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Eight Archetypes of Sustainable Development Goal (SDG) Synergies and Trade-Offs

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Key Points:

- Acting on Sustainable Development Goal (SDG) synergies and trade-offs requires policy-focused systems tools
- We review a systemic approach known as archetypes for SDG synergy and trade-off analysis
- Archetypes can improve the understanding of underlying causal drivers, future behavior, and policy implications

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Achieving the Sustainable Development Goals (SDGs) is contingent on managing complex interactions that create synergies and trade-offs between different goals. It is, therefore, important to improve our understanding of them, their underlying causal drivers, future behaviors, and policy implications. Prominent methods of interaction analysis that focus on modeling or data-driven statistical correlation are often insufficient for giving an integrated view of interaction drivers and their complexity. These methods are also usually too technically complex and heavily data-driven to provide decision-makers with simple practical tools and easily actionable and understandable results. Here, we introduce a flexible and practical systemic approach, termed *archetype* analysis, that generalizes a number of recurring interaction patterns among the SDGs with unique drivers, behaviors, and policy implications. We review eight interaction archetypes as thinking aids to analyze some of the important synergies and trade-offs, supported by several empirical examples related to the SDGs (e.g., poverty, food, well-being, water, energy, housing, climate, and land use) to demonstrate how they can be operationalized in practice. The interaction archetypes are aimed to help researchers and policymakers as a diagnostic tool to identify fundamental mechanisms of barriers or policy resistance to SDG progress, a comparative tool to enhance knowledge transfer between different cases with similar drivers, and a prospective tool to design synergistic policies for sustainable development.

1. Introduction

The Sustainable Development Goals (SDGs) represent a comprehensive agenda that contains both diverging and mutually supportive economic, social, and environmental goals (UN, 2015). The SDGs are diverse and are underpinned by a network of highly interconnected socio-technical and socio-ecological systems, and their achievement depends on understanding and managing these cross-sectoral interactions (Nilsson et al., 2016). This can include both promoting *synergies* (where multiple goals strengthen one another) and limiting *trade-offs* (where multiple goals hinder one another) (Kroll et al., 2019; Pradhan et al., 2017). For example, efforts to mitigate climate change (SDG 13) through negative emissions technology (e.g., afforestation or bioenergy crop plantation with carbon capture and storage) can create synergies with other goals and also enhance the health and well-being of communities (SDG 3) through reducing the negative health impacts of extreme weather conditions (e.g., lowering heatwave frequency and improving air quality). Conversely, they can also have trade-offs, such as negatively impacting terrestrial ecosystem health (SDG 15) and reducing food availability and increasing prices (SDG 2) via competition for land and water (Fuss et al., 2018). Understanding these interactions as *causes and consequences* is important for creating coherent, effective policies that can leverage interdependencies and offer integrated and complementary solutions for sustainable development (Meijers & Stead, 2004). Here, we synthesize across the literature to suggest a systemic approach for understanding these synergies and trade-offs and their causal drivers.

In sustainability science, the study of interactions as synergies and trade-offs has a relatively long history prior to the SDGs, for example, in the context of the Millennium Development Goals (Lo Bue & Klasen, 2013; Sachs, 2012), climate change assessment (Mathy & Blanchard, 2016; Smith & Olesen, 2010; van Vuuren et al., 2012), and the early works on balancing social, economic, and environmental aspects of sustainable development (Ibisch Pierre et al., 2016; Stiglitz et al., 2009). However, interest in interactions gained significant momentum over recent years and with the initiation of the 2030 Agenda. This growing interest has made SDG interaction analysis a field of scientific inquiry in its own right, developed new tools and methods for their study, and generated model-based projections and policy insights for their management (Bandari et al., 2021; McCollum et al., 2018; Nilsson et al., 2016; Pedercini et al., 2019; van Soest et al., 2019).

Past studies have used various quantitative and qualitative methods for SDG interaction analysis, among them consensus-based expert elicitation (Nilsson et al., 2016; van Soest et al., 2019), literature-based content analysis (Bandari et al., 2021; McCollum et al., 2018), indicator-based pairwise statistical correlation (Kroll et al., 2019; Pradhan et al., 2017), statistical modeling of interactions (Anderson et al., 2021), remote sensing tracking (Singha et al., 2021), network analysis (Le Blanc, 2015), and integrated assessment modeling (Gao & Bryan, 2017; Moallemi et al., 2022; Obersteiner et al., 2016; Pedercini et al., 2019; Soergel, Kriegler, Weindl, et al., 2021). Some of these studies have focused only on sector-specific interactions (e.g., energy [Fuso Nerini et al., 2018], health [Schmidt et al., 2015], food [Herrero et al., 2021]), while some others have had a more overarching approach and included many of the SDGs simultaneously (Allen et al., 2019; Kroll et al., 2019; Pradhan et al., 2017; Soergel, Kriegler, Weindl, et al., 2021). Questions addressed so far have been mostly related to understanding interaction behaviors, for example, through mapping the degree of association between various SDGs based on (historical or extrapolated) data (Kroll et al., 2019; Pradhan et al., 2017), monitoring SDG interactions (Singha et al., 2021), or quantitatively projecting their trajectories under future scenarios (Gao & Bryan, 2017; Soergel, Kriegler, Weindl, et al., 2021).

Despite this increasing number of SDG interaction analyses in the literature, several gaps remain. First, apart from a few exceptions, most current studies are often based on quantitative analyzes of large databases and model-based projections (Pradhan et al., 2017; Soergel, Kriegler, Weindl, et al., 2021). Despite their importance, a recent study by Di Lucia et al. (2021) suggested that decision-makers in practice are less concerned about accuracy, precision, or the quantitative nature of SDG interaction knowledge, and instead prioritize simplicity, flexibility, and ease of understanding of the results. This highlights the gap for simpler, qualitative, practical tools that can support nontechnical decision-makers and resource-constrained organizations who may not have the ability to run complex models, process large databases, or need flexible tools that can be adjusted and used across different projects.

Second, while several works have focused on model-based or data-driven interaction analysis (Allen et al., 2019; Kroll et al., 2019), limited efforts (Cavicchi, 2020; Neudert et al., 2019; Zhang et al., 2016) have been made to obtain broader knowledge about archetypal patterns of interactions and their drivers. This highlights another gap for understanding system-level and generalized modes of SDG interactions that can be meaningful across contexts and their insights can be comparable and transferrable across cases and projects.

To address these gaps, we review a systemic approach known as *archetypes* (Meadows, 2008; Senge & Sterman, 1992) that can be used to qualitatively frame and analyze SDG interactions through eight generalized recurring patterns, each with specific underlying causal drivers (e.g., feedback loop and delay), expected dynamic behavior (e.g., acceleration, disruption, and tipping point), and policy implications for sustainability (e.g., how to respond and where to intervene). This can help shift the synergy and trade-off analytical focus from simple behavioral correlations or a limited understanding of interactions between certain goals to a generalized knowledge of recurring patterns, causes, and consequences across case studies. We illustrate the utility of the reviewed interaction archetypes with simple multidisciplinary examples from some of the most frequent SDG synergies and trade-offs that have been observed and reported in previous studies (Kroll et al., 2019; Pradhan et al., 2017). We also list some of the challenges and opportunities to discuss how the archetypes can be operationalized and applied to future research and practice for better understanding and progress toward the SDGs.

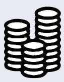
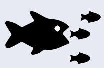
2. Methods

2.1. Using Archetypes as a Systemic Lens

Archetypes have proved useful in broader sustainability research (e.g., for classifying climate vulnerabilities [Vidal Merino et al., 2019], land use decision-making [Malek et al., 2019], governance barriers [Oberlack & Eisenack, 2018], and sectoral interactions [Banson et al., 2016; Pejic Bach et al., 2014]), but their application to the SDGs has not been thoroughly investigated. We adopted *systems archetypes* (Meadows, 2008; Meadows et al., 1972; Senge, 1990) as a lens to frame and conceptualize SDG interactions. These archetypes are often used for identifying generic recurring patterns of behavior and explaining causal drivers common to multiple socio-ecological and socio-technical systems.

10.1029/2022EF002873

Table 1
Summary of Interaction Archetypes in the Sustainable Development Goal (SDG) Context

Causal Driver	Interaction archetype	Description	Dynamic behaviour	Example
Unanticipated side-effect	Fixes That Fail 	SDG interventions end up with opposite effects due to delayed trade-offs with other goals	Slowing progress despite increasing efforts	(Cavicchi, 2020)
	Band-Aid Solutions 	Band-aid solutions with short-term moderate impacts diminish the need for transformative SDG interventions	Slowing progress due to declining presence of long-term interventions	(Neudert et al., 2019)
Time-delayed response	Eroding Ambitions 	Long-term interventions with time-delayed response create uncertainty about SDG achievement and justify lower ambition	Increasing progress, but towards low-ambition goals that can be easily achieved	(Brzezina et al., 2017)
	Downplayed Problems 	The ignorance of trade-offs which are seemingly insignificant due to their time-delayed response but will eventually overshadow all synergistic interactions and can halt or reverse progress	Initial progress due to synergistic interactions, followed by rapid decline from the prevailing effects of downplayed trade-offs	(Zhang et al., 2016)
Path dependency	Escalating Tensions 	Increasing temporary interventions with path dependency result in unsatisfactory progress in conflicting goals	An overall decline in progress in all goals, despite increasing efforts	(Banson et al., 2018)
	Success to the Successful 	Resources are diverted towards goals with historically better performance and away from other more challenging and interacting goals which reduces progress	Increasing trade-offs between conflicting goals with accumulating progress towards one goal at the cost of declining progress towards others	(Bahri, 2020)
Limiting condition effect	Limits to Progress 	Interventions reliant on exhaustible resources can produce diminishing returns over time as resources reach their limit	Progress stabilises or declines despite increasing efforts	(Brzezina al., 2017)
	Tragedy of the Commons 	Pursuing goals in isolation by actors interested in only a specific sector can exhaust common resources and lead to an overall unsustainable outcome for all	Increasing progress in one goal, at the cost of declining progress in other goals and an overall unbalanced achievement	(Sharif & Irani, 2016)

Note. Icons adapted from the Noun Project under a Creative Commons License CC BY 3.0: target by Adrien Coquet, Band-Aid by Alice Design, arrow by Saeful Muslim, iceberg by Colourcreatyp, fists by Vectors Point, coins by Tanmay Goswami, barrier by Optimus Prime, and fishes by Badsha Mia.

We reviewed the application of eight archetypes, which have been mentioned and frequently used in systems science (Hallett & Hobbs, 2020; Kim, 1992; Senge, 1990), for SDG interaction analysis. They include *Fixes that Fail*, *Band-Aid Solutions* (aka Shifting the Burden, or Addiction), *Eroding Ambitions* (aka Eroding or Drifting Goals), *Downplayed Problems* (aka Growth and Underinvestment), *Escalating Tensions* (aka Escalation), *Success to the Successful*, *Limits to Progress* (aka Limits to Success or Growth), and *Tragedy of the Commons* (Table 1). In conceptualizing SDG interactions with systems archetypes, we sometimes modified their original names from systems science to better represent them and suit their new purpose in the SDG context. This is not unconventional given that different sources (Hallett & Hobbs, 2020; Kim, 1992) have used different names for these archetypes depending on their application context.

The selected archetypes are theoretically rooted in systems thinking and modeling. Originally introduced by Senge (1990) in the seminal work, *The Fifth Discipline,* the archetypes have been further popularized through a range of studies (Hallett & Hobbs, 2020; Kim, 1992; Meadows, 2008; Senge & Sterman, 1992). These eight archetypes are universal and comprehensive. The universality and comprehensiveness of these archetypes to represent the diversity of alternative interactions in complex general systems have been tested in several empirical contexts (e.g., biodiversity [Hallett & Hobbs, 2020], water [Zare et al., 2017], and agriculture [Neudert et al., 2019]). They can also be combined to create a much wider diversity of (compound) interactions, representing more complex interactions (Moallemi et al., 2021).

Archetypes are usually depicted using *causal loop diagrams* (Lane, 2008). Causal loop diagrams represent feedback relationships among various system elements (SDGs in the context of this paper) which drive systems behavior over time. Different SDG elements are connected via *causal links*, shown by arrows, which represent (hypothesized) causal relationships rather than statistical correlations. The causal links are assigned *positive or negative polarity* to indicate synergies or trade-offs between two system elements, respectively. Polarity indicates the nature of their relationship (i.e., what would happen to one if there were a change in the other) rather than describing their existing behavior. A positive relationship implies that a change in the cause variable changes the effect variable in the same direction. A negative relationship implies that a change in the cause variable results in a change in the effect variable in the opposite direction. A closed chain of causal relationships creates a *feedback loop*. Feedback loops which influence dynamic behavior are marked with positive or negative identifiers, indicating either a reinforcing (e.g., a positive change in one system element leads to a positive change in another, potentially with exponential behavior) or balancing (e.g., a negative change in one system element leads to a negative change in another) relationship over time, respectively. Unlike the archetypes, the causal loop diagrams have been used for mapping SDG interactions (Cernev & Fenner, 2020; Macmillan et al., 2020; Szetey et al., 2022).

2.2. Analyzing SDG Interactions With Archetypes

In reviewing the eight archetypes, we discussed how they can help SDG interaction analysis in terms of three aspects:

- *Causal Drivers*: We used archetypes to show how SDG synergies and trade-offs, with seemingly simple interactions between systems, can be driven by complex causal drivers, that is, the chain of causes and consequences with feedback loops, side effects, time-delayed responses, and path dependency. We used causal loop diagrams to explain the complexity of the causal drivers underlying SDG interactions in each archetype.
- *Dynamic Behavior*: Each archetype can lead to insights about what the resulting behavior of SDG interactions would be and how it may change over time. We explained the potential dynamic and time-dependent behavior resulting from SDG interactions associated with each archetype.
- *Policy Implications*: Each archetype, with its specific causal drivers and dynamic behavior, can have different policy and planning implications (e.g., when to combine short-and long-term policies and how to proactively respond to side effects). We discussed some of these policy implications.

2.3. Demonstrating Interaction Archetypes With Examples

The archetypes have been used as a systemic lens directly or indirectly related to one or several SDGs (Cavicchi, 2020; Neudert et al., 2019; Zhang et al., 2016). We used multiple illustrative examples of synergies and trade-offs with related case studies to explain what each archetype means in practice.

First, we used results from Kroll et al. (2019), who statistically analyzed the SDG Index and Dashboards database and identified significant synergies and trade-offs observed between 2010 and 2018, to identify a key SDG synergy/trade-off to illustrate for each archetype. For instance, Kroll et al. (2019) identified a trade-off between SDGs 2 Food Security and 13 Climate Action as a significant interaction. We therefore used this trade-off as one SDG interaction example to help explain our archetypes (i.e., Fixes That Fail).

Second, we put the selected illustrative examples into a specific context using case studies addressing multiple SDGs (e.g., poverty, food, well-being, water, energy, housing, climate, and land use) across different countries. Case study selection was based on a mix of suggestions by coauthors based on their knowledge of the field and cases identified through a systemic review of the literature (Table 2). The use of a hybrid approach was necessary due to the inherent limitations of each individual approach in either being restrictive in selecting relevant studies and missing interesting cases due to the inflexibility of search string and search database, or being biased to specific author backgrounds and not being fully representative of application diversity (Grant & Booth, 2009). The details of the systemic review process and the reviewed cases are available in Supplementary Materials.

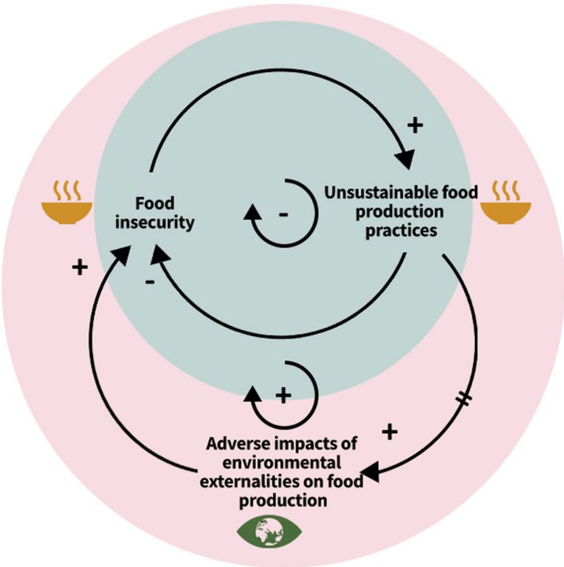
3. Interaction Archetypes

We review eight SDG interaction archetypes supported with empirical examples. We describe their drivers, expected dynamic behavior, and their sustainability policy and planning implications. Table 1 shows a summary of the archetypes grouped based on similarity of causal drivers (first column). Table 2 shows some archetype applications for analyzing SDG interactions identified via systematic review.

Table 2
Systemic Review of Archetype Application for Analyzing Sustainable Development Goal (SDG) Interactions

Interaction(s)	Related archetype(s)	Aim	Analysis	Place/scale/sector	Citation
SDGs 2–16* synergy, SDGs 2–15* synergy	Tragedy of the Commons, Band-Aid Solutions, and Success to the Successful	To characterize recurring problems of village pasture management	Quantitative and qualitative	Azerbaijan and Georgia (Caucasus); regional and local; agriculture sector	Neudert et al., 2019
SDGs 6-7-2-15*, Both synergy and trade-off	Limits to Progress and Success to the Successful	To understand and analyze the dynamic interactions between living and nonliving elements in a reservoir system	Qualitative	West Java (Indonesia); regional (catchment scale); water-energy-food-land nexus	Bahri, 2020
SDG 16* (also implicitly SDGs 2-7-13-15)	Fixes That Fail, Limits to Progress, and other archetypes	To explain causal links between governance structures that influence the policy process pathway over time in the bioenergy sector	Qualitative	Emilia Romagna (Italy) and Hedmark (Norway); regional and sectoral; bioenergy sector	Cavicchi, 2020
SDGs 1–2* synergy	Band-Aid Solutions, Escalating Tensions, Fixes That Fail, Limits to Progress, Success to the Successful, and Tragedy of the Commons	To understand the economic behavior and root causes of problems in the piggery industry.	Qualitative	Ghana; national; agriculture sector	Banson et al., 2018
SDGs 2–8* trade-off	Limits to Progress, Band-Aid Solutions, and Eroding Ambitions	To analyze and anticipate challenges in the development of organic farming in the EU	Qualitative	European Union; regional; organic farming	Brzezina et al., 2017
SDGs 2–15* trade-off	Fixes That Fail, Success to the Successful, and Eroding Ambitions	To understand impacts on soil resources and rural communities from land use change, particularly unintended consequences	Quantitative	North-central USA; regional; land sector	Turner et al., 2017
SDGs 6-2-15* trade-off	Band-Aid Solutions and Tragedy of the Commons	To help setting boundaries for case study analysis	Qualitative	Lake Urmia basin (Iran), Zayendah-Rood basin (Iran); regional, water sector	Nabavi et al., 2016
SDGs 2–6* synergy	New patterns from combining Limits to Progress, and Tragedy of the Commons	To analyze behavior of people, process and policy of food waste and food security	Qualitative	Conceptual analysis in food sector	Sharif and Irani, 2016
SDG 6 synergy and trade-off with all SDGs	Limits to Progress and Downplayed Problems	To map the interlinkages between the SDGs and identify the leverage points	Qualitative	Conceptual analysis in all SDGs	Zhang et al., 2016
SDGs 2–15* trade-off	Band-Aid Solutions, Limits to Progress, Success to the Successful, Tragedy of the Commons, and other archetypes	To gain insight into patterns of behavior in the agriculture sector in response to current policies	Qualitative	Ghana; national; agriculture sector	Banson et al., 2016

Note. Rows in the first column with asterisk indicate studies that did not explicitly refer to the term "SDG", but their contents were still related to one or more goals. See Supporting Information S1 for details of the systemic review process.



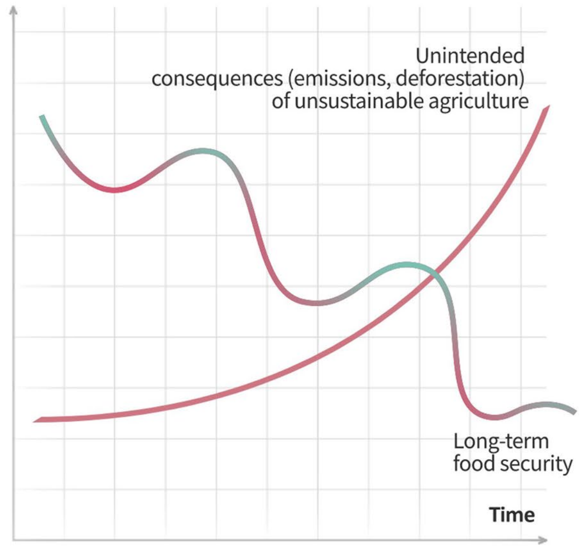


Figure 1. (a) The causal drivers and (b) a potential dynamic behavior in Fixes That Fail. The major feedback interactions in (a) and their corresponding impacts in (b) are color coded. Both (a) and (b) are conceptual figures.

3.1. Fixes That Fail

Fixes That Fail represents SDG interactions that are driven by the interplay and conflict between (short-term) planned and (long-term) unexpected outcomes of interventions, resulting in unanticipated side effects in progress toward sustainability. It implies that interventions which can positively impact a goal in the short-term can sometimes result in unintended consequences and trade-offs with other goals, stopping or even reversing the progress made.

The causal drivers behind this type of interaction involve balancing and reinforcing feedback loops (Figure 1a), which can be explained in the context of food and agriculture and through trade-offs between SDGs 2 Food Security and 13 Climate Action (Table S1 in Supporting Information S1). Within the food and agriculture system, SDG 2 focuses on both achieving zero hunger and promoting sustainable agriculture. While both seem to be supportive of each other, they can also have trade-offs. A quick and seemingly effective fix to address food insecurity can be through boosting food production via unsustainable practices, such as agricultural land expansion or excessive fertilizer use. The expansion of agricultural lands and an increase in food production might seem the quickest solution for addressing food insecurity, but it can also cause side effects, such as deforestation from agricultural expansion and increasing greenhouse gas emissions from agricultural production, both with reinforcing impacts on climate change (SDG 13). These side effects can subsequently reduce agricultural yield and damage food security in the long-term.

A practical example comes from Nigeria, where, during the last few decades of the twentieth century, increasing population and, in turn, the prevalence of unsustainable farming practices such as shorter natural fallow periods to meet food demand, contributed to the proportion of degraded soil increasing to 69% (Onyeiwu et al., 2011). This caused deforestation, eventually leading to further reduced soil fertility, and in turn exacerbating food insecurity (Onyeiwu et al., 2011). A more recent study (Carter et al., 2017) also highlighted how 78% of deforestation in Latin America is driven by agricultural needs, leading to high emissions from agriculture-driven deforestation. This in turn can lead to an exacerbation of climate change and its effects, which already includes higher risks of drought (Reyer et al., 2017) and, in turn, lower agricultural productivity. Other applications of Fixes That Fail (Table 2) also include case studies in relation to different sustainability areas (e.g., bioenergy, food

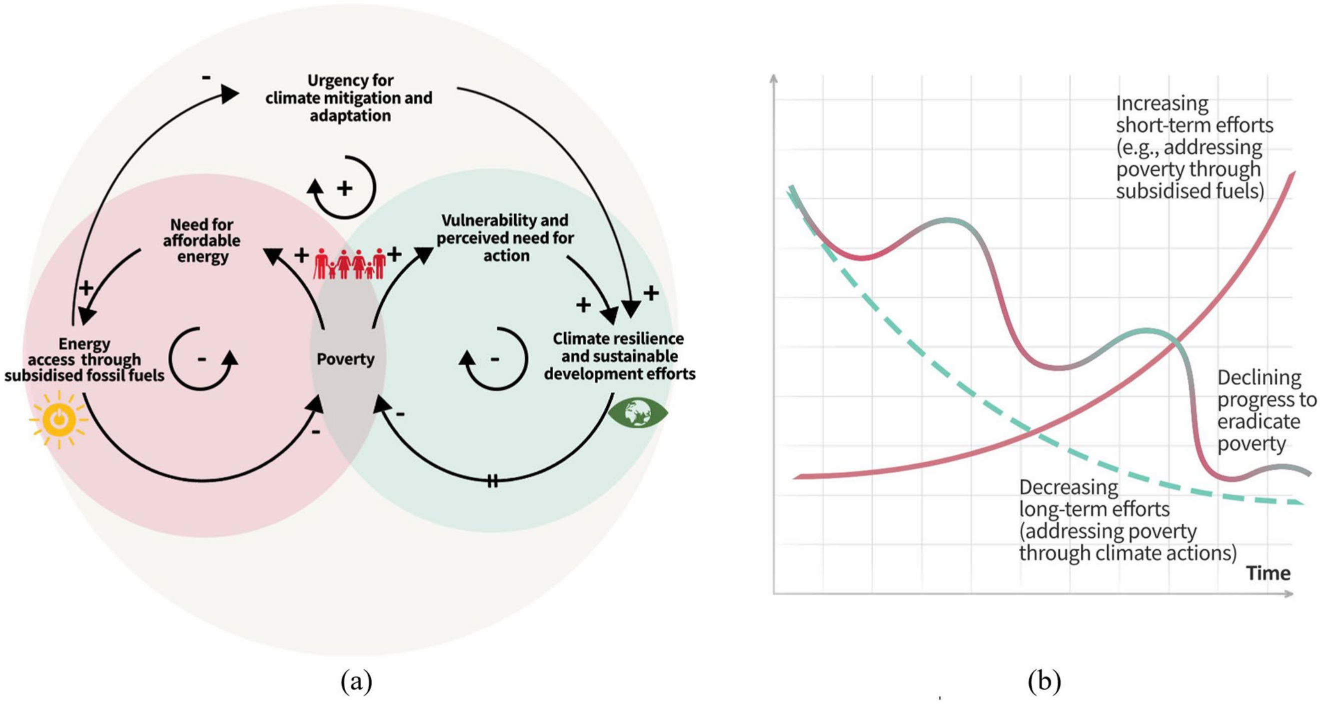


Figure 2. (a) The causal drivers and (b) a potential dynamic behavior in Band-Aid Solutions. The major feedback interactions in (a) and their corresponding impacts in (b) are color coded. Both (a and b) are conceptual figures.

and agriculture, and land sectors), for example, to understand the side effects in the bioenergy governance and policy-making process in regional Italy (Cavicchi, 2020) and the unintended consequences of land use change on local communities in the north central region in USA (Turner et al., 2017).

A potential dynamic behavior is short episodes of progress improvement due to short-term actions but with a steadily worsening long-term trend due to delayed unintended consequences of those temporary actions (Figure 1b). As a result, the original sustainability problems can persist and progress can be slowed (or reversed) despite increasing efforts.

A policy implication of this interaction archetype is the importance of understanding and preparing for policy side effects of short-term fixes. In practice, this means whenever temporary, short-term fixes are necessary to address immediate problems, corrective actions should also be taken to mitigate unexpected negative consequences. At the same time, preparing and planning for long-term, high-leverage interventions can also become important to address the main cause of the problems and ensure long-term progress.

3.2. Band-Aid Solutions

Band-Aid Solutions (aka Shifting the Burden) represent SDG interactions driven by short-term, relatively easy interventions and their undesired effects (unanticipated side effects) in eroding the need for long-term, transformative interventions. It explains how temporary solutions which can only deliver moderate progress can misleadingly diminish the need for and undermine the urgency of fundamental interventions which target the root cause and promote transformation. Band-Aid Solutions are similar to Fixes That Fail in a sense that they both highlight the peril of actions with side effects. However, while Fixes That Fail highlight a more direct definition of side effects in terms of unintended consequences of short-term actions, Band-Aid Solutions show a more complex side effect where the negative effect on progress comes through diminishing the need for bolder interventions.

The typical causal drivers behind this type of interaction involve the interplay between at least two balancing and one reinforcing feedback loops (Figure 2a). We explain them here in the context of interactions between SDGs 1 No Poverty and 7 Energy Security and SDGs 1 and 13 Climate Action (Table S1 in Supporting Information S1). One commonly used solution to improve the living conditions of people in developing countries is to subsidize (or not limit the excessive use of) exhaustible natural energy resources (e.g., petrol/LPG for mobility and traditional gas stoves) (SDG 7). In the short-term, this solution clearly addresses poverty by reducing (or at least not increasing) the cost of living (SDG 1). However, in the long-term, it leads to greater consumption, which subsequently makes energy supply and available infrastructure inadequate to meet the growing demand, thereby perpetuating poverty through limited access to basic needs. More importantly, achieving short-term success with temporary solutions such as subsidized fossil energy may reduce the urgency and perceived need for taking transformational actions to address climate change (e.g., improving climate resilient agriculture, better response to droughts or flooding, using solar energy for cooking, and using natural light reflectors for buildings) as a fundamental reason that can underpin poverty in the long-term. Climate change is inextricably linked to poverty and can disproportionately affect poor people in low-income communities (Soergel, Kriegler, Bodirsky, et al., 2021). A reduced urgency for climate actions can exacerbate poverty in the future (Soergel, Kriegler, Bodirsky, et al., 2021). Other applications of Band-Aid Solutions (Table 2) include, for example, the identification of similar problems in pasture management in the Caucasus (Azerbaijan and Georgia) in relation to the interactions between agriculture (SDG 2), life on land (SDG 15) and governance (SDG 16) (Neudert et al., 2019).

One potential dynamic behavior of such interactions is a temporary period of incremental progress due to increasing short-term efforts (Figure 2b). However, the overall long-term progress has a declining trend, and transformational change is unlikely to be achieved due to a lack of fundamental change. In our poverty example, it means that persisting with subsidies and utilizing more fossil fuels would lead to a short-term decline in the cost of living, but it would be likely to add to poverty due to further impacts of climate change (e.g., wildfires, and flooding), further exacerbated by delays in taking necessary action. Referring again to Nigeria (Onyeiwu et al., 2011), population growth over the second half of the twentieth century led to a large increase in demand for charcoal, which in turn increased deforestation. In combination with other factors, this led to several years of large GDP growth (especially in the '70s), while deforestation exacerbated climate change effects, causing deeper and more frequent droughts and in turn negatively affecting Nigeria's economy (Shiru et al., 2020). Other examples are provided by countries whose economies and energy sectors heavily rely on coal mining, such as Poland (Gençsü et al., 2017), which had longstanding subsidies that declined only slowly over time, in order to limit the short-term economic impact of a large-scale, abrupt transition to cleaner energy sources.

One of the policy implications of this interaction archetype is to better understand and differentiate between the effects of SDG actions, that is, temporary Band-Aid versus fundamental long-term interventions. Similar to the implications from the previous archetype, it is important that policymakers remain aware of temporary intervention side effects and plan in advance for fundamental actions to lay the ground for long-term transformational change and avoid future delays. In our poverty-energy example, several studies, both global and country-specific, have demonstrated that the medium-to long-term benefits of policies aimed at disincentivizing fossil fuel production outweigh the minor short-term costs. For instance, in Turkey (Acar & Yeldan, 2016), the potential removal of subsidies could reduce emissions by 5% with only minor effects on the economy; while in Australia (Nong & Siriwardana, 2018), with related policies such as the Emission Reduction Fund, small (<0.6%) GDP reductions could be expected, leading however to significant emission abatements and contributing to longer-term climate change mitigation (Bourne et al., 2018).

3.3. Eroding Ambitions

Eroding Ambitions (aka Drifting Goals) represent SDG interactions resulting from the time-delayed response of interventions and losing hope in making progress. Delays in achieving expected progress and uncertainty about the effectiveness of long-term actions can undermine the need for their presence and for having ambitious sustainability goals. This can lead to lower-ambition goals that are more achievable in the short-term but are not necessarily adequate for sustainability in the long-term.

The causal drivers that underpin this interaction involve at least two balancing feedback loops (Figure 3a). They can be explained with an example in the context of interactions between SDGs 13 Climate Action and 7 Energy Security and SDGs 13 and 9 Industry, Innovation, and Infrastructure (Table S1 in Supporting Information S1). Commitments to achieving zero carbon emissions (SDG 13) are largely reliant on the transformation of the energy sector toward cleaner (renewable) energy production (SDG 7). However, increasing the share of renewable energy for emissions reduction is not always the first priority in developing countries which often have a strong economy-focused development agenda. Shifting to renewable energy for these countries can result in the replacement of depreciated capacities and improvement of low-efficiency energy infrastructure rather than investing in the expansion of their total energy production capacities (which is more important for economic development). In the short-term, this can

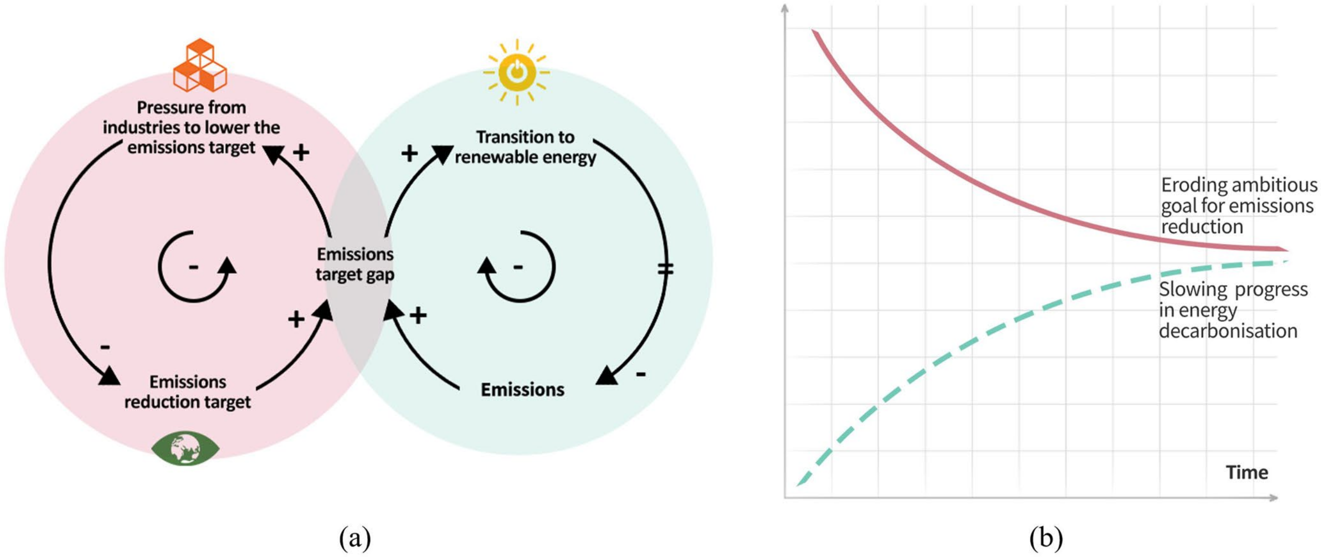


Figure 3. (a) The causal drivers and (b) a potential dynamic behavior in Eroding Ambitions. The major feedback interactions in (a) and their corresponding impacts in (b) are color coded. Both (a and b) are conceptual figures.

make energy supply fall short of growing demand and limit the expansion of industry (SDG 9). Given the limited infrastructure and potential trade-offs with economic growth, a major policy concern can arise around the effects of ambitious climate goals and the ability to achieve net zero emissions in a timely manner. The resulting disruptive impacts on other sectors can challenge the legitimacy of ambitious goals and stall the transition to renewable energy. Such a lack of legitimacy can put pressure to lessen the ambition of emissions reduction targets. Australia is an example of a country with low-ambition emissions reduction targets which have arisen from short-term political goals, the heavy reliance of the country's economy on coal mining, and difficulties with accelerating the transition to renewables (Li et al., 2020). This is in stark contrast with countries such as Germany and the United States where domestic coal mining has already ended or has drastically diminished. Other applications of Eroding Ambitions (Table 2) exist in other sectors (e.g., agriculture [Brzezina et al., 2017], land use change [Turner et al., 2017]). For example, in the development of organic farming in the European Union, which has shown that continuous improvement of ambitious regulatory standards is necessary to ensure long-term performance (Brzezina et al., 2017).

A potential dynamic behavior is gradual progress (i.e., for emissions reduction) toward a low-ambition, inadequate sustainability goal (Figure 3b). In our previous example, this behavior results from increasing tension and trade-offs between pursuing the long-term climate goal with transition to renewables (SDGs 7 and 13), and the short-term goal of supporting industrial sectors and avoiding disruption at the expense of accelerated climate change (SDGs 9 and 13).

One of the important policy implications of this interaction is the importance of perseverance and patience in making tangible progress and achieving ambitious goals. SDG interactions are nonlinear. This means that initial efforts toward long-term goals may start slowly, but they can accelerate and pay off later if they continue. Therefore, the careful management of short-term expectations and a better understanding of nonlinearity between actions and their impacts among stakeholders is necessary to avoid backlash and disappointment. Educational and informational tools (e.g., social media campaigns and fund raising), which can increase public awareness about past achievements and highlight tangible future benefits (e.g., job creation, poverty alleviation, and less pollution), can be helpful for maintaining the legitimacy of ambitious goals and actions. The use of mixed interventions (e.g., philanthropic/NGO and government funding) which support the provision of resources for both immediate (e.g., socio-economic development) projects and those with longer-term sustainability benefits can be another way to increase legitimacy and reduce the pressure to lower ambition.

3.4. Downplayed Problems

Downplayed Problems (aka Growth and Underinvestment) represent a more complex version of Eroding Ambitions with a time-delayed response effect. Interventions, which stimulate and reinforce progress toward one goal,

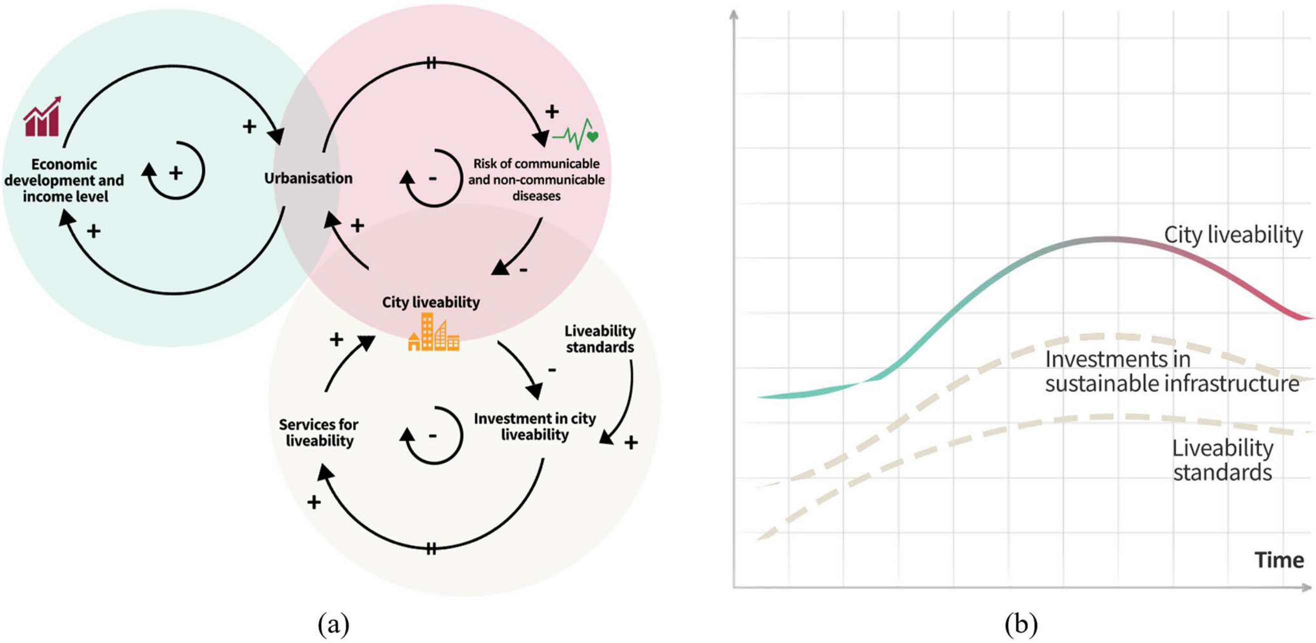


Figure 4. (a) The causal drivers and (b) a potential dynamic behavior in Downplayed Problems. The major feedback interactions in (a) and their corresponding impacts in (b) are color coded. Both (a and b) are conceptual figures.

may not remain effective in the long-term as progress approaches a limit resulting from a (delayed) trade-off with other conflicting goals. Efforts to eliminate or alleviate the trade-off and push the progress limit can take years to materialize. This can justify downplaying the importance of addressing trade-offs with conflicting goals, which will eventually lead to worse effects in the long-term.

The causal drivers behind this type of interaction involve the interlinkage of at least two balancing and one reinforcing feedback loops (Figure 4a). We explain them in the context of synergies between SDGs 11 Sustainable Cities and Communities and 8 Economic Growth and trade-offs between SDGs 11 and 3 Health and Well-Being. With economic growth and improving incomes (SDG 8), people are often attracted to cities where jobs and opportunities exist and where living standards are higher. This leads to demand for expanding cities and infrastructure (SDG 11), in turn providing an even greater capacity to attract more people and promoting further economic growth and development. However, an increasing population can stretch cities beyond their sustainability limits, with trade-offs in health and well-being from communicable and noncommunicable diseases, hazardous chemicals, and pollution (SDG 3). This has been experienced in cities around the world, such as in Bangladesh (Ahmed & Islam, 2014) and in multiple African cities (Boadi et al., 2005), making growing urban areas less livable in the future. Interventions to address this trade-off can include making cities more sustainable by investing and enhancing their livability (e.g., investing in mental health and well-being, public green space, waste management, and air pollution reduction). However, the impacts of these interventions are often observed with lags and delays and require time to materialize, which can reduce confidence in their ability to deliver outcomes. Alternatively, a (misleadingly appealing) approach can be to downplay the trade-off problem by redefining city livability standards to suit the current unsustainable conditions and further stretching the cities beyond their sustainable limits in order to boost socio-economic development. The actual effect of this downplayed trade-off will eventually dominate any positive synergies in the system and could lead to a slowing of economic growth in the long-term. There are other applications of this type of interaction in the literature (Table 2), for example, in the context of water synergies and trade-offs (SDG 6) with other sectors, their downplayed problems, and the leverage points for interventions (Zhang et al., 2016).

A potential dynamic behavior in the short-term is initial rapid progress due to the synergistic reinforcing feedback loop (e.g., between SDGs 8 and 11). However, this will be followed by a longer-term decline in progress due to a delayed trade-off with other goals (e.g., SDG 3) and eroding ambition in other conflicting goals (Figure 4b).

One of the policy implications of this type of interaction is the importance of anticipating and planning for the delayed appearance of limiting progress and the trade-offs that lead to it (e.g., city livability) in advance.

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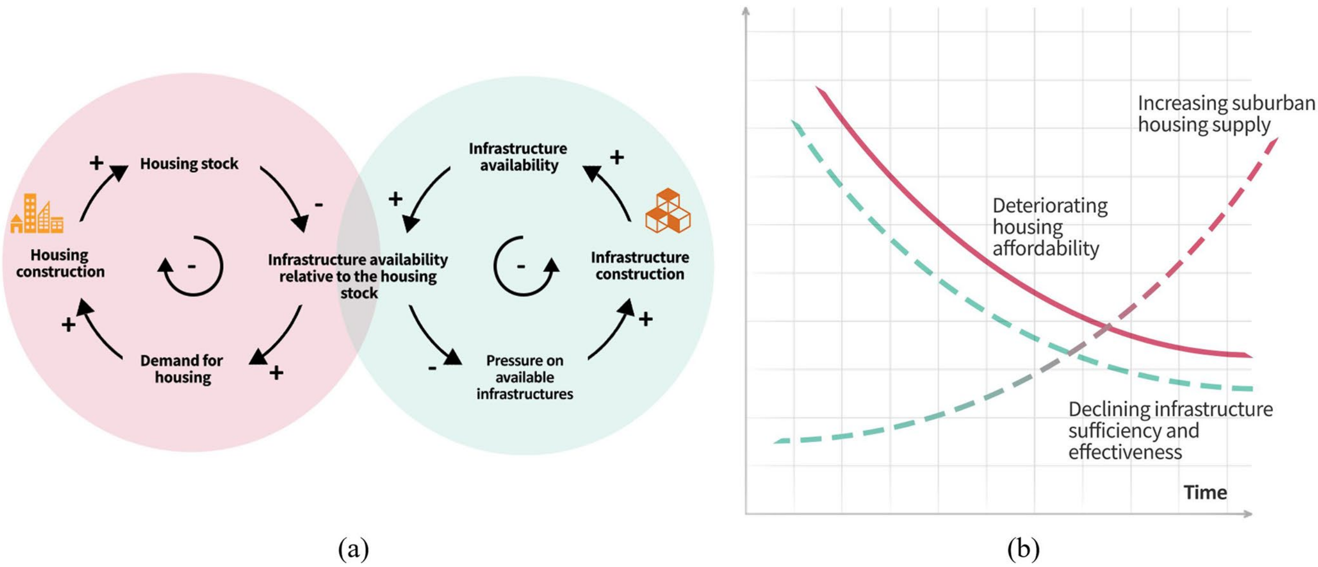

Figure 5. (a) The causal drivers and (b) a potential dynamic behavior in Escalating Tensions. The major feedback interactions in (a) and their corresponding impacts in (b) are color coded. Both (a and b) are conceptual figures.

Anticipating and planning for the delayed trade-offs require a monitoring of the external environment to detect signals that can indicate a slowing in progress toward sustainability goals, thereby enabling policymakers to respond in advance with corrective actions. Another implication stresses the importance of improving public awareness, for example, about the dependency of socio-economic development on environmental sustainability and the necessity of maintaining and investing in high standards for 'sustainable' development.

3.5. Escalating Tensions

Escalating Tensions (aka Escalation) represent SDG interactions driven by path dependency to short-term, temporary interventions with unsustainable outcomes. It implies that short-term interventions which can deliver slow progress can result in unintended consequences which require further temporary fixes to maintain even this slow progress. The increasing number of path dependent temporary interventions can drain resources for taking fundamental actions and can result in progress stagnation (or even deterioration) in the long-term.

The causal drivers underlying this type of interaction involve at least two interlinked balancing feedback loops (Figure 5a). We explain them in the context of interactions between SDGs 11 Sustainable Cities and Communities and 9 Industry, Innovation, and Infrastructure. Expanding cities through constructing houses in sprawling suburbia is often a solution to address increasing demand and ensure housing affordability (SDG 11). Increased suburban housing supply, however, increases pressure on current infrastructure (e.g., road, water, energy, and healthcare) (SDG 9). This mounting pressure, along with the advocacy power of local communities in suburban areas, can be used to justify new infrastructure projects to meet the increasing demand. This is true for cities like Melbourne and Australia, where adding transportation costs to low-affordability housing makes many suburbs extremely expensive to live in (Saberi et al., 2017). New infrastructure projects increase the attractiveness of investing in housing, thereby exacerbating demand. In the long-term, this can further reduce housing affordability and promote the expansion of cities (and subsequently the need for more infrastructure). There are also other applications of Escalating Tensions in the literature (Table 2), for example, in the context of pig farming in Ghana for analyzing how tension and business rivalry behavior for access to resources within the piggery industry can lead to an overall productivity decline (Banson et al., 2018).

A potential dynamic behavior is an initial synergistic effect between the interacting goals (e.g., improving infrastructure in suburbia helps housing affordability). However, this synergy diminishes, leading to declining progress toward both goals over time (e.g., housing affordability deteriorates and infrastructure remains insufficient and ineffective). This diminishing synergistic interaction can appear as generally declining behavior where initial progress, occurring when interventions are imposed, is followed by deterioration due to the effects of other temporary interventions (Figure 5b).

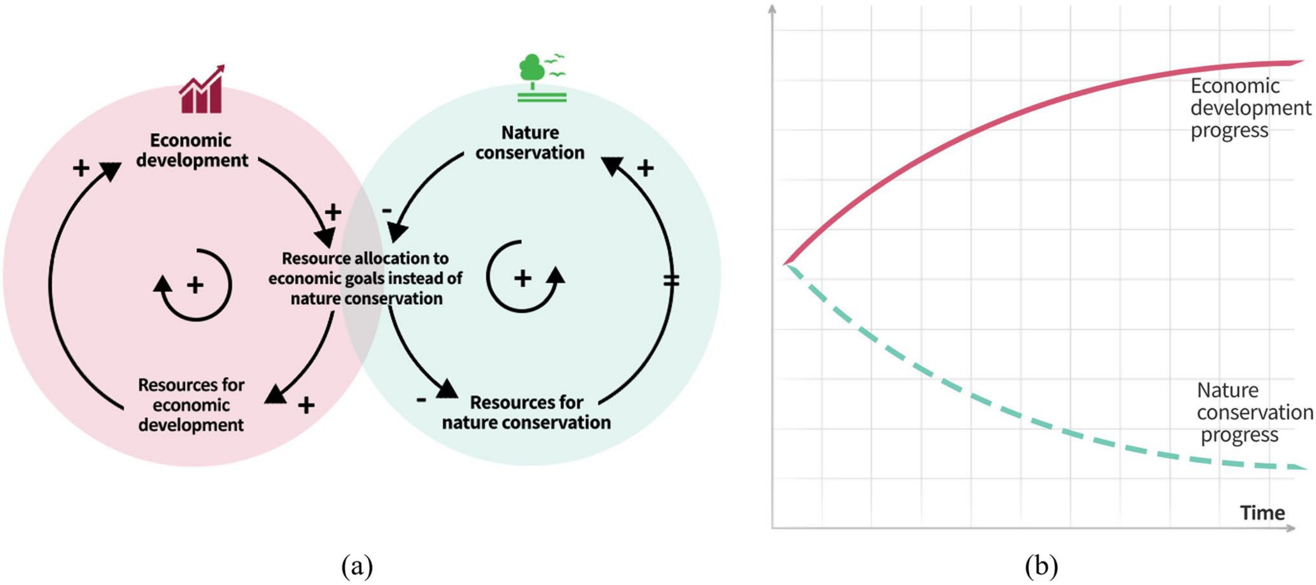

Figure 6. (a) The causal drivers and (b) a potential dynamic behavior in Success to the Successful. The major feedback interactions in (a) and their corresponding impacts in (b) are color coded. Both (a and b) are conceptual figures.

An implication for sustainability planning is that a synergistic interaction, if managed inappropriately and through path dependent and temporary interventions, can result in negative outcomes for the SDGs in the long-term and derail sustainable development. Hence, it is important to consider path dependency in the long-term to maintain and benefit from synergistic SDG interactions.

3.6. Success to the Successful

Success to the Successful represents SDG interactions resulting from a similar path dependency effect. Efforts to make progress exhibit path-dependency with goals which have historically better performance, less uncertain outcomes, higher public legitimacy, and/or less delayed response. Goals with path dependency can attract more resources (e.g., financial, policy support, and human capital) with the expectation that their success will continue in the future. However, they take away resources from other goals and this can limit their progress.

The causal drivers underpinning this type of interaction involve at least two reinforcing feedback loops (Figure 6a). We explain these in the context of competition for resources between economic development and environmental conservation (SDGs 8 and 15). Job creation, economic productivity, and economic growth (SDG 8) are some of the key priorities in development programs. An economy-focused agenda is often able to deliver outcomes quickly, such as reduced poverty, more jobs, and better infrastructure, and typically has more (short-term) successes. Nature conservation and ecosystem protection (SDG 15) is a key priority which can help improve environmental health as well as maintain and even accelerate economic growth (e.g., via halting biodiversity loss and increasing revenue from tourism). However, efforts to integrate ecosystem and environmental protection values into development programs are less common and lower priority due to delays between actions and their tangible impacts (e.g., it may take decades to reverse biodiversity loss and it may be difficult to verify). Hence, there are fewer success stories to convince the public and policymakers. They are also less desirable to policymakers who often favor less change with actions which are part of an incumbent regime and who want to achieve outcomes within their short accountability period. This can redirect the share of resources and give more attention to economy-focused agendas with proven historical performance and shorter-term outcomes. There are other applications of Success to the Successful in a sustainability context (Table 2), for example, in relation to the water-food-energy nexus in West Java in Indonesia for analyzing how resources (i.e., reservoir water) should be divided properly between different sectors to avoid the Success to Successful issue and achieve sustainable development (Bahri, 2020), along with other applications in agriculture (Banson et al., 2016) and land management (Turner et al., 2017).

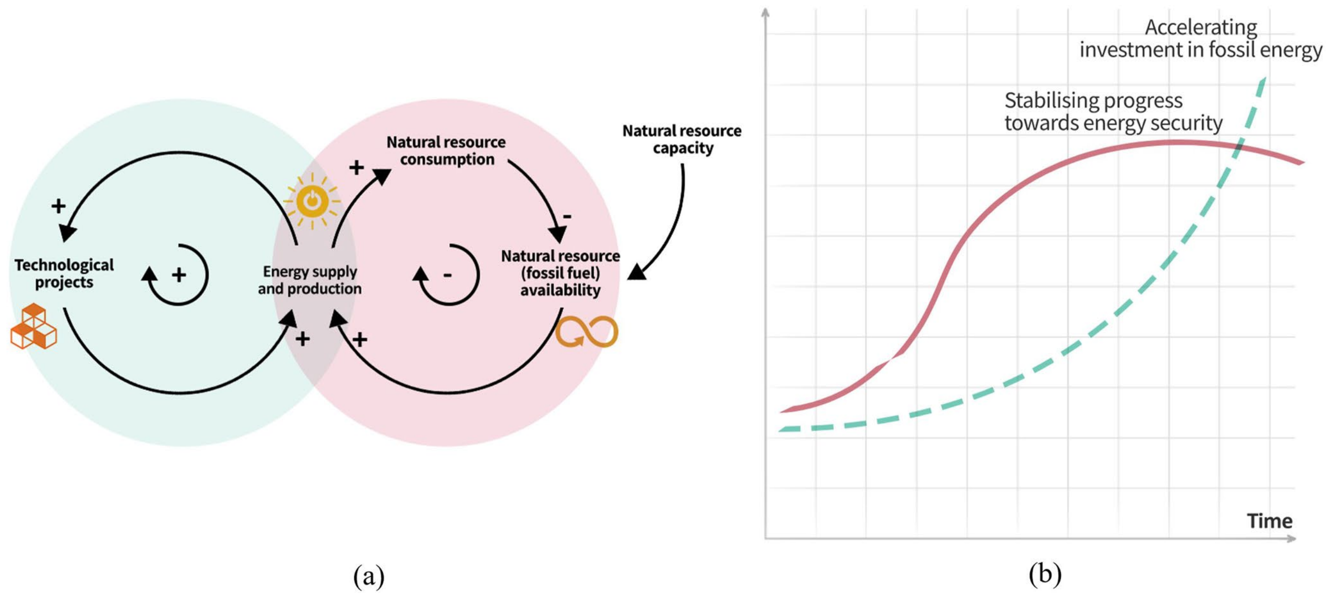

Figure 7. (a) The causal drivers and (b) a potential dynamic behavior in Limits to Progress. The major feedback interactions in (a) and their corresponding impacts in (b) are color coded. Both (a and b) are conceptual figures.

One potential dynamic behavior of this interaction is an increasing trade-off that a path-dependent goal makes with other SDGs (Figure 6b). For any goal, the allocation of sufficient resources is necessary to make progress. Therefore, the allocation of further resources to path-dependent goals brings more success and creates more justification (e.g., growth of interest groups and lobby actions) for yet further allocation of resources in the future. Conversely, progress toward other goals from which resources are diverted from continues to deteriorate and the gap between the goals widens over time.

A lesson learned from this type of interaction for sustainability planning is to maintain focus on the original SDG principle of striving for *balanced* progress across all goals. This needs a better understanding of the origins and sources of competition between interacting goals with shared resources and being aware of those goals that could cause path dependency and deplete resources. As an example, studies have been conducted in the Democratic Republic of Congo to compare economic benefits from improved road connectivity and resulting loss in ecological value due to related deforestation (Damania et al., 2018). Second, it also needs measures that can support goals with less historically proven performance against path-dependent goals. Examples include public awareness campaigns to adjust expectations about uncertainty and delay in progress toward other goals, new finance mechanisms where funds could be made available for experimenting with new goals, and advocacy coalition activities that can work as a catalyst and raise less progressed aspects of sustainable development as new priorities.

3.7. Limits to Progress

Limits to Progress (aka Limits to Growth) represent SDG interactions driven by a limiting condition effect where unsustainable interventions with huge short-term benefits can deplete exhaustible (e.g., natural, financial, and human capital) resources and become counter-effective in the long-term. It captures how efforts to make an initial, accelerating progress may not continue forever if they are strictly reliant on exhaustible resources. Unsustainable interventions can produce diminishing returns over time and the progress can be slowed, stabilized, or even reversed as resources reach their limit.

The causal drivers behind this type of interaction involve the interplay between balancing and reinforcing feedback loops (Figure 7a). In the context of the energy sector, this can be explained by interactions between SDGs 7 Energy Security and 9 Industry, Innovation, and Infrastructure and SDGs 7 and 12 Responsible Consumption and Production. Innovation and infrastructure projects (SDG 9) related to fossil fuel-based energy carriers (e.g., new technologies to improve fossil fuel extraction) can initially boost energy production and improve energy security (SDG 7). Incomes from the fossil fuel energy industry also further reinforce investments in fossil fuel technology and innovation. With this increase in energy production in the short-term, there could be a subsequent rise in per capita energy consumption, and energy demand could increase exponentially. However, energy production based on fossil fuel technologies is restricted by the availability of natural resources and can cause significant trade-offs with sustainable production and consumption (SDG 12). The combination of fossil fuel reliance and resource depletion can mean that energy supply does not increase sufficiently in response to growing demand and energy insecurity may be even more acute in the long-term. A stark example is provided by India's heavy reliance on limited fossil fuel resources to meet their energy needs where recent shortages were predicted a decade ago, as was the need to exploit alternative renewable energy sources (Moallemi et al., 2017; Parikh & Parikh, 2012). Limits to Progress have been used frequently in other sustainability applications such as agriculture (Brzezina et al., 2017), food (Sharif & Irani, 2016), and energy (Cavicchi, 2020), for example, showing that increasing agricultural subsidies does not always generate growth and can be limited by other factors such as market dynamics or intrinsic environmental limits (Brzezina et al., 2017).

A dynamic behavior resulting from this interaction is an initial synergy (e.g., between SDGs 7 and 9), which diminishes over time due to trade-offs with other goals (e.g., SDG 12). With this decreasing synergy, rapid but short-term progress is expected initially (e.g., improving energy production due to technology innovation). However, this does not last long as progress slows, stagnates, or even declines in the long-term due to resource depletion despite increasing efforts and further investment (Figure 7b).

The important sustainability implication is to anticipate in advance and take early actions to address the effects of limiting conditions in the design of SDG actions to avoid stagnation in the long-term. In our energy example, this means adopting measures that can help shift innovation and infrastructure development from fossil fuels to renewable technologies (e.g., imposing a green tax on fossil fuel projects to be invested in renewable energy capacity expansion), such as advocated for India (Moallemi et al., 2017; Parikh & Parikh, 2012), to decouple energy production (SDG 7) from finite natural resources (SDG 12). Such sustainability actions may not deliver outcomes in the short-term due to (decision-making and administrative) delays in adjusting to the new system and lags between policy and impact on the ground. However, they can produce better long-term outcomes.

3.8. Tragedy of the Commons

Tragedy of the Commons represents SDG interactions resulting from a more complex limiting condition effect, where working toward competing goals while sharing limited resources (e.g., water and land) in isolation could lead to the exhaustion of resources and an overall unsustainable outcome.

The causal drivers that underpin this type of interaction involve multiple reinforcing and balancing feedback loops (Figure 8a). The reinforcing loops drive competition between goals, while balancing loops stabilize each goal's progress due to the effect of a shared limited resource. We explain them in the context of trade-offs between the use of water (SDG 6) for energy (SDG 7) and food production (SDG 2). Energy production can have a substantial water footprint. Water is used in energy production for thermal cooling in power plants and in bioenergy and hydropower generation. Increased water allocation expands generation capacity and increases energy production, creating a path dependency with further water demand for energy. Water is also heavily used in agriculture for food production, where increased water allocation leads to the expansion of agricultural activities and more food production. This eventually creates a reinforcing feedback loop, further increasing water demand for expanded agricultural lands. The increasing competition between different sectors for water as a limited resource can increase water use (and potentially water pollution) and drive up the cost of water, diminishing the gains in energy and food production from available water. Notable examples include demand increases for water, energy, and food in the context of growing populations and poor intersectoral policy coordination in South Asian countries such as India, Pakistan, and Bangladesh (Rasul, 2016), and similar problems potentially occurring in other countries such as Chile (Poblete et al., 2012). Tragedy of the Commons has been used in other sustainability applications (Table 2), for example, for analyzing resource-constraint issues in agriculture (Neudert et al., 2019), water (Zare et al., 2017), and food (Sharif & Irani, 2016) sectors.

A dynamic behavior resulting from this interaction is a gradual decline in the gains from the use of the common pool resource (water in our example) despite the increasing cost of resource use due to its limited availability. If left uncontrolled, this can continue until the commons are completely exhausted (or its cost skyrockets) and the achievement of the sustainability goals which rely on the resource can become impossible, with progress halted or reversed (Figure 8b).

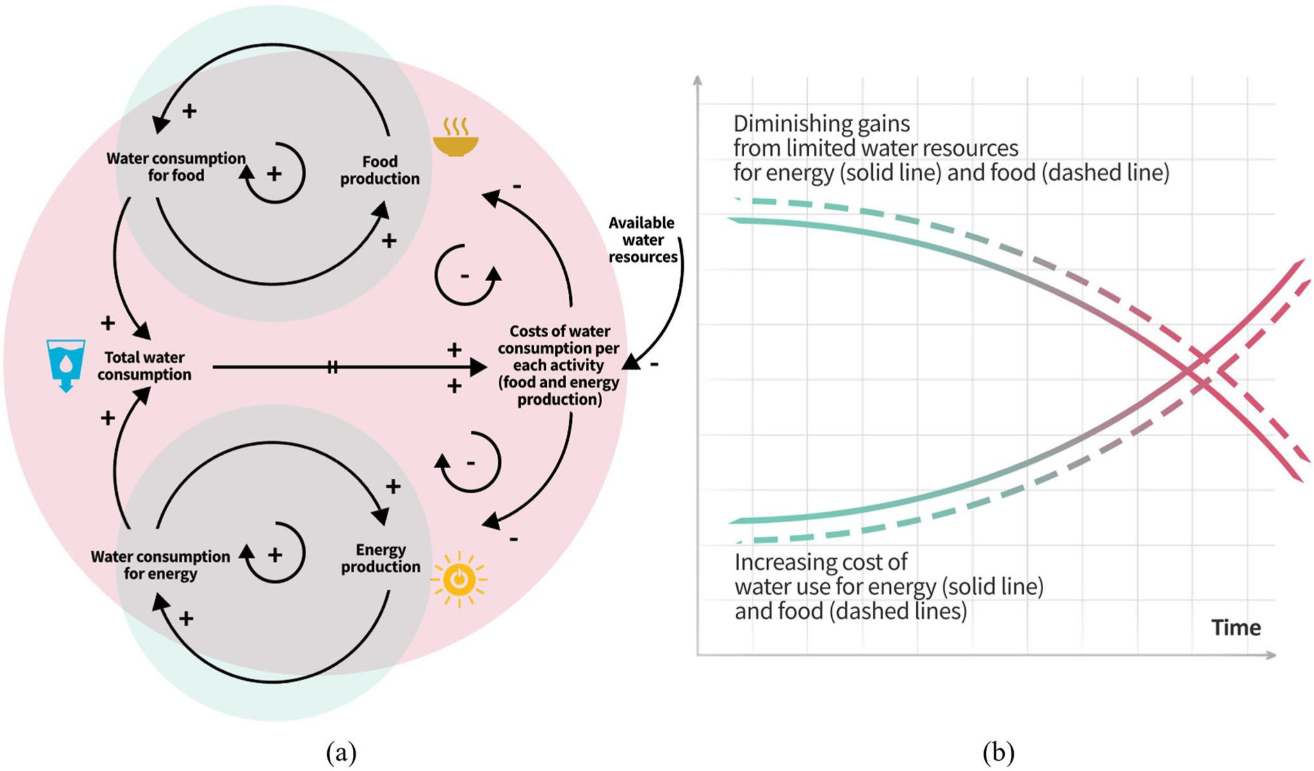

Figure 8. (a) The causal drivers and (b) a potential dynamic behavior in Tragedy of the Commons. The major feedback interactions in (a) and their corresponding impacts in (b) are color coded. Both (a and b) are conceptual figures.

A policy implication of this type of interaction is the importance of understanding connections between sectors from a whole of system level and managing coordinated actions that can make appropriate trade-offs and make the best use of common pool resources. It also signifies the connection between uncoordinated actions toward individual goals occurring in isolation and the diminishing collective outcomes for sustainable development due to overloaded or depleted resources. The competition between goals and the limited resources can be managed through renewing, sharing, and reusing the commons before depletion (e.g., circular economy). The negative effects of competition and limiting conditions can be also reduced by decoupling the progress across interacting goals from the limited resources (e.g., farming less water intensive feed and food crops, shifting to less water intensive renewable energies like wind and solar).

4. Discussion

4.1. Opportunities

4.1.1. Synthesizing Knowledge Across Cases

Interaction archetype analysis can play an important role in linking empirical data to interaction patterns and to causal statements. The presented typology of interactions can serve as a framework for *knowledge synthesis* from a large number of empirical findings compiled through different methods and from many case study applications (Magliocca et al., 2018). Such a knowledge synthesis is independent of narrowly focused case studies and contexts and is generalized at an intermediate level of abstraction (Sietz et al., 2019). It is therefore capable of inferring broader patterns of causal drivers among various sustainability goals that are more generally applicable and understandable. Such a synthesis of knowledge across SDG studies is significant for understanding and acting on various socioeconomic and environmental challenges that operate beyond specific sectors and contexts. Knowledge synthesis can also play an important role in systematic theory development, where assuming a theory or hypothesis for observed sustainability interactions can be tested and/or explained by similar interactions in other cases/contexts. While the idea of synthesizing generalized knowledge across cases has been advocated and shown in other contexts (Magliocca et al., 2018; Sietz et al., 2019), their potential benefits in the SDG context remains to be tested.

4.1.2. Transferring Lessons Across Locations

Many sustainability problems in different geographical locations are very similar in nature, and there are lessons to be learned from how different contexts/locations respond to the same problem, if the knowledge can be transferred through a common framework (see examples in water [AghaKouchak et al., 2015], agriculture [Cabral & Shankland, 2013], biodiversity [Gonzalez et al., 2016], and land use [Meyfroidt et al., 2014]). Classifying typical SDG-related problems and intervention leverages into recurring patterns based on archetypes can help policymakers and SDG planners by providing a *comparative tool* (Kok et al., 2016). This can foster learning about sustainability interactions and the experience of others in different locations and enhance knowledge transfer between areas which share the same causal drivers in a more coordinated way (Eisenack et al., 2021; Neudert et al., 2019; Oberlack et al., 2019). Given the emerging nature of archetype analysis for the SDGs, there is currently no comparative application in the literature. Therefore, the use of archetypes for transferring lessons across locations can be an important topic for future research in this area.

4.1.3. Structuring Knowledge for Modeling

Understanding SDG interactions as archetypes and linking them to their underlying causal drivers and potential dynamic behavior can help structure available knowledge in the form of *conceptual models,* that is, a rich picture of drivers, delays, and feedbacks, which is a key step in the modeling process for sustainability (Szetey et al., 2022). The key to the use of archetypes for developing these conceptual models is the use of causal loop diagrams to map the coevolving nature of socio-economic and environmental processes. The general process to develop the causal loop diagrams is by studying case-specific data and inferring the causality that governs interactions in practice. Data can be collected from various sources such as observations, documents, interviews, and surveys. The knowledge obtained from collected data then informs the structure of the causal loop diagrams.

There are different ways that this general process for developing causal loop diagrams can be conducted. A more qualitative way can be through event history analysis (Poole, 2000); an approach that is frequently used for mapping patterns of change in socio-technical transitions (Hekkert & Negro, 2009; Suurs, 2009). Event history analysis can help conceptualize the causality of interactions by studying different sequences of events, their causation, and critical incidents in a systematic manner in the form of narratives. The advantage of this approach is in the use of storylines or narratives that can capture the richness of information about the underlying interaction drivers in a case study, which can be overlooked when using other (e.g., data-driven statistical and machine learning) methods. The limitation, however, is in the way that events are often framed as discrete instances of change (e.g., in the state of actors, institutions, and resources) while causal loop diagrams are usually associated with continuous time analysis. A more quantitative approach to develop causal loop diagrams is through the use of statistical and machine learning methods that can synthesize causal loop diagrams by exploring data sets in a more automated way. Abdelbari and Shafi (2017) showed a general application of this using a neural network-based methodology to learn from available data and design alternative conceptual structures for modeling.

4.2. Challenges

4.2.1. Biases in Understanding Interactions and Overfitting Data to the Archetypes

The analysis of data in a case study can be influenced deliberately (e.g., personal preferences, beliefs, and values) or unintentionally (e.g., unconscious mental framework, heuristics, and presumptions). There is an extensive theoretical body of literature that has focused on these issues (Glynn et al., 2017; Moallemi, Zare, et al., 2020; Zare et al., 2020). This can lead to potential biases, misjudgment, and overfitted data resulting in archetypal patterns with specific causal drivers. For example, stakeholder strategic motives or self-interest can lead to the deliberate ignorance of side effects of short-sighted actions (e.g., Band-Aid Solutions) and instead blaming the slow progress on natural limiting conditions in the system (e.g., Limits to Progress). A similar shortcoming is the tendency to overfit or *shoehorn* the case study interactions into a specific archetype. Archetypes are a good way to understand many SDG interactions, but not all of them can be meaningful for every interaction. The risks of biases and overfitting include framing relevant archetypes into a distorted representation of SDG interactions and misleading causal drivers. This can lead to sub-optimal polices if they are used in decision-making.

Testing and supporting the recognition of archetypal patterns in case studies with more empirical data is one way of mitigating the risk of biases. Engagement with stakeholders can provide an opportunity to more closely assess the relevance and objectivity of the interactions in a case study and to codevelop them with relevant societal actors with potentially contrasting views of interactions and their causal processes (Sietz et al., 2019). Modeling can also provide a systematic way of testing and evaluating the archetypes of a case study as hypotheses in a way that is less biased and less dependent upon individual judgments. Using a combination of connected archetypes to explain SDG interactions is another way of addressing biases and data overfitting. By mixing two or more of the current eight archetypes together, a new (compound) type of interaction can emerge, which can be used to explain more complex synergies and trade-offs. See Moallemi et al. (2021) for an example of combining multiple archetypes. In mixing and matching archetypes, careful attention should be paid to the increasing number of archetypes that are combined to avoid cluttering the analysis with what is usually referred to as spaghetti diagrams (i.e., very complex causal loop diagrams that cannot be understood and do not give any useful information) (Rahmandad & Sterman, 2012).

4.2.2. Interactions Across Scales

Progress toward the SDGs is shaped by a variety of socio-economic and environmental processes that span multiple local (e.g., community and city), national, regional (e.g., political and economic union), and global scales, and issues that exist at one scale may manifest differently at another scale (Moallemi et al., 2019). However, the use of archetypes for sustainability has remained primarily focused on higher (often national, regional, or global) scales, missing potential interactions that can happen at a local level or across scales. More locally focused approaches to the SDGs are required to better represent and account for bottom-up causal drivers (Bandari et al., 2021; Ningrum et al., 2022; Szetey et al., 2021a, 2021b). Multiscale approaches are also required to create nested patterns of interactions (e.g., regional supported by country-level sub-patterns [Sietz et al., 2017]) and incorporate multiple levels of abstraction, corresponding to interactions across scale (Sietz et al., 2019).

4.2.3. Uncertainty in Interaction Configurations

Socio-environmental conditions and decision-making are inherently associated with uncertainties that could determine how interactions among the SDGs ultimately unfold and their concomitant sustainability outcomes. Such uncertainties can result from incomplete knowledge about the environment and future events (e.g., technological innovations, political shifts, and ecological tipping points) as well as the diversity of stakeholder perspectives (e.g., epistemological, cultural, and policy choices) and therefore lead to ambiguity in framing interactions (Walker et al., 2013). Uncertainty has so far had limited attention in analyzing SDG synergies and trade-offs, and when uncertainty was considered, it was mostly parametric uncertainty in model-based projections (Gao & Bryan, 2017). However, there are more pervasive forms of uncertainty, for example, uncertainty in underlying causal drivers of interactions (e.g., relationships between variables and their feedback interactions), which cause unexpected dynamics and surprises in system behavior and unfolding interactions. This structural form of uncertainty is seldom discussed and needs to be further investigated in relation to the structure of causal drivers in SDG interaction.

Integration with other methods from other areas such as exploratory modeling (Bankes, 1993; Moallemi, Kwakkel, et al., 2020) is one way for a systematic generation and impact assessment of alternative causal drivers and comparing their resulting SDG interactions. In an exploratory approach, the assessment and comparison of alternative causal drivers should not aim for agreement but rather focus on differences in the underpinning causal relationships. This can lead to new insights that would not have been possible without considering a diversity of causal drivers.

Another related challenge is the insufficient assessment of human and governance uncertainties in SDG interactions. Uncertainty analysis in the SDGs is often related to measurable socio-economic aspects (e.g., population growth and GDP) or biogeophysical factors (e.g., climate uncertainty, land productivity, and water-use efficiency), thus leading to an underestimation of uncertainties related to human, behavioral, and governance processes (e.g., lifestyle behavioral change and policy instability). The incorporation of a social science perspective (e.g., incorporating behavioral aspects in the analysis of diet [Eker et al., 2019] and climate change mitigation [Beckage et al., 2018]) can acknowledge this largely overlooked form of (human and governance) uncertainty and provide new insights about SDG interactions and their effective interventions (e.g., social tipping points [Otto et al., 2020]).

5. Conclusion

The SDGs and their underlying sectors are filled with synergies and trade-offs. To draw upon and act on interacting social, economic, and natural priorities in concert, we need to adopt much more systems-oriented approaches to problem solving that can make better sense of complexity by looking at system components and their relationships as a whole rather than by analyzing them in isolation (Matson, 2022). We used one of these systemic approaches to conceptualize synergies and trade-offs as recurring interaction archetypes.

As diagnostic tools, the interaction archetypes can bring a deeper understanding of causal drivers or policy resistance in SDG progress and their potential dynamic behavior in the future (Mokhtar & Aram, 2017; Zare et al., 2017). Via links between drivers and expected dynamic behavior, these archetypes can be used as prospective tools for identifying potential future unintended consequences of both short-term and transformational solutions and for designing sustainable development policies which can minimize trade-offs and capitalize upon synergies (Turner et al., 2017). As a comparative tool, the suggested archetypes can help researchers and practitioners better understand the similarities and differences of sustainability interactions in relation to their feedback-rich drivers and dynamic behavior beyond the limits of specific sectors or contexts.

Our suggested interaction archetypes can be seen as the building blocks or units of analysis in future synergy and trade-off studies. Adopting a systemic approach for analyzing interactions can inform SDG policy through better understanding the causal drivers of different systems and anticipating and managing them to maintain and accelerate sustainable development (Sietz et al., 2019). They can also be seen as the first step toward more integrated policy governance design that can specifically target systemic barriers across various SDGs.

Data Availability Statement

Supporting data behind the literature review are included in Supporting Information S1 and at Zenodo: https://doi.org/10.5281/zenodo.6827681.

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