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Research article

Perspectives on the material dynamic efficiency transition in decelerating the material stock accumulation

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ABSTRACT

The golden rule of material accumulation can be defined as the ability of society to process materials as the benefit of capital, with physical investments as the expense of the process. Societies are incentivized to accumulate resources while disregarding resource restrictions. Since they earn more on such a path, despite how unsustainable it is. We propose the material dynamic efficiency transition as a policy tool for sustainability, with the goal of slowing down material accumulation as an alternative sustainable path.

The material dynamic efficiency transition is characterized by a simultaneous drop in savings and depreciation rates. In this paper, we first examine a sample of 15 countries -using dynamic efficiency measures-in terms of their economies' responses to declining depreciation and saving tendencies. We then construct a large sample of material stock estimation and economic characteristics for 120 countries to examine the socioeconomic and long-term developmental implications of such a policy. We found that investment in the productive sector withstood the scarcity of available savings, whereas residential building and civil engineering investments reacted intensely to the changes. We also reported on the continuous rise in developed countries' material stock, accentuating the civil engineering infrastructure as a focal point of the related policies.

The material dynamic efficiency transition shows a substantial reduction effect of 7.7%–10%, depending on the stock type and development stage. Therefore, it can be a potent tool for slowing material accumulation and mitigating the environmental implications of this process without causing significant disruptions in economic processes.

1. Introduction

Infrastructures support and enable all of civilization's social and economic operations. Elements of this infrastructure, such as houses, roads, wires, workplaces, plants, vehicles, durable goods, etc., provide significant means of shelter, entertainment, education, production, and consumption. These objects are known as material stocks, which consist of various forms of abiotic minerals or biomass accumulated through material flows over decades or even centuries. (Haberl et al., 2017, 2019; Weisz et al., 2015).

As our socioeconomic system evolves, so does the complexity of the material stock necessary to run it (Chester et al., 2019; Luderer et al., 2019), and it continues to do so; if one takes the decentralization of the energy supply network as just one everyday example. Material and energy usage efficiency has increased in tandem with the increasing complexity. In contrast, the need for material stock has increased at the process level (Wang et al., 2022; Whiting et al., 2020) and macro-scale: the ratio of stock building materials has risen globally from 20% to 58% of the domestic extraction between 1900 and 2010 (Krausmann et al., 2017).

Infrastructure-related GHG emissions, both direct and indirect, or operational and embodied, may account for up to two-thirds of total emissions (Ellen MacArthur Foundation, 2019; Resch et al., 2020). Simultaneously, the material stock requires a significant amount of rare natural resources, such as sand (Bendixen et al., 2019; Torres et al., 2017), and generates ever-increasing waste streams. As significant infrastructure projects are being built nowadays, the importance of material stock has recently been underlined. Notably in terms of emissions and resource usage for the critical decades that follow (Haberl et al., 2019; Lanau et al., 2019). Thus, the required sustainability

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transition should primarily address material stock, delivering the desired services for society, such as mobility, housing, consumption, or culture; however, existing policy and pledges almost entirely address emissions and flow-type processes, such as renewable energy investments, emission trading systems, carbon border adjustments, and vehicles emission norms.

There is little doubt in professional and public discourse about the necessity of policy measures, which are intended to influence consumption through carbon or resource price for instance. According to a recent literature analysis by (Krogstrup and Oman, 2019), fiscal policy tools such as taxes, subsidies, and public investments will most likely play an important role in the future; however, the optimal policy mix remains unknown. According to (Johnstone and Newell, 2017), the necessary dramatic shift toward sustainability necessitates more state intervention in economic and social processes. Several research, on the other hand, report on promising fiscal policy instruments that affect capital accumulation. In (Gutiérrez, 2008) model, emissions are a function of capital accumulation, therefore agents can reduce pollution just by reducing savings and capital accumulation. The most eco-sustainable tax structure comprises consumer transfers and production taxes (Pigovian tax). As a result, the overall amount of tax paid by the agents is smaller than in a traditional tax plan on wages and capital income. According to (Dao and Dávila, 2014) model, taxes on capital income provide the optimum policy for all agents only in societies where youthful generations pay more taxes than the transfers received by the elderly.

The price ratio of non-renewable resources was consistent in the twentieth century as (Solow et al., 1978) demonstrated; thus, the prices have limited effects on the overall economy. Numerous raw materials, particularly construction minerals, remain relatively cheap (Sverdrup et al., 2017), therefore commodity prices fail to represent resource scarcity (Popp et al., 2018). As a result, despite rising resource prices, there is a risk that the economy would fail to adapt its production recipe, despite promising models (Distelkamp et al., 2010; Tang et al., 2017), and observed resource taxation successes (Bahn-Walkowiak et al., 2012). Aside from economic efficiency (Krogstrup and Oman, 2019), emphasize 'political and social feasibility' as a deciding factor in successful climate mitigation.

Recently, the authors of this paper proposed a fiscal shift toward the transition to sustainability (Dombi, 2022; Dombi et al., 2022). An economy performs dynamically efficiently when capital gains surpass capital investment (Abel et al., 1989; Ahn et al., 2003). Simultaneously, a zero value for the dynamic efficiency test indicates that the economy has reached the golden rule quantity of capital per worker and optimal consumption per worker (Phelps, 1961; Phelps and Phelps, 1964). According to a sample of 15 countries, societies earn more services from material stock accumulation than from monetary investments, creating a persistent incentive to overlook resource constraints. As a result (Dombi, 2022), proposed a transition, which could theoretically deliver moderated material accumulation by slowing economic growth but increasing consumption in monetary terms, while, as presented by (Dombi et al., 2022), decreasing economic inequalities. The economic context and presence of this transition in the past, however, has not been addressed yet.

In this paper, we first examine the 15 countries (Dombi, 2022) reported on in terms of their economies' responses to declining depreciation and saving tendencies. This sample allows for a thorough examination of the material dynamic efficiency and its relationship to its monetary equivalent. The analyzed countries represent 50% of the world population and 65% of the GDP. The sample covers a variety of the development status as a spectrum of developed, transiting, and developing countries are assessed; with each group represented by at least three economically significant states. We used this existing database to justify the hypothesis that material dynamic efficiency is connected with economic circumstances and outcomes.

Second, we constructed a large sample of material stock estimation and economic characteristics for 120 nations. Our analysis aims to determine if the anticipated simultaneous decreases in savings and depreciation rates, resulted in reduced material stock accumulation levels between 1980 and 2016.

2. Methods and data

2.1. Material dynamic efficiency assessment

In order to create economic value, society employs production factors (labor, land, and capital) at various stages of production, which reduce the natural resource's original form, energy content, and mass. Consequently, the mass of all original natural resources undergoes deduction to become a valuable service without any mass or a product with significantly reduced mass. This amount of material, transformed into services or products, was considered as deduced material in Dombi (2022). Deduced material consists of domestic extraction plus imported materials, less the mass of final used materials. The letter is represented by food consumption, wood usage, metal contents of ores, construction materials, and fossil fuels. To read more about the methodology, see Dombi (2022).

In this context, mirroring the dynamic efficiency in monetary terms in the Introduction, society is said to be in a condition of material dynamic efficiency when the amount of natural resources deducted by capital (material capital gains) surpasses the amount of material needed to maintain and enhance the deduction process's capacity (investments). It refers to material gains available to consume by the members of society in various forms of commodities or services. As Dombi (2022) found, countries tend to keep the level of fiscal investments close so that it could result in the golden rule endowment of capital in monetary terms. At the same time, most countries presented highly efficient material investments, significantly above the material golden rule stock endowment, where material requirements of investments offset the gains (deduced material). The rationale behind the proposed transition is shifting the economies away from the monetary golden rule equilibrium to an underinvestment position to minimize environmental pressure and increase consumption per capita. This state of the economy may eventually evoke a shift away from the material golden rule towards higher material dynamic efficiency. Therefore, we refer to this as material dynamic efficiency transition (hereinafter, MDE transition).

2.2. Concrete material stock data

We considered concrete as an indicator of material stock accumulation due to its crucial part in the material stock composition. According to (Krausmann et al., 2017), the mass of concrete approached half of the total material stock in 2010, surpassing metals and other materials by far. The historical concrete stocks are estimated using a top-down time-cohort-type (TCT) method, which has been used to estimate global cement stocks (Cao et al., 2017). The TCT method divides apparent cement consumption (i.e., production plus import minus export) into sector-specific cement consumption and assigns a specific lifetime to each sector. As concrete is a composite material made of cement, fine aggregates, coarse aggregates, and cement substitutes, we expand the system boundary of the cement cycle to include these material flows. Data on cement production are collected from Mineral Yearbooks of the United States Geological Survey. Data on cement trade are collected from the United Nations Comtrade Database. Sectoral splits are based on our previous research. Lifetime functions are determined based on a global review. Data on aggregates-to-cement ratios are collected from previous studies. Data on cement substitutes are collected from the Getting the Numbers Right Database (Global Cement Concrete Association 2021) (Cao et al., 2017).

2.3. Estimation of the effect of material dynamic efficiency transition

To calculate the impact of the MDE transition on the material stock endowment, we used a matching method for causal inference with time-series cross-sectional data as proposed by (Imai et al., 2021). By doing this, one may match any observation that has been treated with those that have had an identical treatment history. This matched set is then refined for any observable confounding variables. The divergence between the treated units and the weighted average of the control units in the improved matched set is then produced as a Difference-in-Differences (DiD) estimate (Imai et al., 2021).

Since the analysis aimed to reveal the causal relation between a trend shift towards MDE, we specified the treatment variable, describing the MDE transition to only consider substantial changes, and eliminated minor variations in depreciation (d) and savings (s) rates. In order to do so, we chose years with a drop or rise in the variables that were greater than one standard deviation (Hope and Limberg, 2020). As a result, country-year data following a one-standard-deviation reduction in savings and depreciation rates became treated units, whereas a similar joint upward shift signified a reversal into non-MDE country-year observations. We characterized variation in per capita concrete stock volumes in the above-mentioned dataset as the effect of the MDE transition, first the total stock and then the residential, non-residential, and civil engineering categories. In this manner, we have recorded units in 115 countries.

We refined the matching procedure by confounding variables GDP per capita, consumption per capita, income inequality (defined as the ratio of the top 1% of earners), and the macro-level internal rate of return (IRR), which is calculated as the ratio of capital income (GDP minus wages and rents) in total GDP. The s is formulated as a percentage of gross savings in a country's GDP. At the same time, the d is represented in the Penn World Tables as a constant exogenous rate applied continuously on nine types of capital assets. We controlled for the economic performance by using the 2017 USD per capita GDP and consumption. The data source for the savings rate is the World Bank, the inequality measure is the World Inequality Database, and the Penn World Tables 9.1 provides the data for the IRR, consumption, GDP, and depreciation rate. To conduct the estimations, we used R's PanelMatch package (Supporting Information).

As probably a large portion of macroeconomic panel data, the one constructed here to assess the MDE transition is subject to cross-sectional dependence (CSD). In other words, elements of the dataset are deemed to be covariates with each other due to the possible existence of a common influencing factor, for instance, technological progress or global financial crises (Henningsen and Henningsen, 2019). We tested our panel for the existence of CSD with the help of the CD test, which is widely utilized in the literature (Sarafidis and Wansbeek, 2011) in case of panel data with long periods covered for a large set of countries. The test displayed significant CSD. Therefore, we assessed the effect of the unknown confounding factor(s) by comparing a fixed effects (FE) model results and alternative common confounding effects mean group (CCEMG) model proposed by, e.g., (Cao and Zhou, 2022), to estimate the unobserved common factors by cross-sectional averages of the regressand and regressors, augmenting the model with the latter to obtain unbiased estimates (Henningsen and Henningsen, 2019). We used the plm package in R to conduct the tests and estimations. The results obtained by the FE and CCEMG estimators are provided in Table S1. We assessed a FE model, as the F test for individual and time effects shows significant fixed effects, i.e., individual differences between the elements in the panel. The augmented model (CCEMG) delivered a significant, adverse effect of the treatment and a strong reinforcing effect of GDP on the MS; the same as in FE model, which implies the CSD not harming the results substantially.

3. Results and discussion

To examine economies' responses to MDE periods of transition, we first investigated changes in investments, material stock structure, and macroeconomic variables in a sample of 15 countries using dynamic efficiency measures (3.1). Following that, we introduce the causal inference test on a large country sample (n = 115). (3.2). The goal is to determine whether the MDE transition causes statistically significant changes in material stock accumulation.

3.1. Structure of material stock and economic conditions at country level

The material stock has no correlation with monetary dynamic efficiency. On the contrary, considering dynamic efficiency in terms of material, there is an overinvesting group of countries where a large amount of built-in concrete does not yield social benefits. This group includes Asian economies as well as Switzerland (Fig. 1). Korea joined this group in the 1990s, whereas China only recently joined in the 2010s (Fig. S1). Surprisingly, China's residential housing stock per capita has risen to the second highest in the sample, at 60 metric tonnes, while non-residential housing and civil engineering stocks perform significantly higher in developed economies.

JP – Japan; KOR – Rep. of Korea; CN – China; CH – Switzerland; AT – Austria; IRL – Ireland; UK – United Kingdom; HUN – Hungary; GER – Germany; IN – India; SWE – Sweden; USA – United States of America; PL – Poland; BRA – Brazil; NIG - Nigeria.

When we compare the countries based on the deducted material and their stock (Fig. S2), we can see a generally positive relationship with exceptions that correspond to particular cases described in (Dombi, 2022). Brazil mostly produces biomass for export, resulting in significant deduction (inland) yet requiring a small proportion of material stock. Sweden also exports a significant amount of wood and metals. Switzerland imports commodities in large quantities, whereas Japan and China overinvest (Fig. S1). In other countries in the sample, increases in material processing have resulted in increased accumulation and a larger per capita material stock allocation in recent decades. However, savings are negatively related to material efficiency (Fig. S3). While investment is a positive function of savings, the deducted material, which is the purpose of using the stock, does not depend on it. Instead, as the examples above show, it reflects the production sector and international trade. In general, the greater the proportion of a society's income devoted to investment, the lower the material dynamic efficiency performs, and overinvestment occurs (Fig. S3).

With low savings and depreciation rates, Germany and the United Kingdom have exhibited some similarities to the proposed policy in (Dombi et al., 2022). Furthermore, population growth in these countries has been moderate. In 2015, material stock inputs are lower than in 1990 (by 9 and 2%, respectively). Nonetheless, real GDP growth in these two countries (68%) outpaced that of the US (52%) and Switzerland (62%). Household and government real consumption followed a similar pattern. Austria has the fastest GDP growth rate among the industrialized countries in the study, but it is consistently accumulation-based, with yearly material stock inputs increasing by 9% and total stock increasing by 45%.

The MDE transition was observed in three countries during the time period investigated over a number of years. Between 1991 and 1996, Switzerland's depreciation and savings rates declined in lockstep. Material input into stock fell, while real GDP and consumption increased (Fig. S4a). In terms of rising countries, China and Nigeria moved in the direction of the MDE transition recommendations for short periods, i.e., bottom-left in savings-depreciation plots (Figs. S4b and S4c). In the case of China, these periods are 1995–2000 and 2012–2015. During these periods, both investments and deducted materials ceased, and GDP growth slowed, although real consumption of households and the government reacted modestly. The second five-year period had a 26% increase in consumption, comparable to 1990–1995 (+31%),

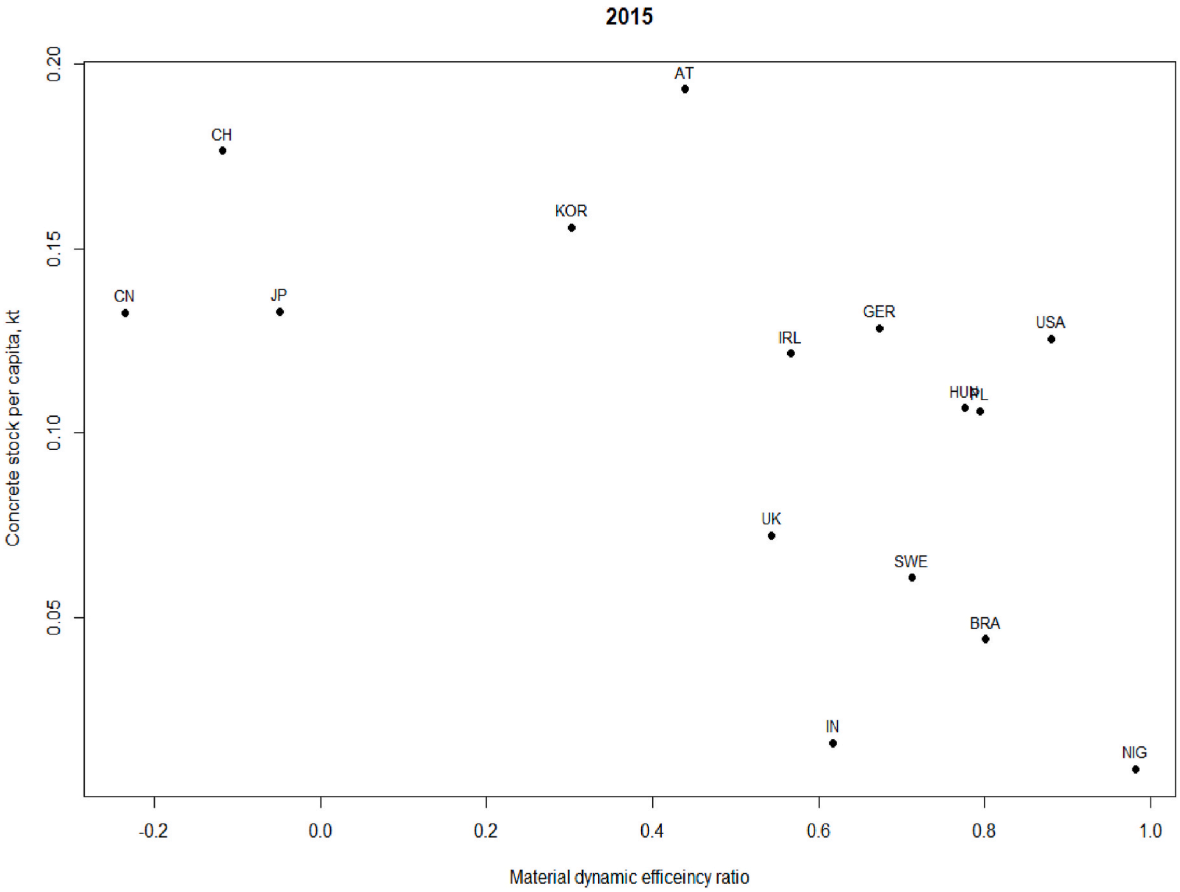

Fig. 1. Material stock and material dynamic efficiency in time among 15 analyzed countries.

demonstrating that the MDE transition allows consumption to rise in monetary terms. Furthermore, the last five years witnessed the sharpest rise in consumption (+35%). The economy performed dynamically efficiently between 1995 and 2000. Results on Nigeria show that demand can still emerge rapidly enough as material input into material stock decreases. However, the available data for the country are somewhat volatile.

One must not ignore that investments in economic infrastructure may pay off with a significant delay. As a result, assessing the functional structure of material stock inputs for these specific scenarios is worthwhile. Germany and the United Kingdom direct concrete into non-residential structures, i.e., the productive sector. Among developed countries, these two have the largest proportion of non-residential structures in total concrete inputs. This contrast shows that with a moderate level of savings, which also implies limited financial inflows into capital markets (supply), productive investments may find ways to be funded without interfering with technological progress and economic performance. A shortage of available savings ultimately halts both the residential housing market and government investment. These findings are consistent with the panel regression results of (Dombi et al., 2022), who reported that the link between non-residential stock and the savings rate was the weakest of the three stock types analyzed.

Consequently, the analyzed country sample contains multiple instances of the MDE transition in the past. These relatively short periods are characterized by a minor deceleration in economic dynamics, real GDP growth, and consumption, as well as sharply declining material throughput. Since the amount of material invested reacts more substantially to changes in savings and depreciation rates than the amount of material deducted, material efficiency has improved in all of the analyzed cases.

3.2. Average effect of the material dynamic efficiency transition on material stock

We defined treatment units as country-year observations between years with a decline and then a rise over one standard deviation in the savings and depreciation rates parallelly, as we introduced in section 2.3. In Fig. 2, the red color indicates treated units, whereas the blue color represents untreated units. It should be noted that d and s may decline at the same time in untreated units; nonetheless, the analysis attempted to identify what changes in material stock have been driven by a long-term shift in these economic features.

Country codes and corresponding countries are presented in Table S2.

Fig. 3 presents the estimated average treatment effect (black dots) and its 95% confidence interval (bars). The total material stock (top-left panel) is significantly lower five years after treatment, but the confidence interval makes it difficult to draw any conclusions from 6 to 10 years impossible. The average treatment effect for residential and non-residential building stock likewise reveals a decreasing accumulation; however, this effect is statistically not robust, as observations within the confidence interval occur in both the positive and negative range. Nonetheless, 95% of the estimated effects on civil engineering structures' material stock (roads, trains, dams, etc.) remain stable below the zero line. Thus, the MDE transition halts the accumulation of these types of structures by all means, and the effect reaches 16% of the mean civil engineering stock in the sample.

To determine the magnitude of the estimated treatment effect, one may examine the distribution of material stock at the start and end of the analyzed period (Fig. 4). Accumulation has made material stock distribution more equitable, with average stock performance of 21.8 and a median of 10.8 t/cap in 1980, compared to 61.2 and 43.3 in 2016. In the

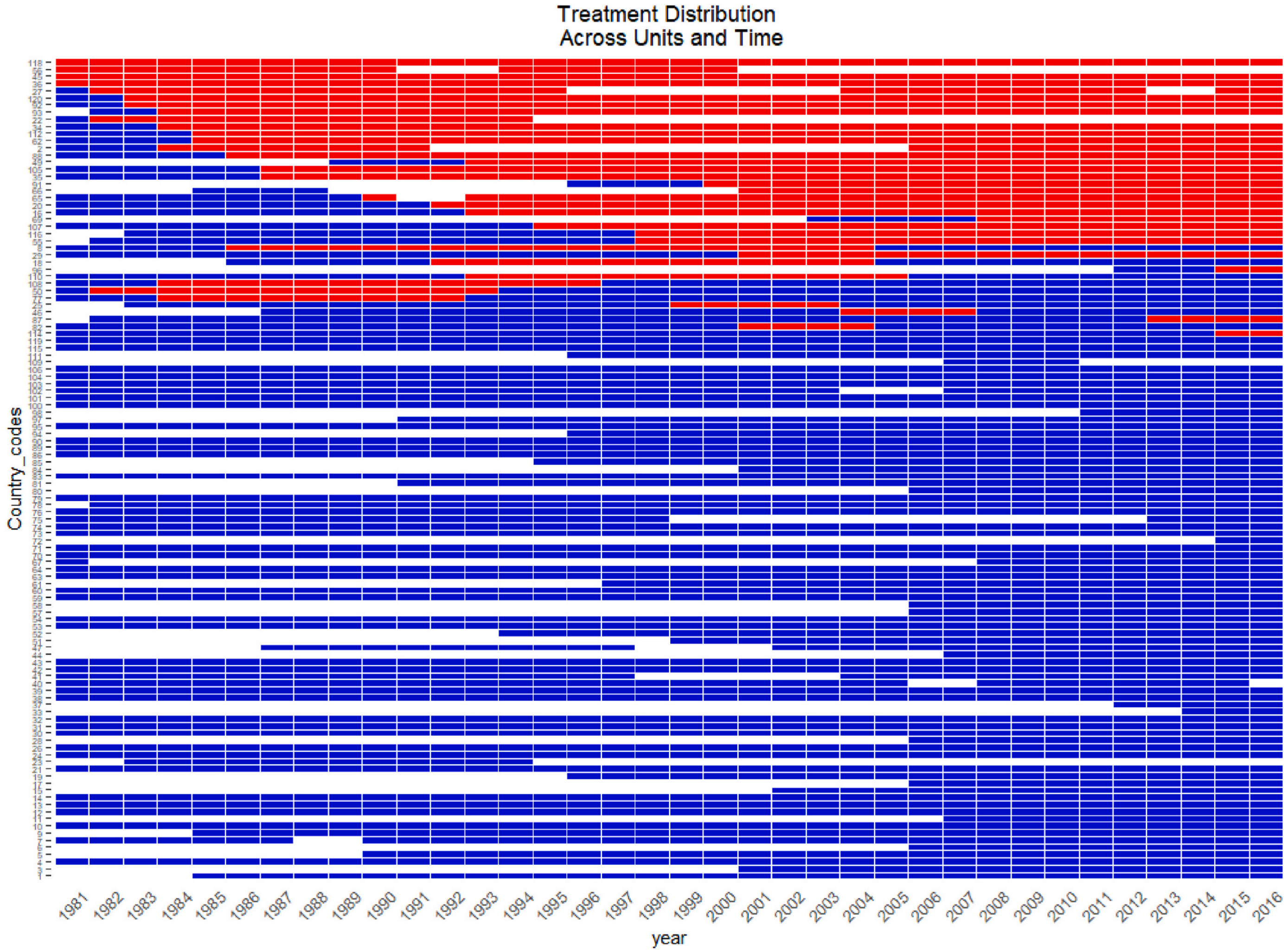

Fig. 2. Treated and untreated units in large country sample (n = 115).

fifth year after treatment, the average treatment effect is −3.19 t/cap, covering 14.6% of the average stock in 1980 and 7.4% in 2016. When the mean of the entire period is considered, the average effect covers 7.7% of the material stock.

As demonstrated by the examination of country-specific cases in section 3.1, the MDE transition limits the growth of civil engineering and residential housing stock. However, the treatment effect on civil engineering stock does not stabilize over time, and its average value (−2.48 t/cap) exceeds 10% of the average stock of that type even in 2016. A large country sample justifies those findings in this manner.

3.2.1. *The connection between MDE transition and economic performance*

Theoretically, an MDE transition results in an altered pathway for an economy characterized by modest economic output but ascending consumption in monetary terms. In this section, we examine whether the results of our analysis validate this assumption based on existing data.

In total, 3045 country-year observations out of 4197 units were included in the sample, implying that 73% of the units witnessed economic growth. In addition, 787 observations (18%) had MDE transition treatment. Almost three-quarters of these latter observations (n = 578) showed economic development at the same time. Furthermore, country-year observations revealed a recession, i.e., drop in real GDP on a year basis, despite emerging savings (n = 609). Similarly, consumption per capita increased for 80% of the observed units, and consumption increased for 85% of the units in an MDE transition. As a result, the treatment appears to be indifferent in terms of economic dynamics.

Following that, we compare the treated and untreated countries in terms of per capita real GDP and consumption. Overall, 39 of the sample's (n = 115) countries experienced an MDE transition, at least in the short term (see Fig. 2 and Table S2), including China, the United Kingdom, Mexico, and Nigeria. In general, the mean and median consumption and GDP of treated countries are lower than those of untreated countries (top panels in Fig. 5). Year on year, the consumption and GDP mean, and median values indicate changes in the treatment status of several countries. For example, in the sixth year of the observation, Norway and Bahrain joined the treated group, which had clearly increased the average level of economic output. Between the 18th and 21st years, China, Uganda, Indonesia, and Nepal transitioned to treated status (1997–2000). The reduction in treated values (red, top panels) during this period reflects these economies' poor financial performance when compared to the untreated group. While average consumption and GDP are lower in the treated group, their patterns are similar after the first decade of observation (bottom panels).

Solid lines indicate median values, while lines with dots stand for mean values.

In line with the theoretical foundations of the MDE transition, the share of household consumption in GDP is remarkably higher in treated units (Table 1). The economic crisis in 2008–2009 vanished this difference temporarily until 2014, the dominance of untreated ones went up to 11%. In contrast, the treated group's consumption to GDP ratio performed 15–24% higher before the crisis.

The question remains whether an MDE transition leads to a rise in

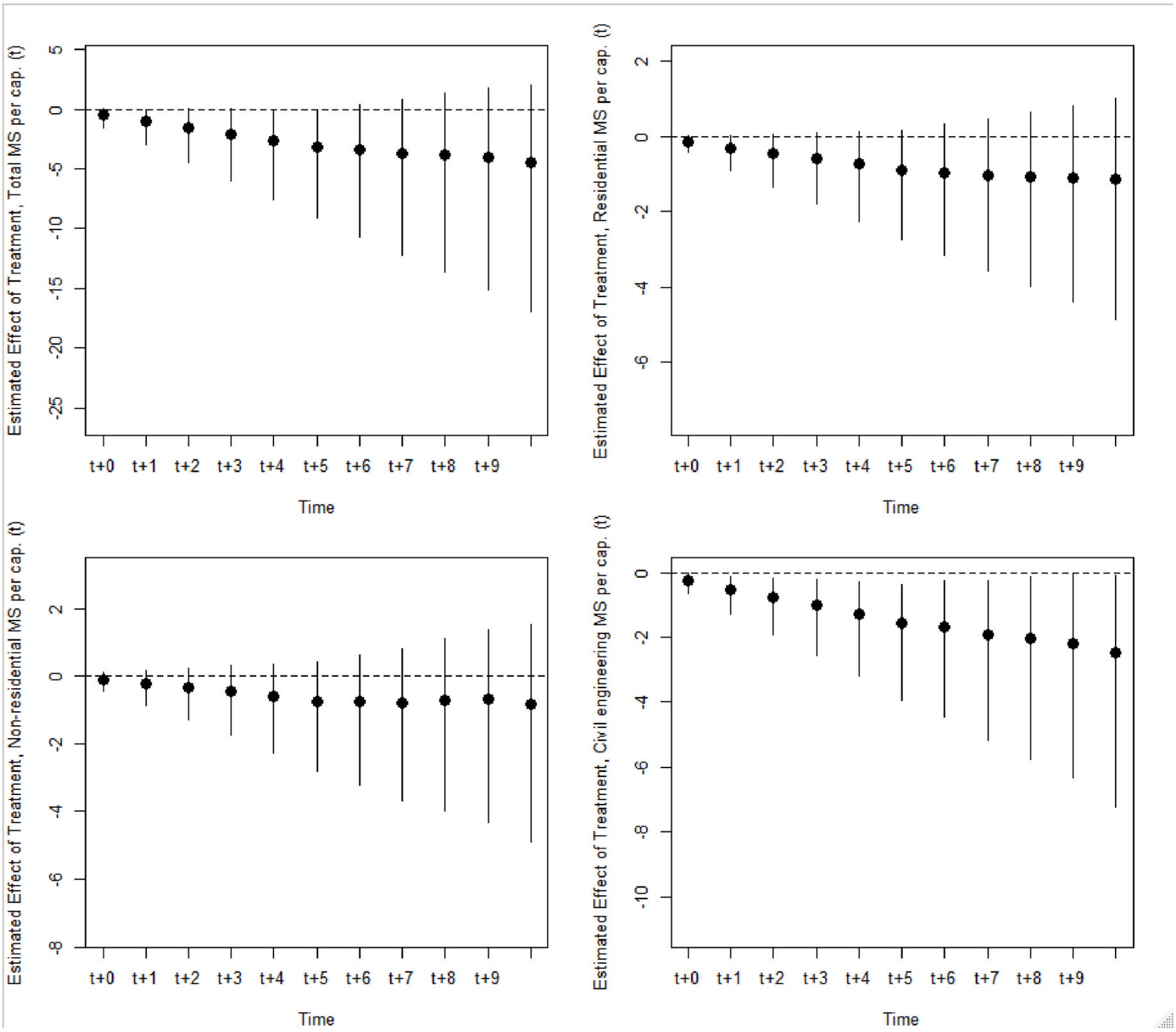

Fig. 3. Estimated effects of the treatment (MDE transition) over time.

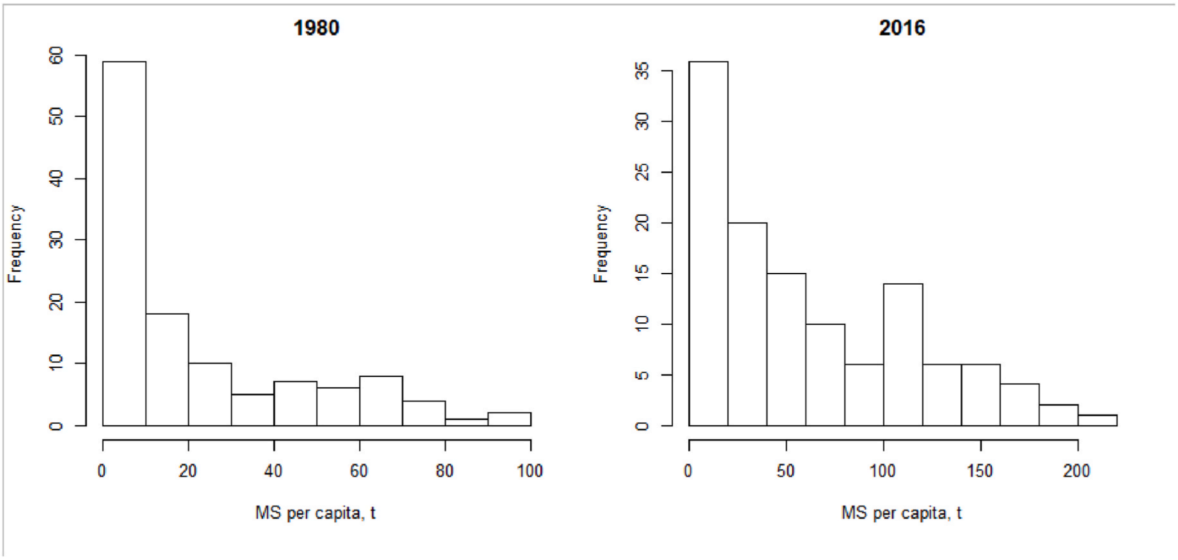

Fig. 4. Histograms of total material stock in the first and final years of the analyzed period.

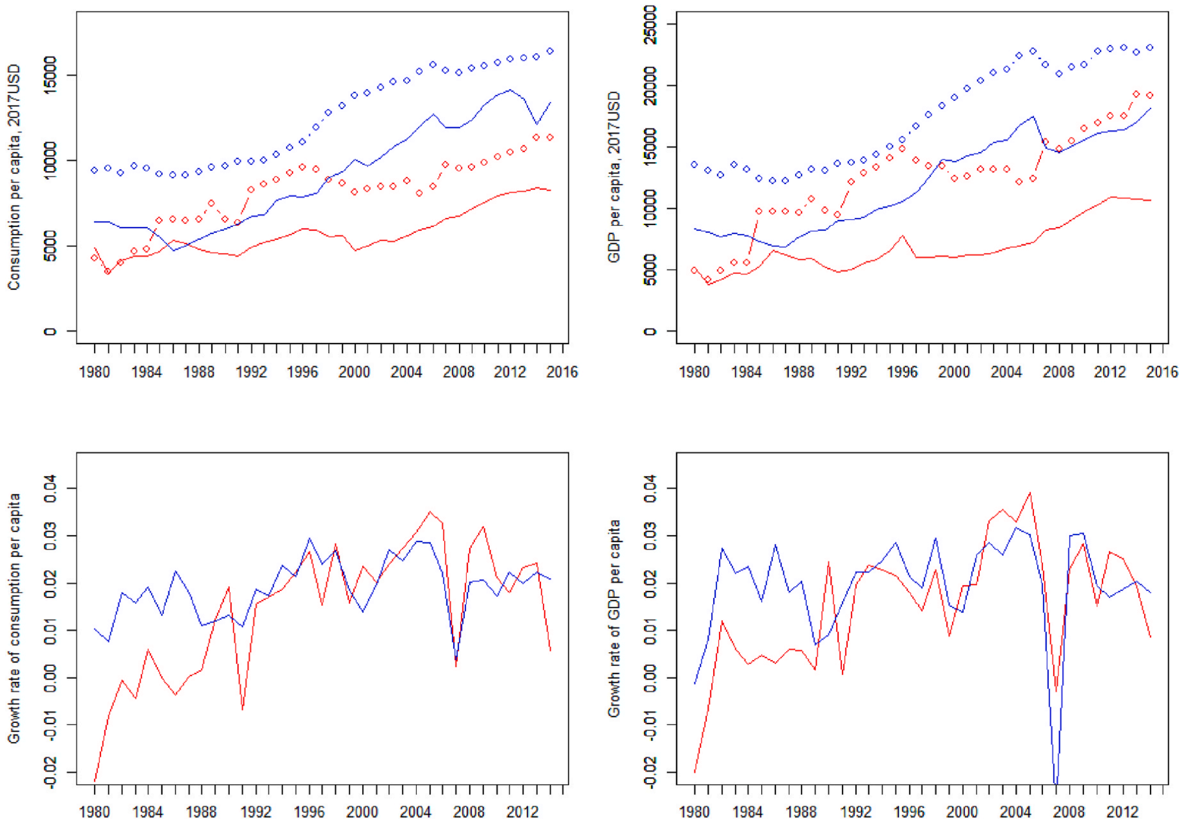

Fig. 5. GDP and consumption per capita of treated (red) and untreated (blue) units. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Ratio of median consumption in GDP.

	1985	1990	1995	2000	2005	2010	2015
Treated units	0.95	0.78	0.93	0.91	0.83	0.79	0.78
Untreated units	0.78	0.71	0.77	0.66	0.72	0.82	0.71

consumption. In an attempt to answer this question, we outlined several countries with significant untreated history in Fig. 6. We considered a country as a treated during the period between a red and a blue line. In reality, the consumption per capita is not solely an effect of the MDE transition; however, the consumption plateaued in several countries (Bahrain, Republic of Congo, Honduras) or speeded up during the treated period (Mexico, Sweden, Guinea). Besides, we must acknowledge that while consumption and GDP are fairly reasonable measures of economic activity, they fail to describe what is considered sustainable (Fanning et al., 2021; Hickel and Kallis, 2019). In other words, even if an MDE transition did not result in a surplus in consumption, the ecological benefits indicated above, namely, a major slowing in material stock accumulation, make it a viable development path.

Red vertical line indicates the year, when a country transited towards a MDE path; while blue vertical line presents the year when the reversal shift occurs.

3.2.2. *Development aspects of MDE transition*

By changing the savings rate, the MDE transition affects the available capital for investments in an economy. Since the amount and quality of existing assets and infrastructures essentially contribute to economic output, this core aspect of the policy inevitably addresses a country's long-term development path. Therefore, we tested the sample for development status effects, or whether economies at different stages of development respond differently to MDE transition treatment. We also looked for evidence of a general saturation of material stock in line with the development and possible discontinuation of the treatment's effect in wealthy countries. To evaluate this development path effect, we used the World Bank's classification, which divides nations into four income groups based on gross national income (GNI) per capita in US dollars converted from the native currency. We did not allow countries to move groups in order to reliably track the accumulation process.

In general, treated units are found throughout all four income groups (Table 2, Fig. S5), with the high-income category having the lowest ratio of treated countries (20%), which is likely due to their less volatile savings and depreciation rate. As per our expectations, the accumulation process loses its dynamics along with emerging income. Even in the most developed countries, average yearly growth in total material stock exceeds GDP growth rates, i.e., 3.2% and 2.4%, respectively. This fact, once again, emphasizes the significance of material stock in the sustainability transition as a major impediment to decoupling natural resource use from economic activity.

Despite the rare phenomenon of material stock saturation in several countries (Fishman et al., 2015; Wiedenhofer et al., 2021; Dombi, 2022), our dataset shows that a considerable number of high-income countries maintain accumulation continuously (Fig. S6). "Clear indications for a saturation of material stocks and a subsequent stabilization of material flows are not evident from historical trajectories", as Wiedenhofer et al. (2021) stated. In contrast, its presence in single countries is probably due to specific physical and socio-economic conditions (Fishman et al., 2016).

Despite being successfully matched to control units, the estimated effects of treatment are statistically not robust in four income groups independently (Fig. S7). It means that the MDE transition's manifestation in moderated accumulation cannot be justified in all probability and that other factors influence material stock dynamics when countries with similar economic conditions are considered. These factors,

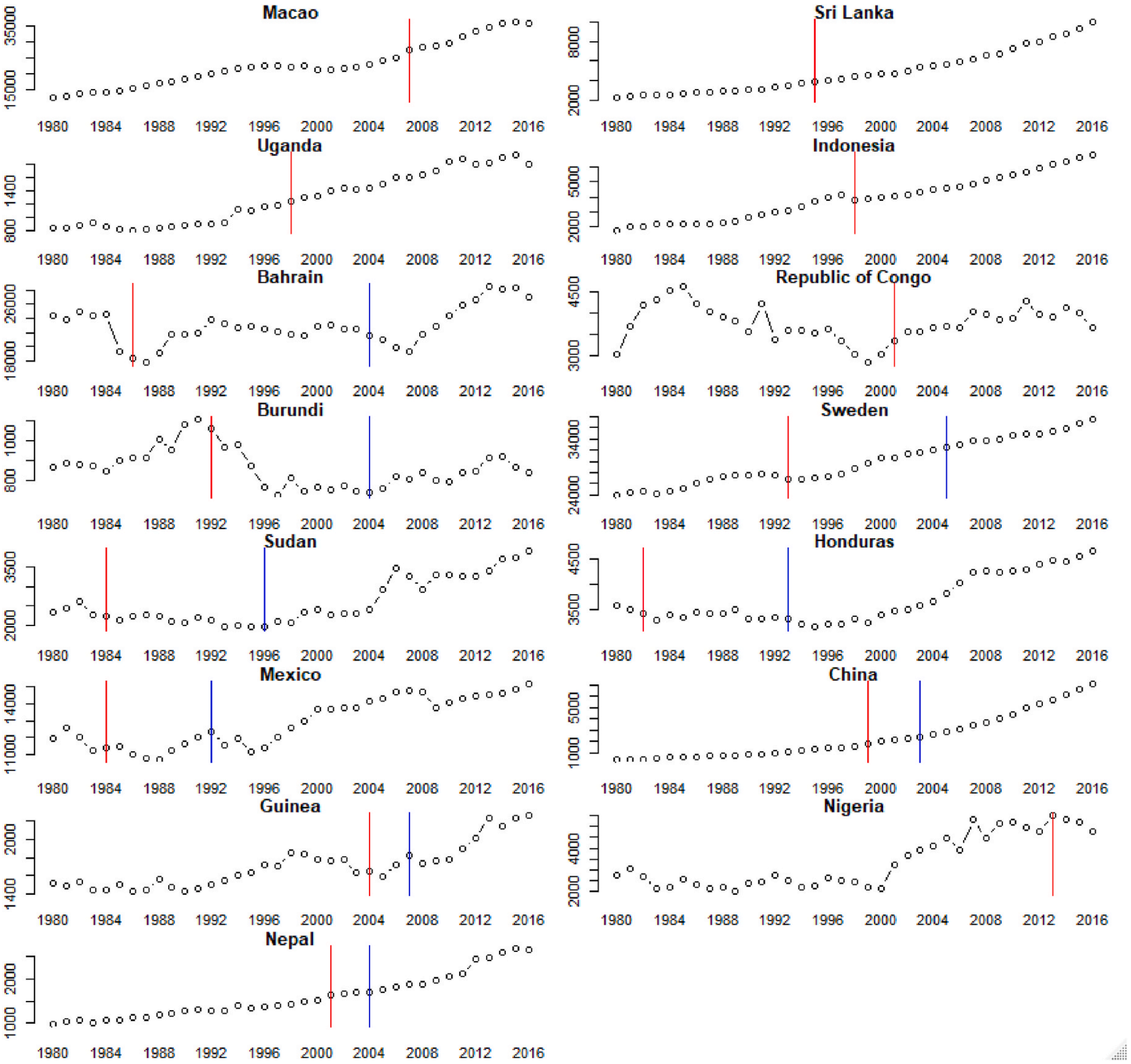

Fig. 6. Consumption per capita of countries under an MDE transition with significant untreated history.

Table 2
Main characteristics of the income groups.

			Material stock per capita (median)		
	Treated (n)	Untreated (n)	1980 (t)	2016 (t)	Average annual change (%)
Low income	8	14	1.17	6.83	13.1
Low-middle income	13	13	3.83	22.4	13.1
Upper-middle income	10	18	12.57	47.73	7.5
High income	8	31	51.04	110.83	3.2

according to recent literature are population density, economic structure, urbanization rate, and spatial planning system (Dombi, 2021; Fishman et al., 2015; Gao et al., 2020; Göswein et al., 2018; Han et al., 2018; Shao et al., 2017; Zhang et al., 2019), are not included in our analysis.

We also assessed the sample as a whole, dividing it into two aggregated income groups based on the same classification: low and low-middle income (LLM) and upper-middle and high income (UMH) (Figs. S8a and S8b). The endowment of material stocks is significantly higher in the UMH income group and is equally distributed among the countries compared to the LLM group. In this case, the average estimated effect produced considerably negative values across the three material stock categories of the LLM group, with an average effect of 0.84 t/cap in the fourth year (10% of the subsample's average material stock). On the contrary, the civil engineering stock had a substantial treatment effect in the UMH group but an uncertain treatment effect in the other stock categories and total stock (Figs. S8a and S8b).

To conclude, material stock accumulation generally continues even in the wealthiest country group, while savings and depreciation rates intensely influence this material stock in countries at their early stages of development more likely. Thus, development status seems to matter if it comes to the savings and depreciation rates' potential ability to adjust the material stock accumulation process. One could argue that the MDE transition inhibits developing economies from following a specific, infrastructure-intensive path but is irrelevant for an already industrialized group of countries, which sparks the concern that principles of just sustainable transition are being disregarded. To address this issue, one should enquire about two characteristics of material stock accumulation. First, would a 10% lower material stock level in the fourth year of an effective MDE transition render developing countries worse off socially than other developing countries? Second, is the MDE transition the country's only policy option? If this is the case, do developed countries have anything else to do because the MDE transition has no effect on their stock?

In terms of socioeconomic conditions, the treated group's median GDP per capita was 31–92% greater, while the treated group's median consumption surpassed the untreated median by 13–88% in the LLM subsample. However, we cannot detect any variations in the dynamics of economic performance between treated and untreated countries. The treated group's median GDP increased 15 years out of 36 in the analyzed period faster than the untreated countries' median, while consumption increased 14 times faster. There was no correlation between these median values. Life quality indicators should be considered to provide a comprehensive picture of the sustainability implications. The median life expectancy at birth, for example, implies no substantial effects: the ratio of treated to untreated values remains between 0.98 and 1.05, with a falling trend over the last decade.

Other policy interventions must underline the importance of spatial decisions made in a country. On the one hand, we refer to the amount of civil engineering stock because the rate of accumulation constantly outpaces the dynamics of total material stock in all income groups. This analysis, on the other hand, intended to show the effects of savings and depreciation on material stock, and it only anticipated an effect that performed within a 7–10% change in stock on average. However, as we discussed in (Dombi et al., 2022) a comprehensive policy of just sustainable transition necessitates significant changes in spatial planning, transportation, and housing regulations, all of which contribute to further lowering material stock accumulation. These developments primarily affect developed countries to a large extent.

3.2.3. Policy implications

As a result, a policy that encourages a lower share of savings and depreciation is a potent tool for slowing material stock accumulation and mitigating the environmental implications of this process without causing significant disruptions in economic processes. Measures to control savings generally include altering consumption taxes (VAT) or imposing large inheritance or wealth taxes. Limiting the savings of the highest income earners is in fact targeted towards their income and their income sources, particularly capital income generated from owning and investing in material-intensive real estate. There are many ways this could be achieved, progressive floorspace-based property taxes, progressive property transfer taxes, progressive second and third home-ownership taxation. A promising financial instrument to prolong the lifetime of an asset and thus lower the depreciation of assets could be the system of mandatory rates of depreciation defined in national accounting legislation. As depreciation deducts the tax paid by the company, a reduction in the annual depreciation of an asset reduces the deduction, so the company should pay higher taxes. Significant extension of the rates defined by law could deliver this effect, especially in the case of buildings, where the depreciation period is much longer compared to equipment or IT assets.

4. Conclusions

Our study has revealed significant effects due to a material dynamic efficiency transition: a simultaneous drop in savings and depreciation rates. When compared to the average material stock of countries without no substantial trend shifts in savings and depreciation, this effect ranges from 7.7% to 10%, depending on the stock type and development stage.

We also explored the socioeconomic and long-term developmental implications of such a policy. According to the two country samples used in this analysis, investments in the productive sector withstood the scarcity of available savings, whereas the residential building and civil engineering investments reacted intensely to the changes. In terms of its dynamics, no substantial influence on economic performance could be detected. The average effect of the material dynamic efficiency transition is influenced by a country's development stage, and less developed countries, at least according to the World Bank's classification, saw major ramifications in comparison to developed countries. The economic conditions of the countries undergoing the material dynamic efficiency transition, on the other hand, remained unaffected. We also reported on the continuous rise in developed countries' material stock, accentuating the civil engineering infrastructure as a potential focal point of the related policies.

To halt material stock accumulation and further ecological damage originating in this process without causing significant disruptions in economic processes, a policy promoting a lower share of savings and depreciation might substantially support the sustainability transition. Limiting the savings of the highest income earners is, in fact, targeted toward their income and income sources, mainly capital income generated from owning and investing in material-intensive real estate. A promising financial instrument to prolong the lifetime of an asset and thus lower the depreciation of assets could be the system of mandatory rates of depreciation defined in national accounting legislation. Our results have proven that policies acting against economic inequalities and excess natural resource use are compatible and feasible without disrupting the economic and even life quality conditions.

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Credit author statement

Mihály Dombi: Conceptualization, Methodology, Software, Formal analysis, Writing - Original Draft, Visualization, Supervision Piroska Harazin: Investigation, Andrea Karcagi-Kováts: Investigation, Faisal Aldebei: Conceptualization, Investigation, Writing - Review & Editing, Zhi Cao: Methodology, Software, Data Curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.117568.

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