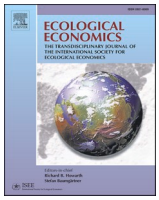
Ecological Economics 227 (2025) 108383

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon



A comparative review of de- and post-growth modeling studies

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ARTICLE INFO

Keywords:
Degrowth
Post-growth
Modeling
Policy evaluation
Scenarios
Transition

ABSTRACT

In recent years, a small but rapidly growing field of modeling alternatives to growth as represented by the de- (DG) and post-growth (PG) discourses has emerged. We compare selected model characteristics of 75 DG and PG related modeling studies, compiled through a systematic literature review (2000−2023), and link model structures and results to different theoretically contested debates surrounding DG/PG. The reviewed studies cover different geographical and temporal scopes, economic theories, modeling techniques and operationalizations of DG/PG. The majority of studies models DG/PG as intentional transition and does not question its compatibility with a capitalist system, while more radical strands of the DG/PG discourse are excluded. Although DG/PG modeling exercises frequently explore the effects of sustainability policies, they represent only a fraction of theoretical DG policy proposals, with the most frequent being: working time reduction, maximum income caps, carbon taxes and a universal basic income. DG/PG modeling studies have demonstrated the importance of integrating biophysical constraints in economic modeling but also have quantitatively assessed the feasibility of environmental integrity and social well-being without growth. Nonetheless, future modeling could be rendered more realistic by paying more attention to the Global South, introducing heterogeneous agents driving sustainability transitions and including multiple planetary boundaries.

1. Introduction

In the context of the persistent failure of the world economy to deliver 'green growth', i.e. to rapidly and strongly decouple economic growth from ecological deterioration (Haberl et al., 2020; Parrique et al., 2019), concepts that provide alternatives to a growth-based economic system, such as 'De(−)growth' (DG) and 'Post-growth' (PG), are on the rise. Nevertheless, as 'umbrella terms' (Chertkovskaya, 2022; Gerber and Raina, 2018; Hardt and O'Neill, 2017) without a universally accepted definition, their concrete meanings are dynamically evolving. For example, PG has been used interchangeably with DG (e.g. Koch, 2020a; Koch and Buch-Hansen, 2021) but also as concept of its own (Paech, 2012), and the concepts have been interpreted as a voluntary societal transition toward higher welfare, lower environmental destruction and more 'democracy/autonomy' (Asara et al., 2013; Corlet Walker et al., 2021; Kallis et al., 2018), but also as an externally imposed halt and reversal of economic growth (Crownshaw et al., 2019; Douthwaite, 2012; Drews and Antal, 2016).

Despite the potential of formal/quantitative models to complement theoretical analysis by assessing the feasibility and plausibility of sustainability proposals, identifying leverage points in the system, and detecting unintended side effects (Capellán-Pérez et al., 2015; Đula et al., 2021; Giampietro et al., 2009; Sterman, 2000), the field of DG/PG modeling is still small. This is in part due to the position of DG/PG outside the (social and scientific) mainstream, skepticism within some parts of the DG movement toward quantitative (economic) modeling approaches (Jackson and Victor, 2020) and the fact that economic DG/PG theory is still in development. Recent years have seen a strong increase in attempts to model dynamics described as 'DG' or 'PG'. This rise of DG/PG related modeling can be linked to advances in ecological macroeconomics, a field that has developed economic models capable of representing alternatives to growth-based systems (Hardt and O'Neill, 2017), as well as to repeated calls to diversify existing Integrated Assessment and Climate Economics research by giving up on the assumption of continuous GDP growth (Hickel et al., 2021). The small but growing field of DG/PG related modeling constitutes a promising development which has the potential to contribute to a certain formalization of the terms, thereby rendering them more tangible. However, a systematic analysis of existing DG/PG modeling efforts, and how they relate to different understandings of DG/PG, is currently missing.

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https://doi.org/10.1016/j.ecolecon.2024.108383
Received 26 February 2024; Received in revised form 12 July 2024; Accepted 7 September 2024
Available online 11 September 2024

Likewise, it is unclear to which extent different policy proposals made by the qualitative DG/PG literature are explored by means of modeling techniques.

Consequently, in this article we systematically review modeling studies that make explicit reference to the terms 'de-' and/or 'post-growth' since 2000. Our analysis pursues two main objectives:

First, we aim at providing a review of relevant model related characteristics of current DG/PG studies that might prove useful to modelers interested in exploring DG/PG dynamics. Therefore, we analyze (1) the growth of DG/PG related studies over time as a proxy for the growing importance of the topic; (2) their geographical scope to highlight both well covered and under-researched territories; (3) the dimensions (economic, biophysical…) represented in the models to illustrate the degree and importance of interdisciplinarity for DG/PG modeling; and finally, different modeling techniques (4) and ways to operationalize DG/PG (5) in order to show the diversity of possibly suitable modeling approaches that are employed to study DG/PG.

Second, we want to shed light on whether and how selected theoretical debates on DG/PG, that are still not fully resolved but highly relevant for a clear-cut definition of DG/PG, are reflected in/translated into the models. These debates involve around (1) the relation between DG/PG, GDP and socio-economic metabolism; (2) the (un)intentionality of DG/PG processes; (3) the (in)compatibility of DG/PG with a capitalist system; as well as (4) key actors and (5) suitable policies for a DG/PG transition (cf. section 2.2). This theory-informed analysis allows us to assess on the one hand whether the results of modeling studies helps to clarify these open theoretical debate, and on the other hand, which aspects of theoretical debates receive more or less attention by the modeling literature.

Thus, although the starting point and focus of our work are *modeling* studies, through the bipartite analysis we intend to bridge qualitative and quantitative approaches to DG/PG: Informed by our analysis, modelers interested in DG/PG will be able to gain insight about the achievements and blind spots of modeling studies conducted so far, while theoreticians might be prompted to improve qualitative work related to DG/PG taking into consideration the results of quantitative studies and their interpretation of DG/PG.

In what follows, we will outline the methods used for our literature review and summarize shortly key theoretical debates before presenting the results of our analysis regarding the model- and theory-related aspects of the reviewed studies. The discussion focuses on achievements and limitations of the studies reviewed, as well as on opportunities for future qualitative and quantitative research on DG and PG, while the conclusion synthesizes the principal results of the article.

2. Methods and theoretical background

2.1. Systematic literature review

We conducted a systematic literature review following the PRISMA 2020 method (Page et al., 2021) to build a comprehensive database representing the state of the art in economy-related DG/PG modeling. Our principal search was carried out in Google Scholar with the search string: *((“quantitative model”) OR (“IAM”) OR (“simple model”) OR (“mathematical model”) OR (“macroeconomic model”) OR (“quantification”) OR (“modeling”)) AND ((“post-growth”) OR (“de-growth”) OR (“degrowth”) OR (“postgrowth”)) AND ((“economic”) OR (“economy”))* [query date: 28.11.2023]. We limited the search to the period 2000–2023 and only considered the first 900 results.[1] We complemented our search by using the same search string in Scopus.[2] As the search string shows, we required the modeling studies to have an explicit reference to the terms 'De-' or 'post-growth' since we are interested in the *use* of these terms by modelers, rather than in an *ex ante* imposed definition of DG/PG. This also had the consequence that studies modeling a 'steady state' or a 'zero growth' economy without making reference to 'DG/PG' did not enter into the scope of the systematic literature review although they could be argued to be related to DG/PG debates (cf. Blauwhof, 2012; Wiedmann et al., 2020). The discussion section covers the implications and limitations of this self-reported PG/DG search criteria for the analysis.

After removing duplicates, we screened all the identified 885 results and removed those that described DG/PG in fields not related to the ecology-economy-society nexus (e.g. from chemistry, engineering, education…) as well as those that treated DG/PG in a purely theoretical way. After the screening process we retrieved 165 results and assessed them for eligibility by reading the abstract and the parts of the papers related to DG/PG. Applying the same exclusion criteria as in the screening stage we identified 61 suitable results. Additionally, we identified, screened and assessed 14 papers through other methods (snowballing and broader non-systematic literature reviews), increasing the body of our literature review to 75 scientific works.[3] The whole procedure is depicted in a PRISMA 2020 flow diagram (Fig. 1). Table A.1 in Appendix A lists all papers included in the review with their assigned ID that we will use when referring to specific papers.

Once the whole body of suitable literature was identified, the relevant information was extracted through an iterative content analysis process, which included the papers themselves as well as their figures, references, appendices and supplementary material.

2.2. Theoretical background: DG and PG as contested discursive concepts

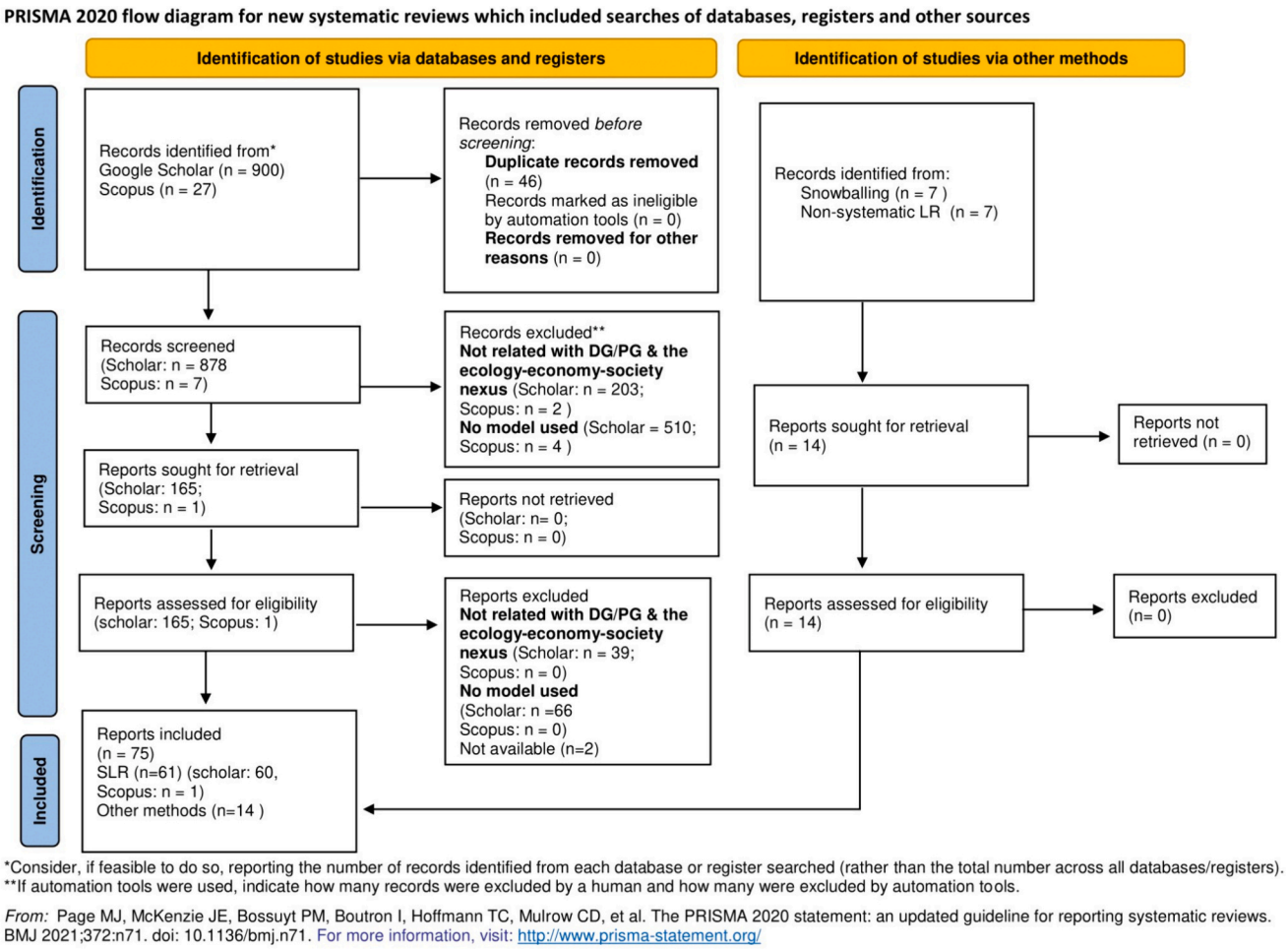
The exact meaning of 'DG' and 'PG' remains contested and is dynamically evolving. While one strand of the literature uses 'DG' and 'PG' interchangeably (Vincent and Brandellero, 2023) another uses 'PG' as umbrella term including various 'alternatives to growth' such as 'DG', steady-state economics, prosperity economics, a-growth and/or post-development (Gerber and Raina, 2018; Hardt and O'Neill, 2017). A third strand attempts to draw clear differences between the terms. For example, Wiedmann et al. (2020) describe 'DG', together with eco-anarchism and eco-socialism as 'radical' approach to sustainable prosperity, whereas 'PG' is seen as part of a 'reformist' approach that also covers a-growth, steady-state economics or prosperity without growth. Likewise, Likaj et al. (2022) attempt at an explicit differentiation between 'DG' and 'PG', placing 'PG' together with 'a-growth' and 'beyond growth' at a middle ground position between 'DG' and 'green growth'.

Partly due to the lack of a commonly accepted clear-cut definition of the terms, five key questions regarding DG/PG dynamics remain contested:

[1] They keywords 'economy' and 'economic' narrowed the search to economy-related results and kept the amount of results in a manageable scope.

[2] Exact search string in Scopus: TITLE-ABS-KEY ((“quantitative model” OR “IAM” OR “simple model” OR “mathematical model” OR “macroeconomic model” OR “quantification” OR “modeling”) AND (“post-growth” OR “de-growth” OR “degrowth” OR “postgrowth”) AND (“economic” OR “economy”)) AND PUBYEAR >2000 AND SUBJAREA (econ OR soci). Query date: 28.11.2023, all results considered.

[3] These 75 results comprise peer-reviewed articles, working papers reports, PhD theses and book chapters. However, in our analysis, we do not distinguish between different published formats and refer to all of them as 'papers' or 'studies'.



*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).
**If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools.

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: http://www.prisma-statement.org/

Fig. 1. Prisma flow diagram of the performed systematic literature review.

First, in the DG/PG context, the evolution of GDP and socio-economic metabolism (throughput) over time is crucial. Depending on assumptions about the (im)possibility of 'decoupling' GDP growth from growth in throughput (Haberl et al., 2020), and on assumptions about the long-term sustainable scale of the global socio-economic metabolism (Daly, 1992; Georgescu-Roegen, 1975), DG/PG can be conceptualized as a reduction or stabilization of GDP and/or socio-economic metabolism on a global or regional scale (only the Global North) (cf. De Mooij and van Den Bergh, 2002; Kallis, 2011; Kallis et al., 2018; Van den Bergh, 2011). The literature stressing differences between 'DG' and 'PG' holds that, while DG sees the downscaling of production and consumption as inevitable, PG appears to focus on low or zero growth which does not forcefully translate into economic contraction (Polewsky et al., 2024). Since modeling necessarily has to make assumptions about these two variables (GDP and throughput), they could help to increase conceptual clarity on this question.

Second, a debate still unsettled, concerns the extent to which the terms 'DG/PG' can be used to describe intentional and voluntary processes or unintentional, undesirable 'imposed' realities. Although widely cited authors of the self-denominated 'research on DG' literature (Kallis et al., 2018) have repeatedly stressed that 'DG' should be understood as an intentional and voluntary process involving the (selective) downscaling of the economy (Hickel, 2021; Smith et al., 2021), mainstream economics still relates the term 'DG' to an unplanned, unintentional reduction of GDP (Blauwhof, 2012). The fact that concepts such as 'DG by disaster' (Elgars and Renars, 2023) are used by scholars, shows that in practice multiple, different meanings are ascribed to the term. The same is true for 'PG' which has been used to describe imposed limits to growth, due to environmental and resource degradation (Crownshaw et al., 2019) or 'secular stagnation' (Jackson, 2019) but also stands for intentional transformative process toward more social equality and ecological integrity (Gerber and Raina, 2018) or a new economic paradigm (Drews and Antal, 2016). Investigating how models depict DG/PG dynamics, thus, shows to which extent modelers adhere to 'mainstream' or 'transformative' uses of the terms DG/PG.

Third, the compatibility of PG/DG with a capitalist system remains a contested issue, partly also due to different conceptions of 'capitalism' among different theoreticians. Drawing on positions that clearly differentiate between 'DG' and 'PG', a general tendency in the literature considers 'DG' to be 'anti-capitalist' (Boonstra and Joosse, 2013; Kallis, 2019) and 'PG' to be more in line with a reformed capitalism (Wiedmann et al., 2020) although this view could be contested (Jackson, 2021; Vincent and Brandellero, 2023). Paying attention to this question could be crucial for modeling studies since, depending on the different assumptions of the main mechanisms operating in the economic system represented in different schools of economic thought (neoclassical, post-Keynesian, Marxist etc.), modeling results regarding (in)compatibility of DG/PG with capitalism will vary significantly. Also, integrating real-life characteristics of contemporary capitalism into models could help theoreticians to detect barriers to successful DG/PG transitions.

Fourth, the key actors of (voluntary as well as imposed) DG/PG dynamics are subjects to debate (Koch, 2020a). Here, the literature moves between decentralized bottom-up transitions by local actors and top-down state-led transitions (D'Alisa and Kallis, 2020; Koch, 2020b, 2022). A sensitivity to these theoretical debates would allow modelers to systematically compare the opportunities, barriers and consequences of

DG/PG transitions led (and opposed) by different type of actors.

Last, in the context of an increasing focus on state-led transitions, the development of policies labelled as 'DG' or 'PG' has gained importance. The two most extensive compilations of DG/PG policies known to the authors are those of Hardt and O'Neill (2017) and Fitzpatrick et al. (2022). Although the former focuses on 'PG' and the latter on 'DG', in practice, they refer to both terms and do not establish clear differences between DG and PG. Given their ability to compare, assess and evaluate different policies with regard to their effectiveness, efficiency and feasibility, modeling studies could prove especially valuable for this part of the theoretical DG/PG literature.

3. Results

3.1. Model-related aspects

Out of the 75 reviewed modeling studies, which comprise 55 peer-reviewed articles, 12 working papers, 3 studies or reports, 3 PhD theses and two book chapters, 53 make reference to a DG discourse and 16 relate to the term PG.[4] 6 studies could not be unequivocally matched to either a 'DG' or 'PG' discourse since they either used the terms interchangeably (ID56, 70, 31, 36) or referred to both without displaying a clear priority for one term (ID45, 71). The modeling literature, hence, mirrors the theoretical literature, with some studies differentiating between the terms while others using them as synonyms. Thus, in the graphs shown throughout this article, the reviewed studies were divided in three groups according to their discourse (DG/PG/both) to illustrate to which extent different discourses translate into different model characteristics and results. This differentiation might be of interest for those modelers and theoreticians striving to clarify the differences between 'DG' and 'PG'.

3.1.1. Growth in DG/PG modeling

The number of DG and/or PG modeling exercises has increased exponentially in the last 10 years (Fig. 2a), reflecting the increased attention paid to quantitative aspects of DG/PG. Although modeling studies referring to 'DG' are clearly the majority, 'PG' increasingly gains traction. Interestingly, none of the studies referring to both concepts without clearly distinguishing them, was published before 2020, indicating that a certain 'merge' between 'DG' and 'PG' has only taken place in recent years.

The first paper (Victor, 2012) that explicitly explores a DG scenario with the LowGrow model was published in 2012 which coincides roughly with the surge of the DG discourse in academia (Kallis, 2011; Martínez-Alier, 2012). The term 'PG' was first introduced by Jackson & Victor (Jackson and Victor, 2011), with the first complex models referring explicitly to PG being the EUROGREEN and the FALSTAFF models published in 2016 (Cattaneo et al., 2016; Jackson et al., 2016).

3.1.2. Geographical scope

The geographical scope of the modeling exercises is global (26 papers) or covers specific regions or countries of the Global North (28 papers) (Fig. 2b). 16 papers model abstract systems instead of concrete territories. Comparing the share of 'DG' and 'PG' related papers in the different geographical scope, 'DG' has a relatively high presence in studies of global scope, whereas 'PG' is more frequent in abstract studies. The latter is explained by the high share of abstract economic models using the 'PG' discourse (cf. section 3.1.3), which do not include an empirical representation of geographical territories.

The Global North is not only the main object of DG/PG modeling but also the main producer of DG/PG related knowledge, since the research institutions that (co)produce quantitative DG/PG research are mainly located in the Global North: 96 % of the analyzed papers are (co)produced by authors affiliated to a research institution based in a high-income country (according to the World Bank classification) with France, UK, Spain and Germany alone (co)producing 72 % of all publications. Authors' affiliations also explain the high proportion of 'PG' related studies focusing on Canada, the UK and Germany, since three important authors often linked to the 'PG' discourse – Victor, Jackson (2018), and Paech (2012) - are based in these countries.

Only 4 % of the reviewed studies were (co-)produced in upper middle income countries, namely China and Ecuador, while research institutions from low and lower middle income countries were completely absent. Furthermore, all studies dealing with DG in the Global South reflect an understanding of the term that differs from the 'research on degrowth' literature: The two publications dealing with DG in Ecuador do not model intentional sustainability transitions but rather externally enforced economic contraction (Espinoza, Fontalvo, Martí-Herrero, et al., 2022; Espinoza, Fontalvo, Ramírez, et al., 2022) while the study covering the achievement of SDGs in Iran operationalizes DG as zero GDP growth in a 'Steady-State Economy', which performs worse than the alternative scenario 'Well-being for people and planet' (Chapariha, 2022). In a similar way, the study covering dematerialization pathways of Beijing (China) (Dai and Shan, 2020) operationalizes DG as reduced GDP growth which performs worse than alternative sustainability strategies.

Fig. S.4 A and B in the Supplementary Material compare the geographical scope of the studies with the geographical affiliation of the modelers.

3.1.3. Dimensions represented

Models also vary with regard to the dimensions they cover: They are mostly bi/pluridimensional (36 papers) or unidimensional (27 papers). However, 12 papers also use multidimensional Integrated Assessment Models (IAMs). IAMs could potentially represent a larger number of aspects of DG/PG as they integrate knowledge from multiple scientific disciplines (Beck and Krueger, 2016), but commonly rely on the 'default' assumption of continuous economic growth (e.g. Hickel et al., 2021). The IAMs used in the analyzed papers do not *ex ante* assume positive growth rates of the economy and are mostly newly developed IAMs, except for an adapted version of MESSAGEix-GLOBIOM used in 2 papers. All pluri- and multidimensional modeling exercises use empirical data as model input whereas half of the papers with a unidimensional model (13 papers) are abstract economic models relying purely on formal mathematics.

Table S1 in the Supplementary Material displays the names of IAMs and bi/pluridimensional models used in the publications.

Fig. 2 resumes these three characteristics of the reviewed studies.

3.1.4. Modeling techniques

The modeling literature refers to a large variety of modeling approaches and techniques employed in the study of different DG/PG related questions.

First, models can be differentiated on the basis of the school of economic thought they draw on. We found that post-Keynesian (e.g. ID12, 19, 20, 40) and neoclassical (e.g. ID9, 17, 21) theories are well represented in the modeling literature while there was only one paper using classical economics (Oberholzer, 2023) and no paper relied on Marxist schools of thought to conduct modeling studies. Also, some works drew on statistical techniques (ID6, 57, 66) or used input-output (IO) analysis as theoretical framework (ID11, 27).

Second, models use different methods to represent the systems they are interested in: Biophysical representation is achieved through LCA, physical (energy) flow accounts or environmentally extended IO tables (e.g. 33, 42, 46), while the monetary dimension of reality can be represented through tools such as stock-flow consistent modeling (e.g. ID14, 15, 19). System dynamics and agent-based modeling are two

[4] In the latter case, this does not mean that the word 'DG' is absent in the studies but that it is clear that the concept of 'post-growth' is the main point of reference. See e.g. Jackson and Victor (2011).

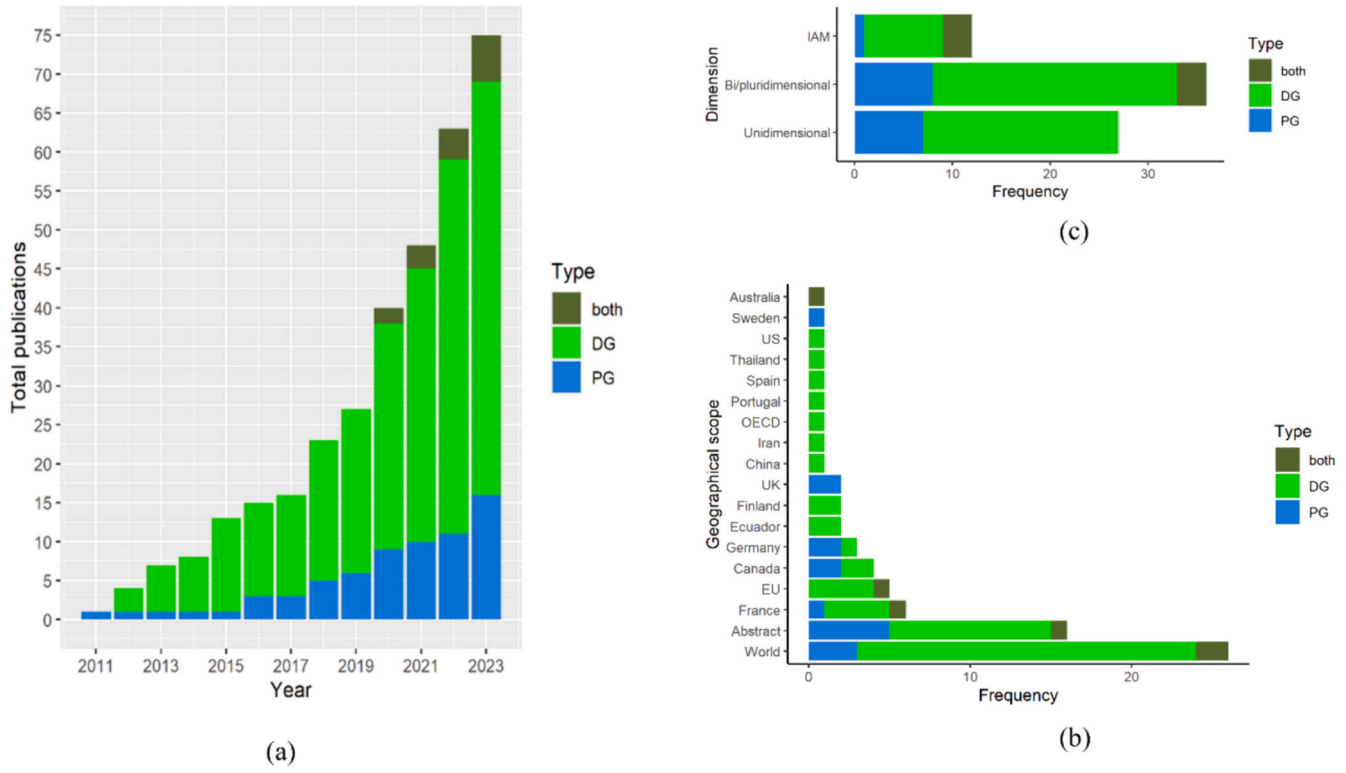


Fig. 2. Overview of basic characteristics of the analyzed papers. (a): Evolution of total publications over time, (b) Geographical scope of the modeling exercises, (c) Model dimensions.

generic tools often used to tackle the complexity of the systems under study (e.g. 13, 31, 64, 75).

Third, we found that modelers often combine different approaches, such as post-Keynesian theory, IO analysis and system dynamics, to build their models (e.g. ID31, 36, 39, 60). However, until now only one paper (Jackson et al., 2023) has added stock-flow consistency on top of the three approaches, thereby featuring the 4 characteristic techniques of ecological macroeconomic modeling identified by Hardt and O'Neill (2017).

Last, across all reviewed studies, simulations are employed with great frequency since they allow the study of time-dependent systems. Although the time periods of the simulations vary greatly, simulations covering more than 100 years only make up 11 % of the simulations, while most simulations are shorter than 50 years (43 %), between 50 and 75 years (26 %) or cover between 75 and 100 years (19 %). While the great majority of simulations unfolds throughout the 21st century, there are also six papers (ID12, 23, 43, 56, 71, 74) that use abstract time units or 'years' without referring to a specific time period (Fig. 3).

More information on modeling characteristics (use of empirical data, scenarios, model names etc.) is provided in Tables S1 – S3 of the Supplementary Material.

3.1.5. Operationalization of DG/PG

The heterogeneity of modeling approaches translates into a great diversity with regard to how 'DG/PG' is operationalized and introduced in the different models. In models where key aspects of the economic system like growth in GDP, consumption, resource demand or working time are exogenous variables, these variables can be set to zero or to negative values by the model user (e.g. ID23, 65). Models in which demand is based on utility functions can introduce DG/PG by modifying this function so that economic actors display 'satiety' behavior (e.g. ID24, 70). In other models which do not use utility functions but where key aspects of the economic system are endogenously produced, DG/PG dynamics can result for instance from introducing both constraints on energy availability and energy intensity reductions or by reducing GDP growth targets (e.g. ID36, 13, 49, 54). Last, constructing DG/PG scenarios allows modelers to systematically compare 'DG/PG' transitions with 'business-as-usual' scenarios or alternative strategies (such as Green Growth) to achieve sustainability.

Nevertheless, the implementation of DG/PG often remains simplistic compared to the complexity of a DG/PG transition in reality, which is explicitly acknowledged by some modelers (e.g. Li et al., 2023).

3.2. Linking DG/PG modeling and theory

3.2.1. Changes in GDP and socio-economic metabolism over time

Analyzing how GDP and the socio-economic metabolism (throughput) changes in the reviewed studies affirms the hypothesis raised in the qualitative literature according to which 'DG' stresses the downscaling of both GDP and throughput while 'PG' does not necessarily consist of absolute reductions (section 2.2): Although 'DG' related studies differ in their descriptions of 'DG', ranging from DG as voluntary equitable downscaling (majority of studies), 'paradigm' (ID25 & 51) or grassroot movement (Millot et al., 2018) to the development of more rural and de-technologized economies (Lallana et al., 2021), in the great majority of these studies 'DG' dynamics are expressed in the models through reductions in GDP (48 papers) and/or reductions in the socio-economic metabolism (36 papers) (Table 1).

In contrast, in most 'PG' related studies GDP growth rates are low or zero (13 papers). The papers referring to both concepts tend to model negative growth rates and reductions in throughput although zero growing GDP and throughput are also present. Two notable outliers from these patterns are Aramendia et al. (2023) and Bastin and Cassiers (2013) that make reference to a shrinking metabolism while GDP growth rates approach zero. Analogously to the 'Green Growth' discourse (Van Vuuren et al., 2017), this understanding assumes a certain degree of decoupling between growth and throughput.

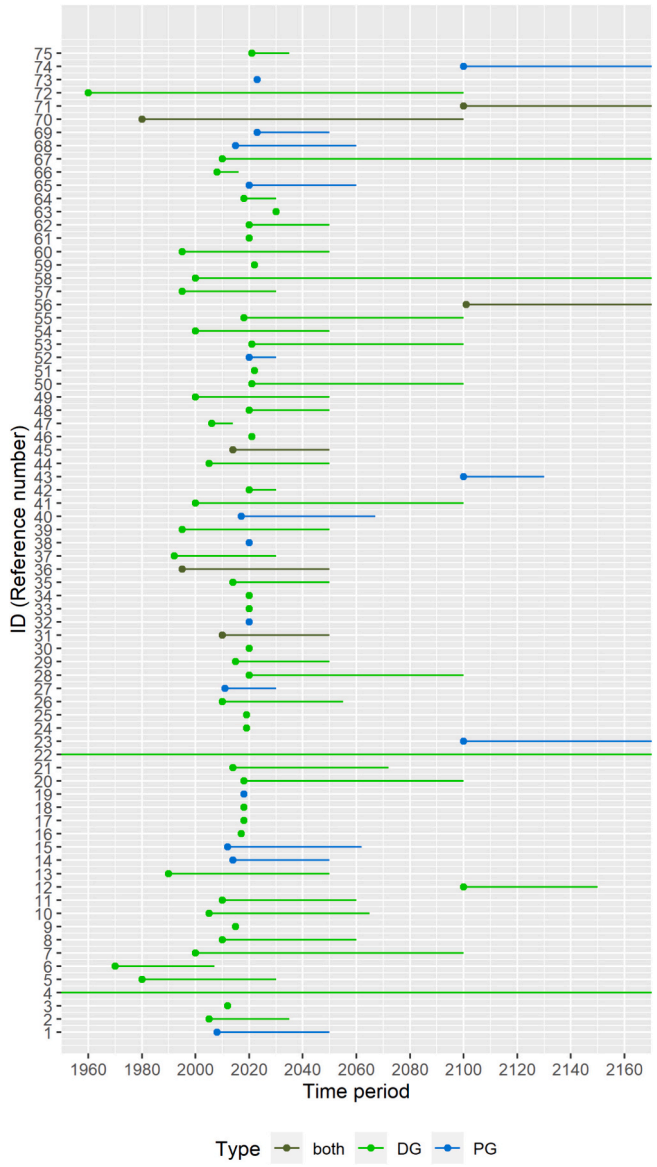


Fig. 3. Time period covered by the papers. The lines starting in 2100 depict simulations in 'abstract' time units, e.g. from '0' to '50' for ID12. Points depict papers without a temporal analysis and only indicate the date of their publication. Exception: ID63 comprises an analysis for the year 2030.

Table 1
Number of papers whose models exhibit certain characteristics regarding GDP and throughput/socio-economic metabolism.

Type of Study	DG	PG	Both
Negative GDP growth rates	48	3	4
Reduction of socio-economic metabolism	36	4	3
Low positive growth GDP rates tending to zero	4	13	2
Low- or non-growing metabolism	2	2	1

3.2.2. *Intentionality of DG/PG*

We find elements of intentionality and unintentionality of economic downscaling in both DG and PG related modeling studies, illustrating that modelers use the terms both in their 'mainstream' and 'transformative' meanings (cf. section 2.2). Among the DG related modeling exercises, a surprisingly high share (12 out of 53 papers) portray unintentional 'DG' dynamics.[5] Most of these studies have in common that they incorporate some biophysical limits to growth in their models, which drives the economy to reduce its size. These limits include increasing scarcity of fossil fuels (ID22, 49, 54, 4) and climate damages destroying production and capital (e.g. ID26, 28, 75). Some studies explicitly establish a link between climate damages and financial instabilities that might lead to a collapse of the global economy (e.g. ID55, 20, 67).

The great majority of DG studies, however, understands DG as an intentional transition process involving different social, ecological and economic policies. Precisely to avoid a "DG by disaster" (Kuhnhenn et al., 2020, p. 9), the literature makes an effort to design viable transition pathways (e.g. ID11, 13, 30) and to evaluate different policy instruments that might favor such pathways (e.g. ID50, 18, 24). Studies on 'DG' pathways in the Global North unambiguously stress the advantages of 'DG' since it reduces the necessary rate of technological innovation and progress such as negative emission technologies (Kuhnhenn et al., 2020; Sers, 2022) or energy efficiency (D'Alessandro et al., 2020) while simulations with a global scope point to the risk that a global 'DG' transition to reach climate goals could result in an increase of extreme poverty (Moyer, 2023).

In contrast, in the case of the PG related studies the line between intentionality and unintentionality gets blurrier. In three papers (Cattaneo et al., 2016; Hartley et al., 2020; Jackson and Victor, 2018), 'PG' is linked to the empirically observable phenomenon of declining growth rates in industrialized countries. Whether these are related to biophysical limits to growth remains an open question. Thus, the post-growth world reflected in low or zero (possibly even negative) growth is assumed to be an externally imposed reality. Consequently, these studies focus on the modeling of policies that reduce inequality and maintain or increase employment in a PG world, i.e. an *intentional* adaptation to externally imposed limits to growth. In a fourth study (Jackson et al., 2023), PG could be understood both as imposed reality as well as a transition process toward more sustainability. The case of Janischewski (2021) is also interesting, given that the author models the potential *unintended* side-effects, namely a stock market crash, of an *intentional* post-growth transition motivated by stringent climate mitigation, demonstrating that the distinction between intentionality and unintentionality cannot always be upheld. However, in the remaining 11 papers, PG is clearly related to a desirable transition process similar to 'DG' in the sense that it is intentional and that it should improve social and environmental conditions. For example, Jacques et al. (2023) find that slower growth rates facilitate a rapid energy transition in line with the 1.5 °C goal, and, thus, argue for an (intentional) PG transition with respective policies. Similarly, Aramendia et al. (2023) who operationalize a PG scenario through declining GDP growth rates, find that in a PG pathway, the energy consumption of the mining industry is three to five times lower compared to conventional green growth scenarios.

Last, all six studies that cannot be matched unequivocally with one discourse, portray DG/PG as intentional transition process.

Thus, the dominant approach to the modeling of both DG and PG consists in focusing on an intentional stabilization or reduction of GDP and throughput.

3.2.3. *Compatibility with capitalism*

Although there are some clear statements in the theoretical literature with regard to the incompatibility between (voluntary) DG and capitalism, in the DG modeling literature the problem barely receives

[5] Interestingly, also some 'PG' related studies use the term *de-growth/degrowth* in a conventional way to describe a reduction in GDP while 'PG' is used to describe a social/structural transition process.

attention. For a minority of studies dealing mainly with technical biophysical questions (e.g. ID60,68) this is due to their focus on the 'biophysical' feasibility of DG/PG rather than on its politico-economic feasibility. For other studies, it might be partly explained by the fact that complex economic models, especially when they are based on empirical data, inevitably represent the current capitalist reality, and modeling transitions from a capitalist to a post-capitalist economy could prove to be extremely challenging.

In only 11 DG and 5 PG related modeling studies the problems of a growth based capitalist system such as rising inequality or ecological degradation are problematized. Out of these studies, only a minority makes clear assumptions that might be incompatible with capitalism such as a democratization of economic decision-making (Kuhnhenn et al., 2020), or highlights the extreme difference between institutions in the current and a potential future economic regime which would likely not be described as 'capitalist' anymore (Briens, 2015; Keyßer and Lenzen, 2021). The paper which raises the clearest doubts on the compatibility between capitalism and a voluntarily shrinking economy is Li et al. (2023) who point to a series of barriers and growth imperatives in the current capitalist economy.

The part of the DG modeling literature focused on voluntary simplicity of a part of the population due to welfare considerations (e.g. ID3, 9, 17) tends to ignore the powerful capitalist incentives to increase consumption and the spread of precarious work which renders '*happy* degrowth' (Bilancini and D'Alessandro, 2012; Nørgård, 2013) unthinkable for a great part of the population even in richer countries. With the exception of the studies with 'unintentional DG', portraying the failure of continued capitalist development, DG related studies, thus, tend to avoid the 'capitalist' question.

Conversely, among the studies referring to 'PG' there is a clearer analytical framework, which allows drawing conclusions regarding the future of capitalism under PG. The modeling results of two authors who explicitly problematize PG transitions under capitalism (Janischewski, 2021; Oberholzer, 2023), point to potential instabilities of a PG capitalist regime while the overwhelming majority of the remaining studies is designed to model policies implemented through the existing institutions (e.g. ID14, 38, 19, 52, 32). In none of these studies, the compatibility with capitalist structures is questioned, indicating that policies designed to deal with a PG reality do not need a radical departure from the current economic system. Barrett (2018) even attempts to show that the stability of the capitalist system does not depend on its growth rate.

Thus, while modeling concerned with voluntary DG transitions either stresses the great structural difficulties of the changes modeled, or avoids to discuss the question, modeling concerned with PG economies not only discuss the question more openly but also tend to find less difficulties of rendering reformist social and environmental policies compatible with existing economic regimes. However, given the relative scarcity of modeling studies explicitly problematizing economic structures, and the underrepresentation of certain strands of economic theory in DG/PG modeling (e.g. Classical or Marxist approaches) these result must be considered preliminary.

3.2.4. Actors of the transition

Even though many models are in principle capable of representing actor heterogeneity and even conflicts of interest between actors, especially between different economic subjects such as workers and capitalists or different income groups (e.g. ID17, 19, 31, 32, 51), the question of strategic actors that could initiate and implement DG/PG remains underexplored in the reviewed papers. For example, different social groups of actors with different organizational capacities and power resources such as social movements, business associations, multinational companies, activists or corporate media are notably absent in the modeling exercises. Instead, many models represent the society and the economy at highly aggregated levels, thereby hiding socio-economic diversity of actors (e.g. ID2, 7, 13, 16, 22, 28, 37, 41). In the modeling of decentralized DG/PG transitions actors are reduced to their roles as anonymous participants in the economy (e.g. ID9, 17) while most models employ a top-down approach through the introduction of certain DG/PG policies without taking into account different interest groups shaping the state's policies. Thus, the potential of modeling to enrich the theoretical debate on key actors of the transition has not yet been translated into concrete modeling results.

3.2.5. Policies

While 21 modeling studies do not include any policies, either because they model 'unintentional' DG/PG dynamics or because they deal with abstract problems, the remaining 54 studies aim to investigate the effects of the introduction of certain policies in their models. Fig. 4 shows the policies found in those studies, as well as the frequency with which they appear. The different names for policy measures with essentially the same content were homogenized, using as reference the list of DG/PG policy proposals developed by Fitzpatrick et al. (2022), since it is the most recent and comprehensive meta study on DG/PG policy proposals known to the authors. Policies not mentioned by Fitzpatrick et al. were homogenized according to the most frequently used denominations. Also, we only considered public policies that can be expected to be realized by public actors and institutions.

The policies modeled with the greatest frequency are those termed 'core policies' by Fitzpatrick et al. (2022) and comprise a Maximum Income Cap, Working Time Reduction, Universal Basic Income and declining caps on resources use and emissions. Together, they were modeled 42 times, which is the same frequency as all the transport, food and housing policies together. Two other policy types frequently modeled were taxes (on carbon, energy, profit, wealth, income etc.) and subsidies (mostly for the development of greener energy), as well as policies promoting structural change toward green or low labor productivity sectors.

For the policies we find a similar relationship to DG/PG related theory across all papers: On the one hand, the studies often focus on structural and technological change/improvements alongside the often stressed redistribution and economic downscaling. Examples for such policies are increased recycling rates, energy efficiency gains or negative emission technologies. Especially the latter, together with a strong focus on public policies such as green quantitative easing or strong public investments in the energy sector, could be viewed with skepticism by 'DG' actors opposing negative emission technologies and advocating for small community-owned, self-sufficient energy systems (cf. Fitzpatrick et al., 2022 and Fig. S.1 - S.3, Supplementary Material).

On the other hand, policies proposed by the qualitative literature and requiring major breaks with the existing socio-economic system, such as common property, not-for-profit cooperatives, time-based currencies, community-based enterprises, legislation on the rights of nature, moratoria on resource extraction or the dismantling of large corporations, are missing in the modeling exercises. Exploring such policies would likely require major changes in the very structures of the currently used models.

Last, we find that policies are distributed rather unequally over the reviewed studies: The 10 papers (ID11, 27, 39, 60, 2, 21, 29, 35, 38, 50) with the highest number of policies (between 6 and 22 policies modeled per paper) account for more than half of all modeled policies. The other half is spread over the remaining 39 papers, of which 18 papers only model a single policy.

4. Discussion

Having analyzed how selected aspects of the theoretical debate regarding DG/PG are reflected and operationalized in modeling studies, in the following we discuss achievements and limitations across all studies, as well as the opportunities for both future theoretical and modeling work arising from our literature review.

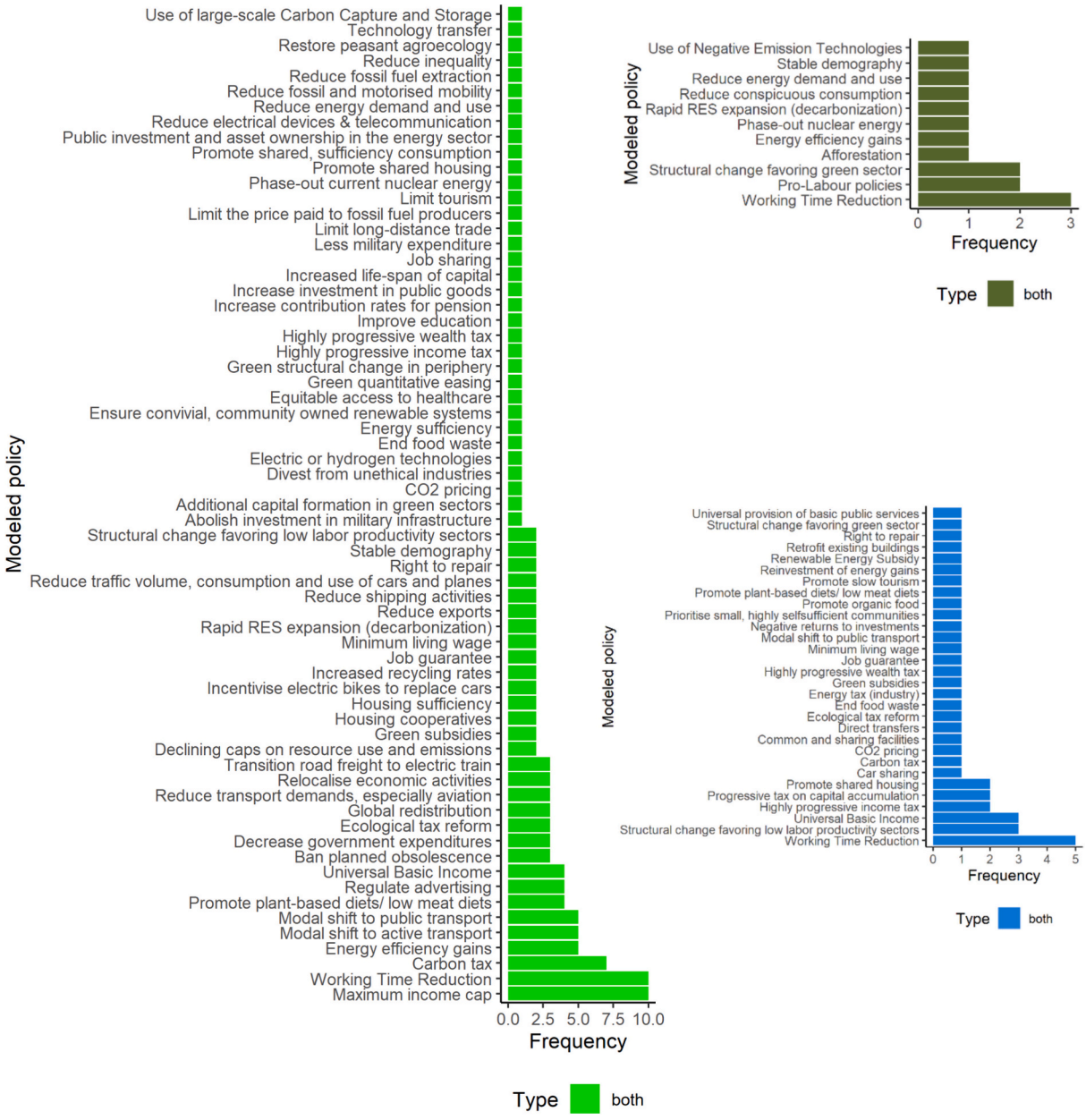


Fig. 4. Policies explored in the reviewed modeling studies.

4.1. Achievements of DG/PG modeling

The modeling of DG and PG is a dynamically, rapidly evolving area of research. Modeling work has been able to shed light on a range of different theoretical questions about degrowing and non-growing economies, including the environmental (emissions, energy, material, land) (ID36, 37, 39) and socioeconomic impacts (disposable income, inequality, etc.) (ID14, 24, 25, 32, 51) of DG and PG transitions, the rate of economic growth/degrowth compatible with different societal goals (ID35 & 62), the interrelation between resource constraints and economic growth (ID13, 22, 49), the relation between DG/PG and financial markets (ID67, 43, 55) as well as the implications of a range of different policy packages (ID11, 29, 36).

Over the years, the scope of DG as well as PG modeling has been extended to countries and regions previously not covered. Equally, the number of models used to conduct research on DG and PG continues to grow, which increases the diversity of methodological tools used to research de- and post-growth-related problems.

Modeling exercises integrate and emphasize different economic aspects of DG/PG (GDP, socio-economic metabolism…) and reflect different positions regarding the intentionality of DG/PG and its relation to the current economic system. This not only illustrates the diversity of existing interpretations of DG/PG but can also prompt scholars to acknowledge the lack of a uniform use of these umbrella terms, and to clarify their exact meaning. The hypothesis hold by all models that further growth in the socio-economic metabolism of global capitalism is unsustainable could thereby act as a first common ground between different DG/PG understandings.

Although modeling exercises are heterogeneous and no study can cover all aspects of ‘DG’ or ‘PG’, taken together, they produce a detailed and diverse picture of quantified knowledge, including policy-relevant knowledge about the effects and side effects of different environmental, social and economic policies that might be relevant in a ‘DG’ or ‘PG’ transition.

A great strength of models, especially of models able to simulate future developments, is that they allow their users to explore a wide

range of 'What-if' questions. 'What-if' questions are thought experiments and construct hypothetical worlds informed by quantitative data that allow to explore the implications of different trajectories (typically through an *ex ante* defined portfolio of policies), assessing and comparing their efficacy. Likewise, they help to detect priorities, potential barriers and unintended side effects, as well as synergies and trade-offs between different goals. Thereby, models support the assessment of the feasibility of DG/PG narratives to achieve environmental and social goals. In the reviewed studies, both DG and PG related modeling exercises in their majority find that reduced growth rates increase the feasibility of reaching environmental goals, and do not have to threaten social goals. Modeling, thus, helps to understand causal chains, which are difficult or impossible to conceptualize given the complex system nature of human societies and the biosphere.

Last, both 'DG' and 'PG' related studies have quantitatively illustrated the link between (1) DG/PG, (2) Well-being objectives (service provisioning, inequality, etc.) (e.g. ID46, 35, 62) and (3) biophysical limitations (climate change, energy restrictions, materials availability, etc.) (e.g. ID13, 31, 36, 39, 60). Thereby modeling exercises have broadened the imagination space of society and scientists alike and revealed the fallacies or inconsistencies of different ideas about sustainability related societal and economic changes.

4.2. DG/PG modeling weaknesses

The current field of DG/PG modeling, however, also exhibits some shortcomings related to the models' scope and structure. For example, the important question of who would be the key agents of change of the DG/PG transition (e.g. central governments versus grassroot movements) is largely left unaddressed. Models also face serious structural limitations to implement the extremely heterogeneous and fine-grained existing DG policy proposals, and often focus on a few selected policies rather than simulating the effects of a large range of policies acting at different time and geographic scales (cf. section 3.3).

Although modeling exercises in principle have the potential to clarify debates about the scale of necessary reductions in the socio-economic metabolism of societies that would be compatible with a DG paradigm (Trainer, 2021), many of the analyzed modeling exercises avoid the 'problem of scale' (Daly, 1992) either because they do not produce quantitative results or because they do not indicate whether the outputs of their simulations in terms of energy and GDP would be 'sustainable' in the long run (e.g. ID14, 25, 34, 58, 62). Exceptions with regard to energy are Lallana et al. (2021) and Kuhnhenn et al. (2020), indicating that a 'sustainable' global final energy consumption might be ~200 EJ/year. However, since these studies focus on only one planetary boundary, especially climate change, and tend to assume optimal conditions for a transition (optimal planning, efficiency gains), they probably overestimate the 'real sustainable' scale of human economic activities.

Furthermore, although the studies with a global scope generally tend to differentiate between economic development in the Global North and South, it seems that the modeling literature has not yet taken into account recent advances in the qualitative literature that theorize on the pertinence of 'PG' in the Global South (e.g. Adityanandana and Gerber, 2019; Bisht, 2022; Gabriel et al., 2019; Gerber and Raina, 2018). These scholars point out that current growth-based development in the Global South is unsustainable and does not focus on the fulfilment of basic needs of the Global South's populations. Modeling exercises often neglect (inter)dependencies between core and peripheral countries (Katz, 2022) as well as differences between Global North and South regarding history, culture and living conditions (Rodríguez-Labajos et al., 2019). Also, none of the papers that differentiate between Global North and South takes into account the great heterogeneity of the countries classified as Global South or 'developing'. Those papers generally assume that the Global South will grow its GDP while the Global North will reduce it, in order to achieve global convergence (ID13, 34, 58). Other approaches assume global GDP degrowth (e.g. ID41 or 72) without complete convergence. However, in both cases it remains unclear which kind of structural economic development the countries of the Global South would realize in such futures.

These shortcomings must be interpreted in the context of more fundamental limitations modeling studies face, such as (i) the need to recur to exogenous variables whereas in the real world all variables are endogenously evolving; (ii) barriers to quantify non-mechanistic aspects such as social behaviors; (iii) uncertainties and ignorance about the future of the social world (the evolution of institutional frameworks, cultural norms, etc.) and biophysics (climate tipping points, Earth's climate sensitivity, material endowments, etc.); (iv) data availability and computational limitations, and last (v) the dependence on modeler decisions and subjectivities (Meadows, 1999; Meadows et al., 2004; Sterman, 1991; Sterman, 2000). Thus, despite their importance in informing policymakers, modeling results should not be confounded with predictions, nor should political decision-making be based completely on particular model outcomes. Rather, in the era of uncertainty and post-normal science (Funtowicz and Ravetz, 1994) quantitative results should be complemented by qualitative research and participatory processes.

4.3. Suggestions for further work

Further work in the field of PG/DG could advance in several directions: (1) improving modeling, (2) improving theoretical literature and (3) complementing/expanding the review of PG/DG works conducted in this article.

Our analysis has shown that, despite the diversity of existing interpretations and operationalizations of DG and PG, the modeling literature mirrors the different standpoints raised on 'DG' and 'PG' dynamics in the theoretical literature with regard to conceptual differences between the concepts as well as their intentionality, compatibility with capitalism and policies to be implemented. Researchers interested in contributing to the evolving 'DG' and/or 'PG' modeling field, could focus more on the Global South, for example by differentiating between economic classes globally and within countries, increasing the models' regional detail, and exploring particular policy proposals that were developed specifically for the social, economic and cultural realities in countries of the Global South (Bisht, 2022; Gerber and Raina, 2018). These proposals align with the need to pay more attention to barriers and key agents for a DG/PG transition, consider regional heterogeneities and realize structural changes in existing quantitative economic models in order to represent different sustainability paradigms. Since agent-based models (ABMs) facilitate the representation of actor heterogeneity, linking ABMs with biophysical models could constitute a method to address these current blind spots. Additionally, considering more than one planetary boundary (Steffen et al., 2015) could produce more realistic sustainable scales of the world economy, and, thus, clarify, whether a sustainable economy requires a strong 'degrowth' of current GDP levels or whether a 'post-growth' condition of low or zero growth would be viable. However, increasing the number of dimensions and planetary boundaries could come with considerable modeling and computational (i.e. excessive simulation times) challenges, principally due to data availability issues and the need to guarantee internal consistency in interdisciplinary models. Also, great uncertainties with regard to the long-term resilience of the Earth system and limits to sectoral energy efficiency gains could obstruct the modeling of long-term sustainable scales of the socio-economic metabolism.

Researchers interested in advancing the qualitative literature on alternatives to growth might take the findings of our comparative review as motivation to further clarify the conceptual differences between 'DG' and 'PG' in order to reduce the confusion created by the simultaneous use of multiple related terms. A closer collaboration between modelers and theoreticians could lead to modeling studies with a strong grounding in different theories of social change exploring pertinent questions for both academia and society.

The main caveat of our review is related with the decision to prioritize self-stated PG/DG in order to analyze the PG/DG state-of-the-art. Although the focus on self-reported DG/PG publications has the advantage of studying how the terms are employed by modelers in practice, it might leave out other studies in the literature which, although they do not explicitly mention DG/PG, may overlap with DG/PG themes. Examples might be studies on the steady state economy (Daly, 1974), on different growth imperatives in the capitalist system (Richters and Siemoneit, 2019; Svartzman et al., 2020), or on biophysical limits to growth (Meadows et al., 1972). Nevertheless, we believe that the obtained sample is representative for the literature, and that it can be used by interested scholars to conduct cross-sectional analyses focusing on the energy, materials and well-being dimensions of DG/PG. We encourage further works on the topic to cover areas outside the scope of this article such as non-English publications, as well as non-economic dimensions of DG/PG. Future reviews could also focus on a systematic comparison of the quantitative outcomes of different DG/PG related studies. Although this might prove extremely challenging due to different modeling approaches, geographical scopes and assumptions of the future evolution of key variables (energy, carbon intensity, population growth, redistribution, environmental damage tolerated by the Earth system and human societies…) made by the modelers, it would help to narrow down existing uncertainties about the quantitative dimensions of DG/PG.

5. Conclusion

In this article, we compared existing modeling exercises focusing on de- and post-growth dynamics by analyzing 75 scientific papers compiled through a systematic literature review. The field of DG/PG modeling is small but rapidly expanding, and displays a great diversity regarding the temporal and geographical scope of the studied DG/PG dynamics, the understanding of key DG/PG characteristics, and the type of modeled DG/PG related policies.

In their majority, 'DG' dynamics are operationalized through shrinking GDP and throughput, and portrayed as 'intentional' transitions, although we also find studies depicting 'unintentional DG' due to biophysical limits to growth. Also, the publications, which often rely on scenario analyses comparing 'green growth' with 'degrowth', mostly avoid the theoretical debate on the compatibility between 'DG' and capitalism.

'PG' studies are more often conducted with purely economic models and frequently focus on specific economic problems. Modeling exercises tend to focus on finding policies that are compatible with existent (capitalist) structure and with a 'PG' reality of low or zero growth rates that might be externally enforced or actively pursued.

Despite these differences, the public policies assessed in the reviewed de- and post-growth modeling studies often intersect, while policy proposals requiring 'radical' departures from the current economic structure are strongly underrepresented. Last, studies that use 'DG' and 'PG' interchangeably, often rely on IAMs and, rather than being interested in conceptual differences, they explore what both terms have in common: alternatives of reaching environmental and social goals in the absence of economic growth.

Although we have found an overlap between policies suggested by the theoretical de- and post-growth literature and policies considered by the modeling literature, only a fraction of the former is currently considered by DG/PG related models.

The reviewed studies represent a broad quantitative knowledge base demonstrating that, at least in the Global North, further growth is not necessary to achieve well-being while a reduction of the socio-economic metabolism would considerably facilitate the pursuit of ambitious climate goals. Future modeling efforts could focus on growth/environment problems in the Global South, the introduction of heterogeneous agents driving sustainability transitions and the inclusion of multiple planetary boundaries to determine the scale of the economy that does not destabilize the biosphere in the long term. Studies could also build on insights from social sciences to model plausible 'DG' or 'PG' transition pathways from the current capitalist state of the system, and, in the case that no consistent and likely transition pathways can be found, explore different adaptation possibilities to an inevitable reduction of societies' energy and material metabolism.

Concluding, we see a considerable potential for theory development on DG/PG and quantitative approaches to cross-fertilize each other. While the former constitutes the foundation for any modeling approach and, thus, should make an effort to clarify the exact meanings of 'DG' and 'PG', the latter can help concretize DG/PG policy proposals, deal with scale issues, identify leverage points and compare the efficacy of different policy measures, even though quantification is complex and subject to many difficulties. Both approaches should co-evolve as better knowledge and more information are gained during the research process.

CRediT authorship contribution statement

Arthur Lauer: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Iñigo Capellán-Pérez:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Nathalie Wergles:** Writing – review & editing, Visualization, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Arthur Lauer reports financial support was provided by Cusanuswerk Sponsorship Organization for Gifted Students. Íñigo Capellán-Pérez reports financial support was provided by Juan de la Cierva-Incorporación Research Fellowship of the Ministry of Economy and Competitiveness of Spain (no. IJC2020–046215-I). Nathalie Wergles reports financial support was provided by EU Horizon 2020 research and innovation programme, grant agreement No 821105. If there are other authors, they 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.

Acknowledgments

We thank Oriane Denantes for supporting us with the visualization of the Prisma Flow Diagram as well as antecedent work on DG policies, and Luis Llases for supporting us with the categorization of models used by the analyzed papers. Also, we are grateful to the three anonymous reviewers of this article for their comments and suggestions which helped us to improve considerably the structure of the article.

A.L. acknowledges financial support from Cusanuswerk Foundation. I·C. acknowledges financial support from a Juan de la Cierva-Incorporación Research Fellowship of the Ministry of Economy and Competitiveness of Spain (no. IJC2020-046215-I). This work has been partially developed under the LOCOMOTION project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement no 821105.

Appendix A. Appendix

In the following, we display the body of analyzed works, selected through a systematic literature review, with their corresponding ID (reference number).

Table A.1
List of selected works modeling DG/PG.

ID	Authors (Year of publication)	Type of paper	DG/PG/both
1	Jackson and Victor (2011)	article	PG
2	Victor (2012)	article	DG
3	Bilancini and D'Alessandro (2012)	article	DG
4	García-Olivares and Ballabrera (2012)	article	DG
5	Varho and Tapio (2013)	article	DG
6	Knight et al. (2013)	article	DG
7	Bastin and Cassiers (2013)	working paper	DG
8	Briens and Maïzi (2014)	article	DG
9	Heikkinen (2015)	article	DG
10	Simoes et al. (2015)	working paper	DG
11	Briens (2015)	PhD thesis	DG
12	Naqvi (2015)	working paper	DG
13	Capellán-Pérez et al. (2015)	article	DG
14	Cattaneo et al. (2016)	study/report	PG
15	Jackson et al. (2016)	working paper	PG
16	Germain (2017)	article	DG
17	Heikkinen (2018)	article	DG
18	Larch et al. (2018)	article	DG
19	Jackson and Victor (2018)	working paper	PG
20	Bovari et al. (2018)	article	DG
21	Millot et al. (2018)	book chapter	DG
22	Court et al. (2018)	article	DG
23	Barrett (2018)	article	PG
24	Monserand (2019a)	working paper	DG
25	Monserand (2019b)	working paper	DG
26	Ansari et al. (2019)	study/report	DG
27	Walz et al. (2019)	article	PG
28	Court and McIsaac (2020)	article	DG
29	Kuhnhenn et al. (2020)	study/report	DG
30	Heikkinen (2020)	article	DG
31	Nieto et al. (2020a)	article	both
32	Malmaeus et al. (2020)	article	PG
33	Kalaniemi et al. (2020)	article	DG
34	Althouse et al. (2020)	article	DG
35	D'Alessandro et al. (2020)	article	DG
36	Nieto et al. (2020b)	article	both
37	Dai and Shan (2020)	article	DG
38	Hartley et al. (2020)	article	PG
39	de Blas et al. (2020)	article	DG
40	Jackson and Victor (2020)	article	PG
41	Keyßer and Lenzen (2021)	article	DG
42	Lallana et al. (2021)	article	DG
43	Janischewski (2021)	working paper	PG
44	Đula et al. (2021)	article	DG
45	Cieplinski et al. (2021)	article	both
46	Oswald et al. (2021)	article	DG
47	Luukkanen et al. (2021)	article	DG
48	Sers (2021)	PhD thesis	DG
49	Espinoza et al. (2022a)	article	DG
50	Dafermos and Nikolaidi (2022)	article	DG
51	Monserand (2022)	article	DG
52	Kern et al. (2022)	article	PG
53	Sers (2022)	article	DG
54	Espinoza et al. (2022b)	article	DG
55	Bordenave (2022)	working paper	DG
56	Dafermos et al. (2022)	working paper	both
57	Ivanova and Büchs (2022)	article	DG
58	Bodirsky et al. (2022)	article	DG
59	Martinet et al. (2022)	article	DG
60	Pulido-Sánchez et al. (2022)	article	DG
61	Gavriluță et al. (2022)	article	DG
62	Chapariha (2022)	article	DG
63	Malerba and Oswald (2022)	book chapter	DG
64	AlAteibi (2023)	PhD thesis	DG
65	Jacques et al. (2023)	article	PG
66	Mura et al. (2023)	article	DG
67	Martin et al. (2023)	working paper	DG
68	Aramendia et al. (2023)	article	PG

(continued on next page)

Table A.1 (*continued*)

ID	Authors (Year of publication)	Type of paper	DG/PG/both
69	Mastrucci and van Ruijven (2023)	article	PG
70	Li et al. (2023)	article	both
71	Herbert et al. (2023)	article	both
72	Moyer (2023)	article	DG
73	Oberholzer (2023)	article	PG
74	Jackson et al. (2023)	working paper	PG
75	Shaaban et al. (2023)	article	DG

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108383.

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