases. Consequently, certain cases may be overrepresented in this case due to the binary design of 0 and 1 (Collier 1995). This limitation also applies to the approach in this paper as it could not be overcome. This methodological limitation needs to be recognised.

Regarding the qualitative data sources, information on green procurement was obtained from the European Commission (2020b) and the status of cities as a signatory of the "Circular City Declaration" functions as an additional indicator of regional recognition of CE (Circular Cities Declaration 2022). The existence of a regional CE strategy is based on research undertaken by Jonker, Montenegro Navarro (2018) and Salvatori et al. (2019). The indicator "smart specialisation strategies" is based on a dataset by the Joint Research Centre (2022) for the 2014-2020 programming period that was examined for words that indicate the implementation or support of CE ("circular", "sustainable production", "recycling", "resource efficiency", "cradle to cradle"). The indicator can be questioned since CE in regional strategies can be both a prerequisite and a result of a strong regional CE. Despite that ambiguity, it was decided to include the indicator as an additional measure of CE awareness in regional policy.

4.2 Methods

To calculate a benchmark value that allows for a comparison of European regions in terms of CE, we set up two indexes(indices): first a "static" index based on the most recent data and second, a "trend" index covering the development in past years. The division is derived from Silvestri et al. (2020). Two steps: (1) normalisation of the original data and (2) aggregation of the normalised values to receive a composite measure were applied for the index. The first step was necessary due to different scales and dimensions. Thanks to this normalisation, each variable is expressed in an interval between 0 and 1. A value closer to 1 corresponds to a superior CE performance, whereby a value approaching 0 indicates a lower performance. Relatively better values in each indicator lead to a higher value in the overall index and indicate a more developed CE system. The normalisation function is given below, where X_{jk} represents the value of the k-th variable for region j.

$$Y_{jk} = \frac{X_{jk} - \min(X_{1k}, \ldots, X_{Jk})}{\max(X_{1k}, \ldots, X_{Jk}) - \min(X_{1k}, \ldots, X_{Jk})}$$

Variables with a negative impact on the CE performance were calculated as follows:

$$Y_{jk} = \frac{\max(X_{1k}, \ldots, X_{Jk}) - X_{jk}}{\max(X_{1k}, \ldots, X_{Jk}) - \min(X_{1k}, \ldots, X_{Jk})}$$

In Step 2, the normalised variables were aggregated using an arithmetic average. First, the arithmetic average was calculated for the six dimensions individually, before

Table 1: Indicators for CE assessment on NUTS 2 level in Europe

Dimension	No.	Indicator	Base Year Static	Base Year Trend	Index	Data Source
Policy	1.1	Regional circular economy strategies	2022	2012	(+)	Jonker, Montenegro Navarro (2018)
	1.2	Circular city declaration	2022	2012	(+)	Circular Cities Declaration (2022)
	1.3	Green public procurement	2020	2012	(+)	European Commission (2020b)
	1.4	Smart specialisation strategies	2021	2012	(+)	Joint Research Centre (2022)
Innovation	2.1	GERD per capita	2017	2011	(+)	Eurostat
	2.2	Patents per employee	2018	2012	(+)	PATSTAT
	2.3	Patents in CE-related technologies	2018	2012	(+)	PATSTAT
	2.4	Gross fixed capital formation	2018	2012	(+)	Eurostat
	2.5	Employees in scientific R&D	2018	2012	(+)	Eurostat, SBS data
Circular Employment	3.1	C33 repair and installation of machinery and equipment	2018	2012	(+)	Eurostat, SBS data
	3.2	E38 waste collection, treatment and disposal activities, materials recovery	2018	2012	(+)	Eurostat, SBS data
	3.3	E39 employees in remediation activities and other waste management services	2018	2012	(+)	Eurostat, SBS data
	3.4	G45 wholesale and retail trade and repair of motor vehicles and motorcycles	2018	2012	(+)	Eurostat, SBS data
	3.5	S95 repair of computers and personal and household goods	2018	2012	(+)	Eurostat, SBS data
Consumption and Production	4.1	total waste generated by households	2014	2006	(-)	ESPON
	4.2	food waste generation	2014	2006	(-)	ESPON
	4.3	electric and electronical waste colledted	2014	2006	(-)	ESPON
	4.4	plastic waste generation	2014	2006	(-)	ESPON
	4.5	waste generated by construction acitivties	2014	2006	(-)	ESPON
	4.6	waste generated by manufacturing activities	2014	2006	(-)	ESPON
Waste Management	5.1	Disposal - incineration	2018	2010	(-)	Eurostat
	5.2	Recovery - energetic recovery	2018	2010	(+)	Eurostat
	5.3	Disposal - landfill and other	2011	2010	(-)	Eurostat
	5.4	Recycling - material	2011	2010	(+)	Eurostat
	5.5	Recycling - composting and digestion	2011	2010	(+)	Eurostat
Socio-Economic Development	6.1	GDP per Capita	2018	2012	(+)	Eurostat
	6.2	Tertiary education	2018	2012	(+)	Eurostat
	6.3	Unemployment rate	2018	2012	(-)	Eurostat
	6.4	Households with broadband access	2018	2012	(+)	Eurostat

Source: Computations by the authors.

the results were combined for the final index. This intermediate step allows for a more detailed view of how the final index is composed and acknowledges the fact that the indicators in each dimension might be correlated. This potential drawback is minimised by separating the dimensions. Also, it was decided to abstain from applying different weights to the individual variables and dimensions since an objective relevance of each indicator for circularity cannot be identified. The function is given below whereby a higher Z_j value indicates a stronger CE performance in region j.

$$Z_j = \frac{1}{K} \sum_{k=1}^{K} Y_{jk}$$

For the trend index, the static index was calculated for an earlier year to measure the development in between the two points in time. The difference between the two static indices is calculated to be the trend index.

5 Results

To calculate the static index of CE performance, the methodology was applied to 278 European NUTS 2 regions with 2018 as the general base year. Country-specific gaps in different indicators have been observed due to data being classified as "confidential" in the Eurostat database or changes of the statistical NUTS classification between 2013 and 2018 that did not allow for a comparison of data. Significant gaps were observed in employment data in Italian regions as data was not available at all. Gaps in French, Irish, and several Polish regions are also observed in the consumption and production dimension. In terms of waste management, Finland, Sweden, Slovenia, Spain, Greece, Ireland, Czech Republic, Denmark, and some French regions had to be excluded due to a lack of data. Applying a weighted average to calculate the total index considered these gaps. The findings reveal a concentration of strong circular performance in Central European and Scandinavian regions (see Table 2). The best performing regions are predominantly regions with a strong urban character. It is worth noting that the indicator set gives too much weight to development and innovation indicators, but excluding this dimension did not significantly change the results.

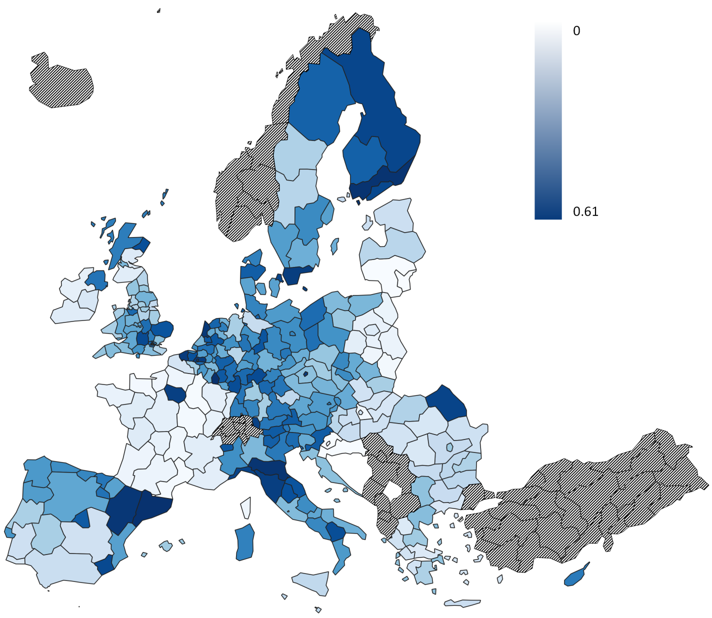
The pattern of strong CE performance in certain regions is illustrated in Figure 2. In countries such as England or France, the capital regions acquire a higher CE performance than the rest of the country while the picture in Spain is constituted by a comparable pattern but with more than one centre. The map reflects existing economic disparities, e.g., between Northern and Southern Italy or between Northern UK and the central London region. The largest concentration of CE performance can be observed in Scandinavian regions as well as large parts of Central Europe, while Eastern European regions are performing worse in terms of CE. The apparently low performance in France is primarily explained by data gaps in one dimension. Striped regions did not provide sufficient data for calculation.

The results are in line with other studies conducted on the environmental and economic performance of European regions. For instance, the strong CE performance in Central European countries such as Netherlands, Germany, Austria, or Belgium, accompanied by parts of Scandinavia as presented by Banjerdpaiboon, Limleamthong (2023) is confirmed in our study. However, the low performance that the authors attributed to Finland, or Czechia is contradicted by our analysis. Apart from this, our findings can provide new insights, focuses, and differentiations to enrich the general discussion about regional CE performance in Europe. For instance, the findings of Mazur-Wierzbicka (2021) of locating the most advanced countries in terms of CE principles in Central Europe with the lowest-ranking countries in Eastern and Southern Europe are complemented by a more differentiated perspective. Our analysis reveals that certain countries such as Romania do not perform generally worse but individual Romanian regions perform above average. Therefore, the previous finding of particularly less developed EU countries continuing to focus on linear rather than CE principles cannot be confirmed (Mitrovic, Veselinov 2018). In comparison to Silvestri et al. (2020), who chose a similar methodological approach, the structural findings in this paper are similar. However, the larger data set

Table 2: Top 20 European regions – static index

Rank	NUTS ID	Region	Index Value
1	LU00	Luxembourg	0.6140
2	ES51	Cataluña	0.5921
3	FI1C	Etelä-Suomi	0.5858
4	ITH5	Emilia-Romagna	0.5774
5	UKI3	Inner London — West	0.5731
6	ES24	Aragón	0.5663
7	NL32	Noord-Holland	0.5662
8	CZ01	Praha	0.5661
9	BE25	Prov. West-Vlaanderen	0.5651
10	BE24	Prov. Vlaams-Brabant	0.5634
11	SE22	Sydsverige	0.5633
12	ITI1	Toscana	0.5620
13	FR10	Ile-de-France	0.5619
14	AT34	Vorarlberg	0.5590
15	ITC3	Liguria	0.5522
16	RO21	Nord-Est	0.5518
17	DK01	Hovedstaden	0.5507
18	FI1D	Pohjois- ja Itä-Suomi	0.5499
19	FI1B	Helsinki-Uusimaa	0.5435
20	ES62	Región de Murcia	0.5430

Source: Computations by the authors.



Source: Computations by the authors.

Figure 2: Map of European regions - static index

and the inclusion of regions that were missing (e.g., Scandinavia or the UK), as well as the inclusion of new indicators and new dimensions with more recent data, allow this paper to paint a more complete picture of CE in European regions. Moreover, the CE performance in Eastern Europe, particularly in urban regions, is found to be stronger than what Silvestri et al. (2020) assumed. This can be attributed to the inclusion of different data bases.

Generally, the new methodology does not contradict previous findings but helps to explain them in a more reflected manner. For instance, national level analyses often assumed that countries in Eastern Europe were underdeveloped when it comes to CE whereby it could be shown that certain regions in Eastern Europe perform above average when it comes to CE. This is easily overseen when all regions of a country are accumulated. Our findings combine and refine previous approaches, which explains why no major contradictions have been identified.

6 Discussion

For the trend index, the static index values were compared with the values in 2012 as the general base year. The indicator set (see Table 1) was applied to 278 European NUTS 2 regions whereby those regions that revealed missing data in more than two dimensions had to be excluded. Consequently, the trend index consists of 264 European NUTS 2 regions (see Appendix B). The missing data have either occurred due to changes in the statistical NUTS classifications that did not allow for a comparison of regions over time or gaps in the data availability. In terms of waste management statistics, Bulgaria, Czechia, Denmark, Germany, Ireland, Greece, Spain, France, Italy, Finland, Sweden, as well as some Polish and British regions had to be excluded. This was done either because they did not report any data or because there were missing data in the trend index so that no comparison could be conducted. The same holds for French regions in the consumption and production dimension. The indicator "circular city declaration" in dimension 1 (Policy) was removed for the trend index since the initiative was not in place in 2012.

In terms of the trend index, a relatively even geographical distribution among Europe is observable when examining the top 20 best performing regions. Eastern European regions are reflected as well as Scandinavian, Southern, or Central European regions (see Table 3).

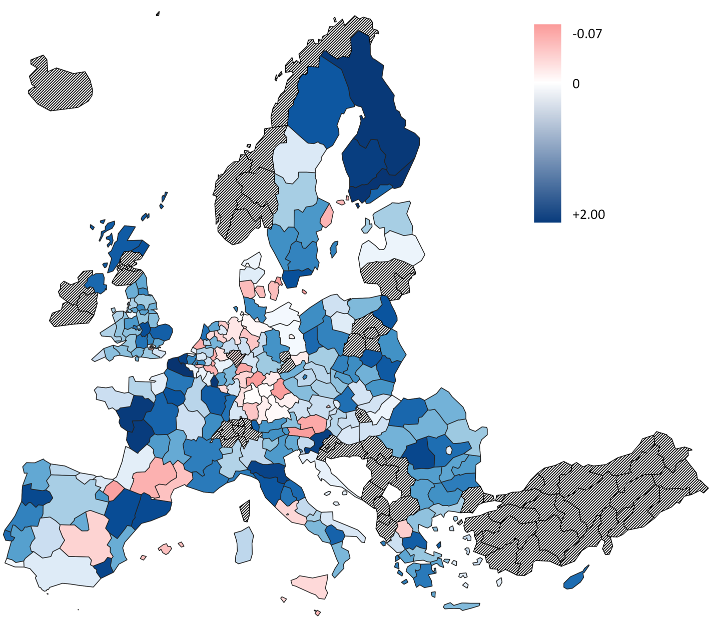
Figure 3 provides a geographical overview of the trend index in European regions. While a relatively even distribution can also be observed, the light red regions have faced negative development in terms of CE in recent years. These regions are also evenly distributed, while large parts of Germany stand out in a negative way. Generally, the figure highlights that positive developments over the period under review are also found in those regions that rank comparable low in the static index which indicates a catch-up process. Comparing the static and the trend index reveals that Finnish regions rank particularly high in both indexes. The favourable position in which Finnish regions are situated in the static index corresponds to a remarkable development in the trend index rather than a structural advantage over other regions. Starting from a worse position than others, Finland proves that catching up in terms of CE performance is possible. Structurally, countries like France tend to move towards regional convergence with a positive trend in regions that do not rank high in CE performance; while the structure in England appears to be structurally preserving with particularly positive development in already prospering regions around the capital. Striped regions did not provide sufficient data for calculation.

Although the CE performance tends to be positively related to agglomeration areas which combine a high level of infrastructure with a critical mass of stakeholders, the analysis shows that also sparsely populated areas such as Finnish regions can perform extraordinarily well. While the CE concentration in strong urban and industrial regions is not surprising (and has also been acknowledges by other studies, e.g., Niang et al. 2023), it is noticeable that not all capital regions rank high in terms of their CE index. Instead, also non-capital regions with a lower centrality and more rural structure appear

Table 3: Top 20 European regions – trend index

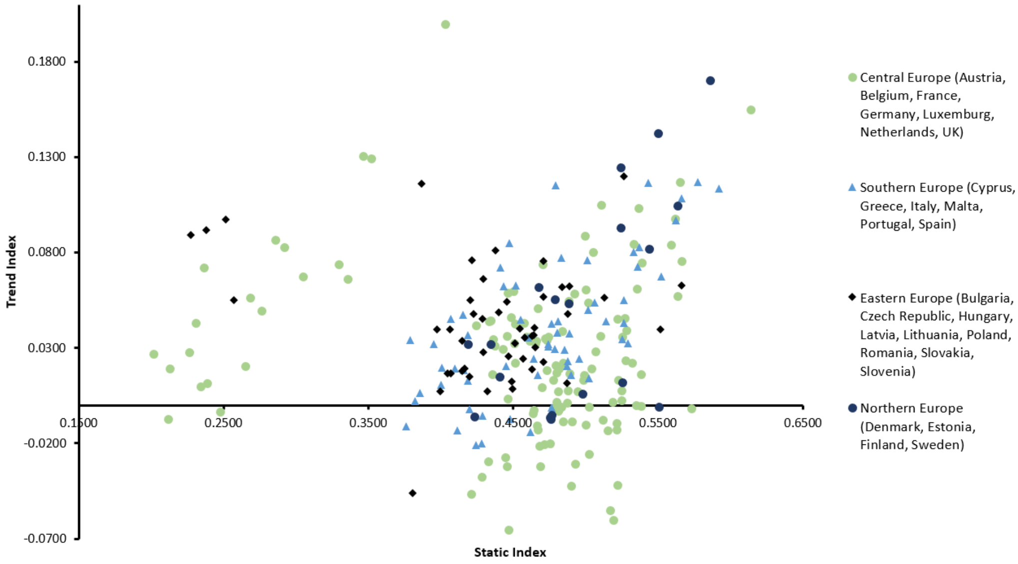
Rank	NUTS ID	Region	Index Increase
1	FRE1	Nord-Pas de Calais	0.1998
2	FI1C	Etelä-Suomi	0.1705
3	LU00	Luxembourg	0.1551
4	FI1D	Pohjois- ja Itä-Suomi	0.1428
5	FRG0	Pays de la Loire	0.1307
6	FRI3	Poitou-Charentes	0.1292
7	FI19	Länsi-Suomi	0.1246
8	SI03	Vzhodna Slovenija	0.1199
9	BE25	Prov. West-Vlaanderen	0.1170
10	ITH5	Emilia-Romagna	0.1168
11	ES62	Región de Murcia	0.1165
12	RO41	Sud-Vest Oltenia	0.1160
13	PT11	Norte	0.1151
14	ES51	Cataluña	0.1137
15	ES24	Aragón	0.1083
16	UKF2	Leicestershire, Rutland and Northamptonshire	0.1049
17	SE22	Sydsverige	0.1047
18	UKM5	North Eastern Scotland	0.1033
19	FR10	Ile-de-France	0.0975
20	PL84	Podlaskie	0.0973

Source: Computations by the authors.



Source: Computations by the authors.

Figure 3: Map of European regions – trend index



Source: Computations by the authors.

Figure 4: Static and trend index

in the top-20. It appears that the CE performance is not fully explained by structural characteristics but qualitative factors such as regional policy and governance. While it is beyond the scope of this article to further elaborate on these factors, certain authors have started looking into institutional factors as influencers of regional CE (see e.g., Ranta et al. 2018, Budde Christensen 2021) and the role of structural factors for CE-compliant individual behaviour (Neves, Marques 2022). Domenech, Bahn-Walkowiak (2019) analysed national strategies on CE and identify Germany, Austria, and Finland as frontrunners. Regions from these countries also rank highly in our static index. Generally, several of the top-20 regions in the static index are also known for their regional circular strategies, for instance London, Prague, Helsinki, and Paris (Mairie de Paris 2017, City of Helsinki 2020, Circular Prague 2022, ReLondon 2023). Although we cannot concretely assume a causal correlation, our study confirms the important role that policies play for the CE transition and the role of governments in this context (see also Chembessi et al. 2021b, Hartley et al. 2023, Niang et al. 2023). Moreover, the distribution of strong CE regions among Europe can be understood as a promising signal as CE can be successfully implemented in different socio-economic and geographical contexts. Also, it needs to be recognised that the assessment methodology does not quantify phenomena such as outsourcing of urban metabolisms, which provides an additional perspective on rural-urban interactions (Tanguy et al. 2020, Bahers, Rosado 2023).

Another perspective to compare the static and trend indices is a scatter-plot provided in Figure 4. To achieve a clearer picture in terms of geographical trends, four regional groups were distinguished: Central Europa (Austria, Belgium, France, Germany, Luxemburg, Netherlands, UK), Southern Europe (Cyprus, Greece, Italy, Malta, Portugal, Spain), Eastern Europe (Bulgaria, Czechia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia), and Northern Europe (Denmark, Estonia, Finland, Sweden).

Eastern European regions (represented by black diamonds) generally find themselves in a modest position with an average performance in the static index and a slightly positive development in the trend index. Central European regions (represented by light green dots) do not present a clear picture, which can be attributed to the diversity of the group consisting of some of the worst and some of the best performing regions. In Northern European regions (represented by darker blue dots) there appears to be a trend that those regions ranking high in the static index also perform above average in the trend index. A similar development pattern is observed in Southern Europe (represented by lighter blue triangles). Geographically speaking, several regions in Central and Southern

Europe appear to lose touch with the other regions in case that the negative development trend continues. These regions come under relative pressure from catching-up regions and leading regions expanding their position. Generally, Eastern or Southern European regions do not perform worse than Central or Northern European regions. However, it appears that high-performing regions with an urban character have an advantage when it comes to CE. This might be due to structural characteristics such as the availability of an established infrastructure for waste collection and the treatment or the existence of environmentally conscious social groups in urban centres that push regional governments for more CE action.

7 Conclusion

The benefits of a CE range from economic and environmental up to social benefits. However, when it comes to implementation, the role of regions in the transition towards CE is still under-researched even though the regional perspective is becoming increasingly important. For Europe, it is particularly striking that a thorough methodology to quantify CE on a regional level is missing. The article at hand proposes a multi-dimensional framework of 29 indicators in six dimensions to overcome previous limitations (see Table 1). While several of these dimensions have been chosen for CE measurement before, the methodology at hand is the first to combine them for a regional analysis. The data selection followed a pragmatic approach to select consistent, harmonised, and standardised data which were used to calculate a static and a trend index. Since monitoring schemes are a necessary instrument to quantify the effective implementation of policies and to identify their regional implications, the framework provides policy makers with an objective and adaptable methodology to develop CE instruments for Europe. It also highlights the current gaps in data availability on the regional level that need to be addressed to improve monitoring instruments in the future to gain deeper insights into CE development.

The results of quantifying regional CE performance in European regions partly confirm previous studies conducted on the environmental and economic performances of European regions but also draw a more differentiated picture: As some studies suggest, Eastern and Southern European countries are not utterly uncoupled from Central and Northern Europe but show a high level of interregional differentiation. Certain regions, particularly the urban capital regions, reveal a relatively high CE performance while more rural regions perform worse. The inner-country development patterns also differ among countries so that the differentiating line would not be drawn between North and South or West and Eastern Europe but rather between individual regions. The assumption of a natural correlation between urban areas and high CE performance can be rejected as a result from the findings. Instead, regional CE performance appears to be determined by regional policy rather than structural characteristics alone. Further research could involve qualitative case studies on why structurally similar regions perform that different in terms of CE. A first hint is identified by examining the instrument of smart specialisation. This European strategy for innovation and regional development has been used by some regions, particularly in Scandinavia, to facilitate regional CE development. These regions have proven to perform well in terms of CE, which might support previous claims that CE and smart specialisation might have the potential to benefit from each other. Comparing the regions focusing on CE in their S3 and the regions with high CE performance values reveals some overlaps (see Figure 1 and 2). Although it is hard to derive whether CE has been named in regional strategies as a result of strong CE performance or whether the policy has been the foundation for strong CE development, there appears to be a relation between both that should be further analysed. It has been shown that both policy makers and researchers increasingly discuss S3 and CE together but to derive a recommendation for European policy in general, the separated case studies need to be scaled up and a more holistic approach is required (Vanhamäki et al. 2021).

Generally, the analysis at hand can help policymakers to track their regional performance and progress in terms of CE so that it can be used as a basis for the design and enhancement of regional strategies. The instrument of smart specialisation can particularly be a relevant tool in this regard as it focuses on the identification of regional capabilities and the exploitation of development potentials. The integration of CE knowledge into this process can help to improve CE visibility and create incentives for directed investments as also claimed by Fusillo et al. (2021). On a superior level, CE policy in Europe should recognise the disparate development trends particularly when urban and rural regions are compared. To avoid a further deepening of regional inequality, tailored support is required to support the worse-performing regions, so they do not lose ground in the transition towards CE and sustainability. However, the presented methodology cannot raise a claim for completeness. The identification of dimensions is based on a literature review to assess the CE performance in regions but relies on a high level of pragmatism related to the limited availability of data on regional level. Therefore, drawbacks had to be accepted when it came to regional coverage and data gaps, as well as the years analysed. Improving data quality and the development of new indicators will allow for a revision and fine tuning as well as potential complements of the methodology.

Acknowledgements

The authors would like to express their sincere gratitude towards the anonymous reviewers for their helpful comments and recommendations, the editor of the journal for his continuous support and everyone else involved from the journal side for their accurate and professional work.

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A Appendix: Potential additional indicators for CE benchmarking on NUTS1-level

Dimension	No.	Indicator
Policy	1.1	Expenditure on environmental protection
Innovation	2.1	Private investment, jobs and gross value added related to CE sectors
	2.2	Total investment in environmental protection
	2.3	Patents related to recycling and secondary raw materials
	2.4	Energy productivity
	2.5	Water productivity
Employment	3.1	Gross value added in environmental goods and services sector
Consumption and Production	4.1	Generation of waste excluding major mineral wastes per GDP unit
	4.2	Generation of waste excluding major mineral wastes per domestic material consumption
	4.2	Generation of packaging waste per capita
	4.3	Generation of waste electrical and electronic equipment (WEEE)
	4.4	Generation of biological waste
	4.5	Material consumption
	4.6	Resource productivity
Waste Management	5.1	Recycling rate of all waste excluding major mineral waste
	5.2	Recycling rate of e-waste
	5.3	Recycling of biowaste
	5.4	Recovery rate of construction and demolition waste
	5.5	Circular material use rate
	5.6	Contribution of recycled materials to raw materials demand
	5.7	Trade of recyclable raw materials between EU member states and with the rest of the world
Regional Sustainability	6.1	Exposure to air pollution
	6.2	Air emissions accounts by NACE Rev. 2 activity
	6.3	Settlement area
	6.4	Share of busses and trains in total passenger transport
	6.5	Population living in households considering that they suffer from noise
	6.6	Share of renewable energy in gross final energy consumption
	6.7	Soil sealing index

B Appendix: CE performance in Europe, static and trend index, NUTS2 regions, 2018, 2012-2018

NUTS ID	Region	Static Index	Trend Index
BE10	Région de Bruxelles-Capitale/ Brussels Hoofdstedelijk Gewest	0.5345	0.0000
BE21	Prov. Antwerpen	0.4775	0.0133
BE22	Prov. Limburg (BE)	0.4817	0.0193
BE23	Prov. Oost-Vlaanderen	0.5352	0.0609
BE24	Prov. Vlaams-Brabant	0.5634	0.0573
BE25	Prov. West-Vlaanderen	0.5651	0.1170
BE31	Prov. Brabant Wallon	0.5213	-0.0095
BE32	Prov. Hainaut	0.4459	0.0033
BE33	Prov. Liège	0.4633	-0.0041
BE34	Prov. Luxembourg (BE)	0.4696	0.0095
BE35	Prov. Namur	0.4810	0.0074
BG31	Severozapaden	0.4226	0.0480
BG32	Severen tsentralen	0.4289	0.0455
BG33	Severoiztochen	0.4401	0.0487
BG34	Yugoiztochen	0.4291	0.0663
BG41	Yugozapaden	0.4560	0.0464
BG42	Yuzhen tsentralen	0.4203	0.0553
CZ01	Praha	0.5661	0.0628
CZ02	Střední Čechy	0.4568	0.0244
CZ03	Jihozápad	0.4630	0.0364
CZ04	Severozápad	0.4645	0.0405
CZ05	Severovýchod	0.4466	0.0258
CZ06	Jihovýchod	0.4651	0.0302
CZ07	Střední Morava	0.4580	0.0356
CZ08	Moravskoslezsko	0.4879	0.0479
DK01	Hovedstaden	0.5507	-0.0007
DK02	Sjælland	0.4761	-0.0070
DK03	Syddanmark	0.4754	-0.0063
DK04	Midtjylland	0.5251	0.0122
DK05	Nordjylland	0.4975	0.0062
DE11	Stuttgart	0.4467	-0.0651
DE12	Karlsruhe	0.5023	-0.0256
DE13	Freiburg	0.4988	0.0158
DE14	Tübingen	0.4903	-0.0085
DE21	Oberbayern	0.5017	-0.0549
DE22	Niederbayern	0.4283	-0.0375
DE23	Oberpfalz	0.5023	-0.0006
DE24	Oberfranken	0.4929	-0.0306
DE25	Mittelfranken	0.5188	-0.0602
DE26	Unterfranken	0.5383	-0.0003
DE27	Schwaben	0.4454	-0.0320
DE30	Berlin	0.4900	-0.0420
DE40	Brandenburg	0.4869	0.0013
DE50	Bremen	0.5214	-0.0128
DE60	Hamburg	0.5220	-0.0417
DE71	Darmstadt	0.5153	-0.0132
DE72	Gießen	0.4778	-0.0018
DE73	Kassel	0.4888	0.0165
DE80	Mecklenburg-Vorpommern	0.4795	0.0018
DE91	Braunschweig	0.5320	0.0223
DE92	Hannover	0.4842	-0.0085
DE93	Lüneburg	0.4207	-0.0463
DE94	Weser-Ems	0.4442	-0.0273
DEA1	Düsseldorf	0.4680	-0.0215
DEA2	Köln	0.5244	0.0078
DEA3	Münster	0.4845	0.0221
DEA4	Detmold	0.5040	0.0193
DEA5	Arnsberg	0.4326	-0.0293
DEB1	Koblenz	0.5098	0.0365
DEB2	Trier	0.5268	0.0459
DEB3	Rheinhessen-Pfalz	0.5380	0.0161
DEC0	Saarland	0.4751	-0.0202
DED2	Dresden	0.4686	-0.0318
DED4	Chemnitz	0.4815	:
DED5	Leipzig	0.5021	:

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NUTS ID	Region	Static Index	Trend Index
DEE0	Sachsen-Anhalt	0.4884	0.0546
DEF0	Schleswig-Holstein	0.4923	0.0584
DEG0	Thüringen	0.4657	0.0336
EE00	Eesti	0.4184	0.0322
IE04	Northern and Western	0.2772	:
IE05	Southern	0.3444	:
IE06	Eastern and Midland	0.3972	:
EL30	Attiki	0.4551	0.0448
EL41	Voreio Aigaio	0.4006	0.0196
EL42	Notio Aigaio	0.3999	0.0106
EL43	Kriti	0.4185	0.0367
EL51	Anatoliki Makedonia, Thraki	0.3952	0.0320
EL52	Kentriki Makedonia	0.4601	0.0354
EL53	Dytiki Makedonia	0.3760	-0.0109
EL54	Ipeiros	0.4095	0.0193
EL61	Thessalia	0.4475	0.0851
EL62	Ionia Nisia	0.4519	0.0629
EL63	Dytiki Elláda	0.4066	0.0455
EL64	Sterea Elláda	0.3788	0.0343
EL65	Peloponnisos	0.4412	0.0722
ES11	Galicia	0.4807	0.0441
ES12	Principado de Asturias	0.4872	0.0250
ES13	Cantabria	0.4896	0.0157
ES21	País Vasco	0.5020	0.0141
ES22	Comunidad Foral de Navarra	0.4762	-0.0011
ES23	La Rioja	0.5059	0.0538
ES24	Aragón	0.5663	0.1083
ES30	Comunidad de Madrid	0.5265	0.0430
ES41	Castilla y León	0.4741	0.0320
ES42	Castilla-La Mancha	0.4114	-0.0131
ES43	Extremadura	0.4448	0.0205
ES51	Cataluña	0.5921	0.1137
ES52	Comunitat Valenciana	0.4766	0.0429
ES53	Illes Balears	0.4476	-0.0071
ES61	Andalucía	0.4189	0.0128
ES62	Región de Murcia	0.5430	0.1165
ES63	Ciudad de Ceuta	0.4200	-0.0022
ES64	Ciudad de Melilla	0.4244	-0.0210
ES70	Canarias	0.4789	0.0296
FR10	Ile-de-France	0.5619	0.0975
FRB0	Centre — Val de Loire	0.2919	0.0827
FRC1	Bourgogne	0.2126	0.0192
FRC2	Franche-Comté	0.2682	0.0562
FRD1	Basse-Normandie	0.2260	0.0278
FRD2	Haute-Normandie	0.2343	0.0099
FRE1	Nord-Pas de Calais	0.4030	0.1998
FRE2	Picardie	0.2363	0.0724
FRF1	Alsace	0.3295	0.0741
FRF2	Champagne-Ardenne	0.2017	0.0268
FRF3	Lorraine	0.2857	0.0865
FRG0	Pays de la Loire	0.3465	0.1307
FRH0	Bretagne	0.2651	0.0205
FRI1	Aquitaine	0.2384	0.0115
FRI2	Limousin	0.2761	0.0494
FRI3	Poitou-Charentes	0.3516	0.1292
FRJ1	Languedoc-Roussillon	0.2119	-0.0074
FRJ2	Midi-Pyrénées	0.2477	-0.0032
FRK1	Auvergne	0.2309	0.0433
FRK2	Rhône-Alpes	0.3354	0.0661
FRL0	Provence-Alpes-Côte d'Azur	0.3049	0.0677
FRM0	Corse	0.2353	:
FRY1	Guadeloupe	0.1315	:
FRY2	Martinique	0.2635	:
FRY3	Guyane	0.1425	:
FRY4	La Réunion	0.2771	:
FRY5	Mayotte	:	:
HR02	Panonska Hrvatska	:	:
HR03	Jadranska Hrvatska	0.4574	0.0094
HR05	Grad Zagreb	:	:
HR06	Sjeverna Hrvatska	:	:

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NUTS ID	Region	Static Index	Trend Index
ITC1	Piemonte	0.4853	0.0291
ITC2	Valle d'Aosta/Vallée d'Aoste	0.5293	0.0326
ITC3	Liguria	0.5522	0.0674
ITC4	Lombardia	0.4638	0.0243
ITF1	Abruzzo	0.4876	0.0232
ITF2	Molise	0.4743	0.0308
ITF3	Campania	0.4888	0.0378
ITF4	Puglia	0.4670	0.0157
ITF5	Basilicata	0.5368	0.0830
ITF6	Calabria	0.4803	0.0380
ITG1	Sicilia	0.4279	-0.0198
ITG2	Sardegna	0.4953	0.0245
ITH1	Provincia Autonoma di Bolzano/Bozen	0.5263	0.0552
ITH2	Provincia Autonoma di Trento	0.5250	0.0347
ITH3	Veneto	0.5015	0.0502
ITH4	Friuli-Venezia Giulia	0.5140	0.0440
ITH5	Emilia-Romagna	0.5774	0.1168
ITI1	Toscana	0.5620	0.0969
ITI2	Umbria	0.5358	0.0725
ITI3	Marche	0.5330	0.0805
ITI4	Lazio	0.4619	-0.0142
CY00	Kýpros	0.5011	0.0762
LV00	Latvija	0.4321	0.0073
LT00	Lithuania	0.3806	-0.0461
LT01	Sostinės regionas	:	:
LT02	Vidurio ir vakarų Lietuvos regionas	:	:
LU00	Luxembourg	0.6140	0.1551
HU11	Budapest	0.4059	:
HU12	Pest	0.2296	:
HU21	Közép-Dunántúl	0.4163	0.0193
HU22	Nyugat-Dunántúl	0.4295	0.0276
HU23	Dél-Dunántúl	0.4199	0.0151
HU31	Észak-Magyarország	0.4048	0.0168
HU32	Észak-Alföld	0.3997	0.0073
HU33	Dél-Alföld	0.4147	0.0178
MT00	Malta	0.4285	-0.0055
NL11	Groningen	0.4664	-0.0106
NL12	Friesland (NL)	0.5217	0.0455
NL13	Drenthe	0.4983	0.0133
NL21	Overijssel	0.4667	-0.0128
NL22	Gelderland	0.5282	0.0393
NL23	Flevoland	0.4714	-0.0204
NL31	Utrecht	0.5276	0.0234
NL32	Noord-Holland	0.5662	0.0754
NL33	Zuid-Holland	0.4638	-0.0024
NL34	Zeeland	0.4877	0.0076
NL41	Noord-Brabant	0.5069	0.0282
NL42	Limburg (NL)	0.4809	-0.0028
AT11	Burgenland	0.4796	0.0170
AT12	Niederösterreich	0.4794	0.0208
AT13	Wien	0.5001	-0.0101
AT21	Kärnten	0.4834	-0.0006
AT22	Steiermark	0.4813	-0.0021
AT31	Oberösterreich	0.4731	0.0186
AT32	Salzburg	0.5253	0.0361
AT33	Tirol	0.5016	0.0539
AT34	Vorarlberg	0.5590	0.0840
PL21	Małopolskie	0.4647	0.0400
PL22	Śląskie	0.4710	0.0568
PL41	Wielkopolskie	0.4837	0.0618
PL42	Zachodniopomorskie	0.5127	0.0562
PL43	Lubuskie	0.5079	0.0787
PL51	Dolnośląskie	0.4509	0.0323
PL52	Opolskie	0.4885	0.0624
PL61	Kujawsko-pomorskie	0.4491	0.0124
PL62	Warmińsko-mazurskie	0.4643	0.0369
PL63	Pomorskie	0.4630	0.0187
PL71	Łódzkie	0.3056	:
PL72	Świętokrzyskie	0.2381	0.0918

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NUTS ID	Region	Static Index	Trend Index
PL81	Lubelskie	0.2573	0.0552
PL82	Podkarpackie	0.2276	0.0892
PL84	Podlaskie	0.2514	0.0973
PL91	Warszawski stołeczny	0.3598	:
PL92	Mazowiecki regionalny	0.2739	:
PT11	Norte	0.4791	0.1151
PT15	Algarve	0.3823	0.0021
PT16	Centro (PT)	0.4431	0.0624
PT17	Área Metropolitana de Lisboa	0.4834	0.0775
PT18	Alentejo	0.4153	0.0474
PT20	Região Autónoma dos Açores	0.3857	0.0064
PT30	Região Autónoma da Madeira	0.4157	0.0186
RO11	Nord-Vest	0.4375	0.0812
RO12	Centru	0.3973	0.0397
RO21	Nord-Est	0.5518	0.0398
RO22	Sud-Est	0.4148	0.0338
RO31	Sud-Muntenia	0.4215	0.0759
RO32	Bucureşti-Ilfov	0.4495	0.0088
RO41	Sud-Vest Oltenia	0.3868	0.1160
RO42	Vest	0.4061	0.0398
SI03	Vzhodna Slovenija	0.5261	0.1199
SI04	Zahodna Slovenija	0.4710	0.0225
SK01	Bratislavský kraj	0.4872	0.0117
SK02	Západné Slovensko	0.4706	0.0756
SK03	Stredné Slovensko	0.4071	0.0166
SK04	Východné Slovensko	0.4453	0.0542
FI19	Länsi-Suomi	0.5241	0.1246
FI1B	Helsinki-Uusimaa	0.5435	0.0818
FI1C	Etelä-Suomi	0.5858	0.1705
FI1D	Pohjois- ja Itä-Suomi	0.5499	0.1428
FI20	Åland	0.4232	-0.0060
SE11	Stockholm	0.4763	-0.0049
SE12	Östra Mellansverige	0.4882	0.0536
SE21	Småland med öarna	0.4676	0.0618
SE22	Sydsverige	0.5633	0.1047
SE23	Västsverige	0.4789	0.0556
SE31	Norra Mellansverige	0.4344	0.0322
SE32	Mellersta Norrland	0.4404	0.0149
SE33	Övre Norrland	0.5239	0.0932
UKC1	Tees Valley and Durham	0.4501	0.0598
UKC2	Northumberland and Tyne and Wear	0.4333	0.0441
UKD1	Cumbria	0.4514	0.0426
UKD3	Greater Manchester	0.4345	0.0445
UKD4	Lancashire	0.4374	0.0314
UKD6	Cheshire	0.5183	0.0019
UKD7	Merseyside	0.4507	0.0324
UKE1	East Yorkshire and Northern Lincolnshire	0.4240	0.0420
UKE2	North Yorkshire	0.4653	0.0325
UKE3	South Yorkshire	0.4482	0.0460
UKE4	West Yorkshire	0.4459	0.0589
UKF1	Derbyshire and Nottinghamshire	0.4363	0.0345
UKF2	Leicestershire, Rutland and Northamptonshire	0.5108	0.1049
UKF3	Lincolnshire	0.4455	0.0363
UKG1	Herefordshire, Worcestershire and Warwickshire	0.4744	0.0357
UKG2	Shropshire and Staffordshire	0.4667	0.0508
UKG3	West Midlands	0.4704	0.0738
UKH1	East Anglia	0.5330	0.0845
UKH2	Bedfordshire and Hertfordshire	0.4997	0.0606
UKH3	Essex	0.4575	0.0433
UKI3	Inner London — West	0.5731	-0.0016
UKI4	Inner London — East	0.5244	0.0024
UKI5	Outer London — East and North East	0.4945	0.0073
UKI6	Outer London — South	0.5117	-0.0076
UKI7	Outer London — West and North West	0.5226	0.0132
UKJ1	Berkshire, Buckinghamshire and Oxfordshire	0.5386	0.0746
UKJ2	Surrey, East and West Sussex	0.4612	0.0338
UKJ3	Hampshire and Isle of Wight	0.4837	0.0391
UKJ4	Kent	0.4355	0.0162
UKK1	Gloucestershire, Wiltshire and Bristol/Bath area	0.4728	0.0340

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NUTS ID	Region	Static Index	Trend Index
UKK2	Dorset and Somerset	0.4588	0.0357
UKK3	Cornwall and Isles of Scilly	0.4510	0.0222
UKK4	Devon	0.4616	0.0361
UKL1	West Wales and The Valleys	0.4426	0.0293
UKL2	East Wales	0.4718	0.0352
UKM5	North Eastern Scotland	0.5362	0.1033
UKM6	Highlands and Islands	0.4995	0.0887
UKM7	Eastern Scotland	0.3681	:
UKM8	West Central Scotland	0.4640	:
UKM9	Southern Scotland	0.3378	:
UKN0	Northern Ireland	0.5050	0.0805

Funded by