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Tools and indices for WEF nexus analysis

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1. Introduction

George Box poignantly observed that "All models are wrong; some are useful" (Collins, 2009). This is particularly true of complex systems where the constituent parameters, aside from being interlinked with each other, fluctuate spatially and temporally while varying in the units that they are measured with. Many decision- and policymakers, academics, and private and public practitioners desire a universally applicable model to inform their context. Yet there is seldom a one-size-fits-all solution. Rather, actors entrusted with responsibility within a multifaceted environment must carefully consider the relative strengths and weaknesses associated with a specific model or method to inform that situation.

Within the discipline of sustainability science, the number of components, variables, unknowns (both known-unknowns and unknown-unknowns) and indicators are myriad. Practitioners should be aware of what tools are available to them. They must also garner sufficient information to weigh these methods against one another and then select the optimal tool for the task at hand. While doing this, they must be cognizant that any model is an approximation of reality based on assumptions, and constrained by several factors (e.g., data availability for complex system replicability, knowledge of governing equations of the system, placement of system boundaries, etc.). The assumptions and limitations associated with the selected method must be both understood and clearly communicated.

The WEF nexus is the context under analysis, and offers a framework that provides a perspective on integrated resource management and security. It

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also provides an integrated perspective on the performance of SDGs 2, 6, 7, and 13. Reasons for assessing the "nexus" include the following:

1. a desire to have a multicentric approach, seeking to prevent a "silo" approach to resource management, and
2. to seek to exploit potential synergies and avoid tradeoffs associated with the implementation of resource-based policies.

Meadows et al. (1972) cautioned almost half a century ago, before the word "sustainability" became a buzzword, "If the present growth trends in world population, industrialisation, pollution, food production and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years." Approximately 30 years later, it has been reported that "the human economy is exceeding important limits now and that this overshoot will intensify greatly over the coming decades" (Meadows et al., 2004). The goal of this chapter is to introduce some prominent tools and/or approaches to studying the WEF nexus from different perspectives and to highlight indices by which to analyze the anthropogenic effects on earth and efforts toward reversing detrimental trends.

2. Tools and approaches to analyze the WEF nexus

2.1 Conceptual maps and causal loop diagrams

Conceptual maps and causal loop diagrams are closely related approaches and/or tools that are discussed together. Conceptual maps can be thought of as a mapping of the most important connections within a system at an abstract level that is usually accessible for nonexperts to understand. Conceptual maps can help define the system boundary as well as identify the main issues under investigation, including the connections between those issues. They can start to elucidate the mechanisms of the interactions. Conceptual maps should be developed as much as possible with the involvement of local experts and with a wide group of interested stakeholders. This will help ensure that the developed map is representative of the case study and as accurate in reflecting WEF nexus issues as possible. Conceptual maps are usually developed iteratively over a series of meetings or workshops, with details being gradually added to the level desired of the study and to refine ideas. Conceptual maps can be "high level conceptual maps" where the main sectors and major links are highlighted without details (Fig. 5.1), or "extended conceptual maps" where details with specific nexus sectors and the links among its subsectors and all the other sectors of the system are shown (Fig. 5.2). In Fig. 5.1, a high-level map between the water, energy, food, land, and climate sectors in the Netherlands is shown, indicating the connections between sectors and potential mechanisms. For example, a connection is shown between the climate and water sectors, indicating that climate change may impact on future water availability in the Netherlands. In this example, each sector has its own separate

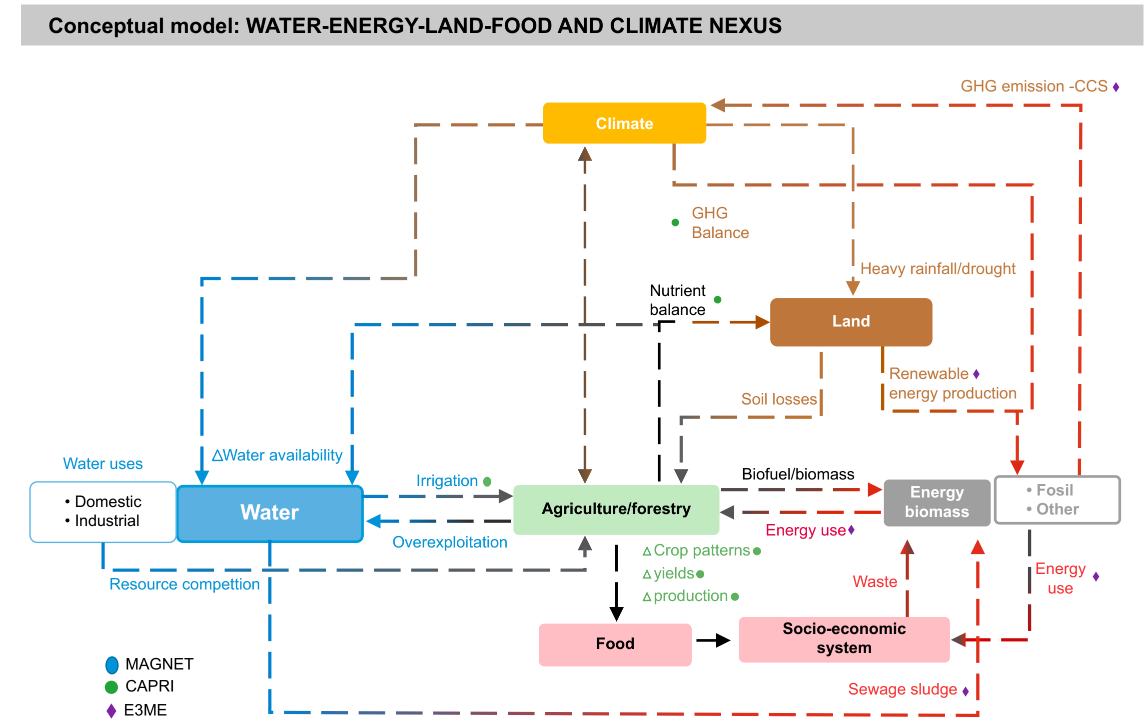


FIGURE 5.1

"High-level" nexus conceptual map for the Netherlands case study in SIM4NEXUS (www.sim4nexus.eu; Vamvakeridou-Lyroudia et al., 2019).

conceptual map developed (e.g., food sector in Fig. 5.2), thus forming a "Russian doll" of nested conceptual maps. A detailed example of conceptual model development for the Songwe River Basin, located in the border between Malawi and Tanzania, is shown in Chapter 7. Within each sector, more detail is added on how that sector behaves and the detailed connections to the other nexus sectors. Through such high-level understanding, communicating complex nexus issues to nonexpert stakeholders becomes considerably easier than when trying to communicate model output. Although these maps seem simple, their development and refinement may take weeks to months, especially when developed in a collaborative setting with expert advisors. Their importance should not be underestimated, as they play critical roles in data mapping and quantitative model development and in communication regarding complex nexus issues in an accessible way.

Causal loop diagrams (CLDs; Ford, 2010) are a mapping of interconnections between system elements to better understand causal connections between those elements. They go beyond conceptual maps (but are complementary to them) by introducing the concept of causality between elements, allowing

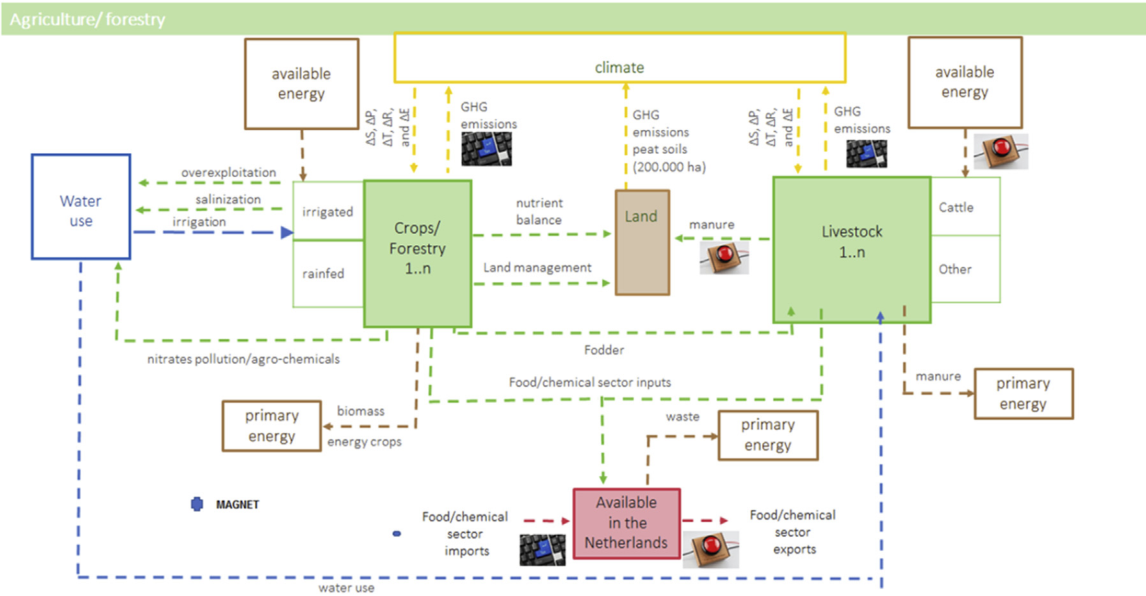


FIGURE 5.2

"Extended" nexus conceptual map for the Netherlands case study in SIM4NEXUS (www.sim4nexus.eu; Vamvakeridou-Lyroudia et al., 2019).

one to define reinforcing and balancing feedback connections and loops. They offer different information than conceptual maps. CLD is an approach that can be applied in the process toward developing quantitative systems models (Binder et al., 2004) and are helpful in assisting nonexpert stakeholders in developing a better understanding of the main interconnections in a complex system, such as the WEF nexus. Wolstenholme (1999) explains that CLDs are able to be developed and applied independently of any quantitative modeling exercise. Through this mapping, complex feedback loops through a system can be explored. CLDs assign "polarity" to connections between variables (Sterman, 2000). Connections with positive polarity (indicated with a "+" next to the arrowhead) indicate that variable "A" changes *with the same direction* as variable "B" (e.g., if "A" increases, "B" also increases). Connections with negative polarity (indicated with a "−" next to the arrowhead) mean the opposite (i.e., if "A" increases, "B" decreases). Tracing polarities around loops allows one to assign a "type" to a complete feedback loop. Reinforcing feedback loops suggest runaway behavior, potentially leading to exponential growth in a system. This is the situation when the values of a system double in the same period of time. For example, if it takes 10 years to go from 10,000 to 20,000 people, it would also take 10 years to go from 1,000,000 to 2,000,000 people. Fig. 5.3 shows an example of exponential growth, using world population over time

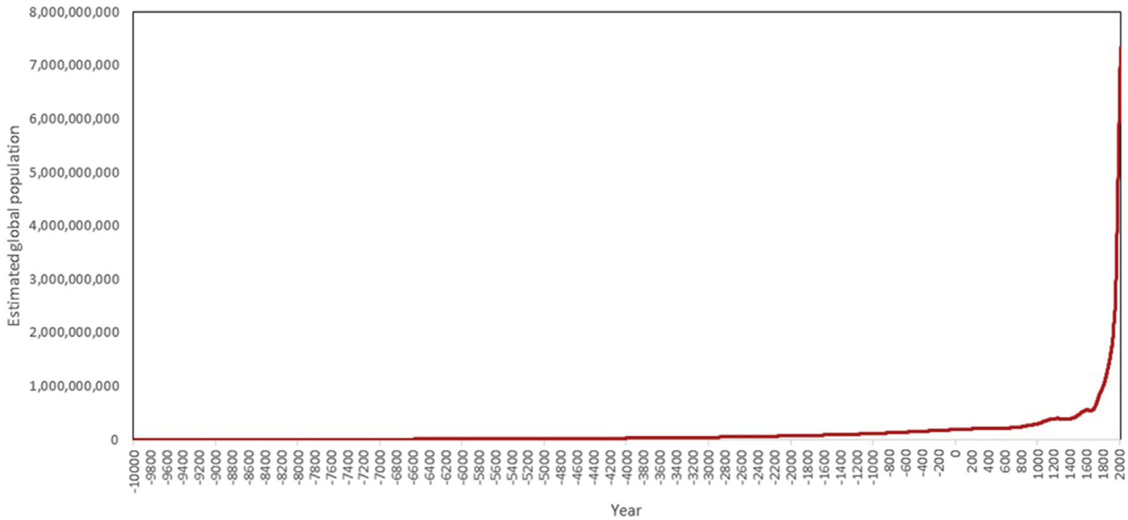


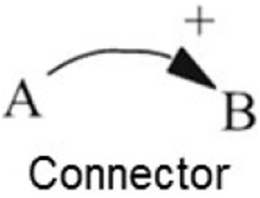
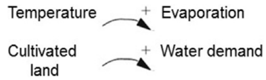
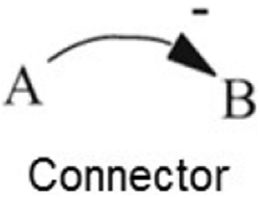
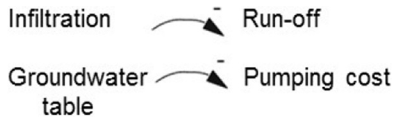
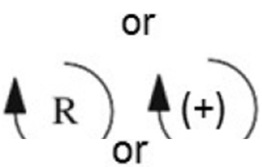
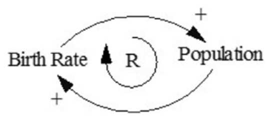
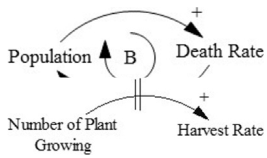
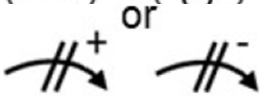
FIGURE 5.3
Example of exponential growth using world population as an example. *Data source: Our World in Data (ourworldindata.org).*

as an example. In a CLD, two, four, six, or any even number of positive connections through an entire loop mean that loop has a reinforcing character. Balancing feedback loops suggest "goal-seeking" behavior resulting in dampened growth. A good example is that of an ecological predator–prey dynamic between two species. Rises in prey populations are followed by temporally delayed rises in predator numbers, who consume members of the prey population, which subsequently starts to decline. This is followed by a decline in the predator population, which allows the prey population to rebound again. This behavior can continue over time, resulting in wave-like patterns of population numbers, oscillating around an approximate mean value. While simplistic, this gives an idea of the notion of dampening of system behavior and oscillatory behavior. Interactions between reinforcing and balancing loops can lead to oscillatory system behavior as the system transitions between dominant behavior modes. Table 5.1 summarizes visual representation of CLD notation. CLDs can be very useful in guiding the development of system dynamics models, especially when developed with (local) experts in the fields of water, food, energy, and systems analysis (Purwanto et al., 2019, 2021).

2.2 System dynamics modeling

System dynamics models (SDMs; see Ford, 2010 for a comprehensive introduction) may be thought of as the "next step" from CLDs, with CLDs guiding the development of SDMs. The concept of SDM was developed in the 1960s by Jay

Table 5.1 Basic elements in causal loop diagrams.

Notation	Description	Example
	Change in A causes change in B in the same direction. If A increases/decreases, B also increases/decreases	
	Change in A causes change in B in the opposite direction. If A increases/decreases, B also increases/ decreases	
	Reinforcing or positive feedback loop, if it contains an even number of negative causal links	
	Balancing or negative feedback loop, if it contains an odd number of negative causal links	
	Delay, the situation when the systems respond slowly in certain condition	

Modified from Mirchi, A., Madani, K., Watkins, D., Ahmad, S., 2012. Synthesis of system dynamics tools for holistic conceptualization of water resources problems. Water Resour. Manag. 26, 2421–2442.

Forrester (Forrester, 1968) as an approach to study problems of control and feedback in industrial systems. SDM is, therefore, ideally suited for studying complex systems governed by complexity, delay, and feedback, such as the WEF nexus. One of the earliest and perhaps well-known applications of SDM was in the classic *Limits to Growth* study of Meadows et al. (1972), which considered prospects of human growth and industrial development in the context of living on a planet with finite resources being degraded by pollution. Although at the time the Meadows et al. (1972) study was heavily criticized for not being realistic, more recent work has demonstrated that the *trends* predicted in the model simulations were broadly correct for many parameters (Turner, 2008). SDM has been applied to a vast diversity of environmental issues (e.g., Kojiri et al., 2008; Davies and Simonovic, 2011; Rehan et al., 2011; Sušnik, 2015, 2018; Sušnik et al., 2012, 2013a, b; Ghashghaei et al., 2014; Sahin et al., 2014; Mereu et al., 2016; Hayward and Roach, 2018; Bakhshianlamouki et al., 2020; Purwanto et al., 2021) and is useful for nonexpert communication (Tidwell et al. 2014).

SDMs typically comprise three main model elements, i.e., stocks, flows, and converters (Fig. 5.4). Stocks store material (e.g., water in a reservoir) and have units that are non-time dependent (i.e., they integrate over time; e.g., m^3, number of people). Flows move material into and out of stocks (e.g., river discharge, evaporation; m^3 s^{-1}). Finally, converters alter the rates of flows (e.g., runoff coefficients or evaporation rate). Changes in stock levels are calculated through finite difference equations. Long-term trends in stock levels and

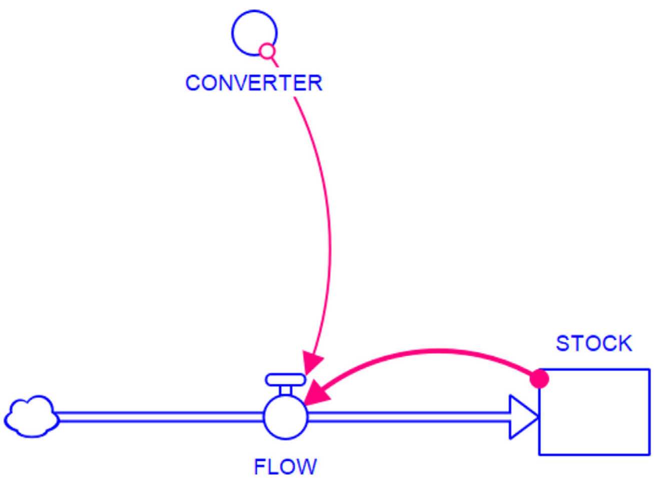


FIGURE 5.4
The three major SD modeling elements: stocks (square box), flows (large arrow with the "valve"), and converters (small circle). Connections (pink lines) transmit information between modeling elements. SD, system dynamics.

derived indicators (e.g., www.wefnexusindex.org) can be tracked according to changes in system variables. Model elements are linked to form feedback loops that can include delay and nonlinear functions. Mathematical, logical, statistical, or control expressions define element interaction and can be probabilistic, utilizing Monte-Carlo sampling.

One main advantage of SDM over other modeling approaches is the ability to build models from "the ground up." This means models can cross disciplines, allowing truly "systems" or "nexus" thinking to analyze the connections between WEF nexus sectors, and how these may respond to external driving forces such as population change or policy implementation. It can also be applied at almost any spatial (e.g., household, regional, national, global) or temporal (e.g., daily, monthly, yearly) scale, offering the flexibility required to study WEF nexus issues, which are operational at different scales (see Chapter 5). Another advantage of the bottom-up modeling approach is the ability to involve stakeholders in the modeling process (cf. Tidwell et al. 2014; Sušnik et al., 2018), which leads to models better representing the system under consideration as well as to better understanding of the model outputs by stakeholders, meaning that results and recommendations are more likely to be accepted and taken up. However, there are aspects that SDM is less able to deal with, including interactions between people and the environment, spatially distributed phenomena, and fine-detailed analysis of individual systems. In these regards, other approaches may be better suited.

2.3 Agent-based modeling

Agent-based modeling (ABM) has its roots in complexity science and is not dissimilar to cellular automata. ABM allows to capture or generate emergent phenomena that result from the interactions between individual entities. Two of the main characteristics of this tool are its flexibility and its ability to produce a natural description of the system, i.e., the most probable scenarios that can happen in reality (Bonabeau, 2002). In ABM, groups of "things" with similar characteristics (e.g., people, animals, classes of people such as farmers) are represented as agents. Each agent has its own set of decision-making rules. These might define, for example, how a farmer responds to changes in agricultural policy or how they change crops depending on rainfall patterns. Or the rules could define how a city spreads out as it grows, perhaps being guided by proximity to major infrastructure. Complexity and emergent behavior comes about through the interactions of agents with each other and with their background "environment." As such, ABM has been defined as "… *a computerized simulation of a number of decision-makers (agents) and institutions, which interact through prescribed rules*" (Farmer and Foley, 2009). Due to this ability of agents to respond to changes in the environment and vice versa, ABMs are adept at simulating human–environment interactions. Similar to SDM, bottom-up model development is favored to capture the detailed decision rules to be employed by each agent and to properly characterize the interaction with the environment. In some ABMs, the agents can learn, adapting to new circumstances or environmental changes, a feature again very useful in modeling human–environmental systems.

There are several ABM methods (see An, 2012 for a thorough review). *Microeconomic models* are focused on resource-related studies where the agents aim to "maximize" profit or revenue while not violating constraints (e.g., in resource availability). One major assumption is that agents always make rational decisions, which is not always the case. Applications include agents using land for different purposes (e.g., Reeves and Zellner, 2010). One major point to consider is the choice of variable and the form of those variables to enter in the utility functions of microeconomic ABMs. *Space theory models* concern decisions made when space, certain characteristics in space, or distance to other objects is of primary concern. For example, some decisions may be made based on ground slope or aspect relative to the sun. Many ABMs predicting city expansion use rules linking expansion-to-distance-to-infrastructure such as road and rail networks (Haase et al., 2010; Hosseinali et al., 2013; Firdausiyah et al., 2019). Distance to green spaces or to coastlines may also be considered as critical decision-making factors. However, there can be arbitrariness in deciding what environmental/socioeconomic elements and what relationships between the agent's decision and the chosen elements should enter the model. *Psychosocial models* are based on beliefs, concepts, memory, and experiences of a system. They tend to aim to represent the net effect of peoples' thought process and actions within a system. One subset is fuzzy cognitive mapping, using nodes and edges to represent relationships between elements in a system (e.g., Martinez et al., 2018). Another is actor-centred theory that postulates that actors influence and/or are influenced by changes in social structures. Although a rich area of research, more understanding is needed of the role that social networks play in human decision making. Closely related are *institution-based models*, which aim to assess the interactions of institutes with each other and in response to changes in their environment. *Experience/preference-based models* are based on real-world experiences and the decisions brought about from those experiences. They are, therefore, easier to communicate and understand as they represent more closely real-world choices. However, they can incorporate more uncertainty due to the diversity of choice options, which is where blending with fuzzy logic methodologies can come in useful to estimate the degree of likelihood of a particular course of action based on a ranking of the "desirability" of different options. Decision rules in this type of model are often updated. *Participatory models* are built with the express involvement of stakeholders, who help define how the models are to be built (cf. Sušnik et al., 2018). Through such involvement, stakeholders are more likely to trust model outputs, and the model may better represent the system under study due to the expert knowledge from the stakeholders. *Empirical rule models* derive their ABM rules through analysis of (statistical) trends and relationships in data, measurements, and observations. Occasionally, methods such as neural networks as used to learn the rules form complex data sets; however, this has the disadvantage of the user not knowing how the rules came about. While useful for deriving rules from large and complex data, this method suffers from the downside that one cannot understand why the rule is made—it is more a mechanistic procedure to be implemented. *Evolutionary programming*—based ABMs are a type of empirical model as described earlier, but utilizing concepts borrowed from the theory of natural selection. Agents contain various attributes regarding decision-making, and those agents with the attributes most likely to succeed and adapt will "survive." Just as in the natural world, agents and their attributes can copy, cross-breed, or mutate rules, leading to better chance of survival. The final major type of ABM are *assumption-based models*. These are implemented where hypothetical rules are used in the absence of sufficient data, knowledge, or information about a process to utilize one of the aforementioned approaches. They can be useful in modeling social systems, for example, when making assumptions about how many hours working adults are out of the house for in a workday (Perez and Dragicevic, 2009). Of course the main downside is that the rules may not be correct, and because of the lack of information, there is no possibility to test if the rule is correct or not. Another issue is that while the model may produce good results, it may be for the wrong reasons. This suite of models must be used with caution.

2.4 (Multiregion) input—output modeling

Multiregion input—output (MR)IO modeling is a top-down approach to environmental accounting. Such IO tables and analysis help demonstrate how much product a given economic sector produces (the output) and how much other product is needed (the input) to realize this output. As databases have become more comprehensive (e.g., the widely used EXIOBASE database; www.exiobase.eu/), it is possible to consider primary resource use and emissions within any given sector, allowing the wider intersectoral linkages within an economy, such as energy needed in the production of a given product, to be identified and quantified (Tukker and Vivanco, 2018). (MR)IO therefore combines all the information about economic relations, pressures on different nexus resources, and how consumption relates to these pressures in a consistent framework. When "flows" of good and resources are between regions and nations, it becomes a multiregional study. Such studies help elucidate the wider "footprint" of resource use in the production and consumption of products, as well as being able to assess the resource use of country or sector within a country, including where the input material originates from, and where the produced material is consumed, along with the wider environmental impact (Tukker and Dietzenbacher, 2013). A well-known example of a footprint is the so-called water footprint (e.g., Hoekstra and Mekonnen, 2012; and www.waterfootprint.org), which allows assessment of which countries/regions virtually “import” or “export” water through the trade of goods and services. Because the resource demands and impacts from production and consumption of products within and between countries is analyzed, nexus wide connections can start to be assessed. For example, how much water or energy fuels are embedded in the production or consumption of a specific product and are given countries net water or energy importers or exporters? These approaches are internally consistent, allowing for direct comparability.

As an example, Meng et al. (2019a) analyzed the urban water—carbon nexus in Beijing, showing that the electricity sector had the greatest absolute direct water consumption, followed by construction and metal smelting. However, in terms of the intensity of water use (defined as volume of water needed to generate a unit of economic return, m^3 US^{-1}), metal smelting was by far the most intense water user. In terms of carbon emissions, the electricity and transport sectors showed the greatest direct carbon emissions, while metal mining was the most carbon intensive sector. Embodied water and carbon consumption were also analyzed, with food and tobacco representing the greatest embodied water consumption, and metal mining and construction representing the greatest carbon emissions. Similarly, Wang et al. (2018) perform an MRIO analysis in China, showing that Beijing and Shanghai are resource “importers.” Generally, embodied water was transferred from western to eastern and from northern to southern regions in China.

(MR)IO models are sensitive to sectoral price assumptions and sectoral aggregation (Meng et al., 2019b). Results are also sensitive to the weighting factors assigned for different resource use and impact, with many factoring approaches available (Tukker and Vivanco, 2018). Another downside is that the tables, though sophisticated, are static and must be regularly updated. They are not able therefore to deal with dynamically changing situations. The damage and impact to ecosystems and their services is not usually explicitly considered. Also, as the system boundary is expanded, the assessment becomes evermore complex. It is to be recognized that (MR)IO analyzes connections within economic systems and is not a nexus analysis tool per se. Despite this, it can be useful to gain insight into certain nexus connections and relationships.

2.5 Life cycle assessment

Life cycle assessment (LCA) is related to MRIO, but is a bottom-up approach, allowing a finer resolution of the inputs and outputs of specific products through various stages of the life cycle, including from cradle-to-grave (i.e., all process related to the production, use, and waste management of a product; van der Voet and Guinee, 2018). LCA is a method that computes and evaluates inputs, outputs, and environmental impacts from design to disposition of a product or technology (Guinee, 2002) using detailed databases such as SIMA-Pro. LCA is composed of four main stages: (1) define the goal and scope; (2) inventory analysis; (3) impact assessment; and (4) interpretation (ISO, 2006). As with MRIO analysis, the definition of the system boundary is critical to ensure accurate results and the tractability of the analysis. LCA assesses the demands of materials throughout an entire product life span, or through parts of it. For example, in principle, an LCA could be undertaken for the whole chain depicted in Fig. 5.5, or just for individual elements in the chain. The majority of LCA studies are conducted to assess the environmental impact associated with a certain product or process.

As mentioned earlier, one critical aspect to consider is the definition of the system boundary as illustrated in Fig. 5.6. For example, on the manufacturing side, one LCA could consider the resources required to produce the cotton involved in making a shirt. This may include the land, water, and energy resources associated with the cotton harvesting, and the subsequent water, energy, and human resources involved in the production of the shirt. But in principle, a study could go another step "back" in the chain and attempt to assess the metals and energy consumption involved in the production of the machinery used to harvest the cotton. This adds another layer of complexity. One can imagine going ever-further "deeper" into the production system until the assessment is too complex to carry out, even in principle. Therefore, the boundary is critical to define, with everything outside of the boundary taken as a given exogenous input.

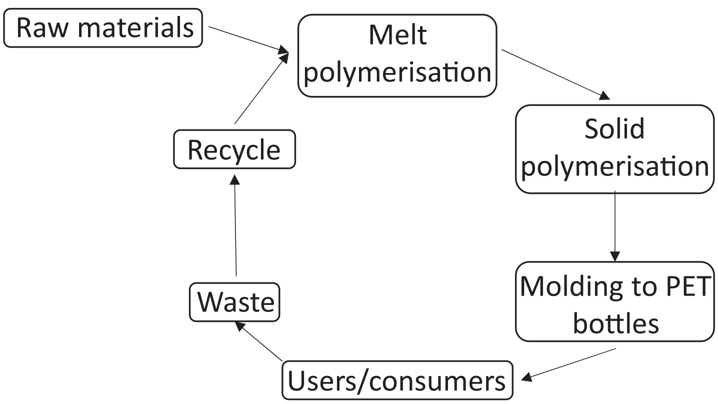


FIGURE 5.5
Flow diagram for PET bottle production. *Adapted from Marathe, K.V., Chavan, K.R., Nakhate, P., 2019. Life-cycle assessment (LCA) of PET bottles. In: Thomas, S., Kanny, K., Thomas, M.G., Rane, A., Abitha, V.K. (Eds.). Recycling of Polyethylene Terephthalate Bottles. Elsevier.*

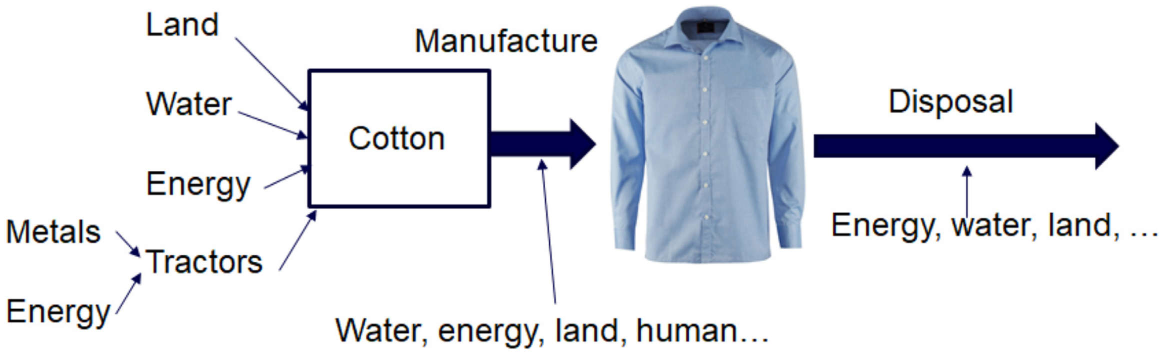


FIGURE 5.6
Where to draw the boundary of LCA studies to ensure tractability of assessments? *LCA*, life cycle assessment.

Because LCA attempts to account for all the resources consumed during a product life cycle, also accounting for environmental impacts (e.g., global warming potentials arising from the use of resources associated with a product during its life cycle), it can account for whole-nexus implications. However, like MRIO, the method is not dynamic, so changes in demand over time and space cannot be dynamically accounted for (van der Voet and Guinee, 2018). Rather, a current situation "snapshot" of a steady state is afforded. In addition, it is up to practitioners on which unit-process data to use, and what allocation choice to make in LCAs. This can lead to considerable uncertainty and variability in the results of LCA analysis for the same product and processes. Another point to be aware of is that LCA tends to use most useful for microprocesses, and it is typically not suitable for upscaling to larger systems (van der Voet and Guinee, 2018). Current research is attempting to extend LCA methodologies to include social and economic impacts, to extend the spatial applicability of LCA studies, and to allow for better dynamic interlinkage analysis, rather than only considering static snapshots of small systems.

2.6 Integrated assessment models

Integrated assessment models (IAMs), largely stemming from the climate and energy sciences (Hamilton et al., 2015), are used to attempt to assess multisectoral impacts of various pressures using scenarios. IAMs have undergone recent rapid development in terms of approaches, sophistication, resolution, and the sectors assessed (e.g., Hamilton et al., 2015; Krey et al., 2019). Accounting for feedback between processes and the ideas of integration and cross-cutting assessment are becoming more prevalent (Huppmann et al., 2019; Krey et al., 2019). Typically, IAMs either consist of the integration of many models to assess multisectoral impacts ("soft linking," the assemblage approach; Voinov and Shugart, 2013) or from developing models from the ground up to integrate different aspects (the integral approach). Therefore, IAMs and their results, data, approaches, and assumptions differ depending on the origins of the various models that are combined to form the IAMs. Some may have energy-based origins, while others are economic or climatic in origin for example. In terms of what is "integrated," Hamilton et al. (2015) identify 10 dimensions of integration, divided into three broad categories: (1) key drivers of integration (stakeholders, issues of concern, governance setting); (2) methodological aspects for integration (sources and types of uncertainty, methods, models, tools, and disciplines); and (3) system aspects to be integrated (spatial scale, temporal scale, natural setting, human setting). As a result of the fundamental underlying differences between IAMs and due to differences in, for example, the detailed implementation of different energy-generating technologies (including capital costs and operation and maintenance cost assumptions, and the relative carbon reduction impacts of the technologies), while IAMs tend to agree on broad high-level issues and trends, there tends to be disagreement on finer-scale details. This is explored in detail in Krey et al. (2019). As an example, while the electricity sector is generally projected to decarbonize under climate policy, the speed of this transition and especially the nature of the resulting technology mix in power generation can be very different across IAMs. These differences in data, assumptions, technical (model) implementation, and integration methods must be fully acknowledged and considered, and attempts could be made to add coherence between IAM results. Another issue is that some IAMs are so complex that it can be unclear as to how and why certain results are obtained, leading to a lack of transparency and trust in results. Indeed, IAMs have come under criticism for being "subjective" and having created their own "reality," which has been accused of being misleading (Ellenbeck and Lilliestam, 2019) and none as yet cover all WEF sectors comprehensively or coherently. Other potential issues with IAMs are that they may lack full representation of sectoral interconnections and that they tend to address more abstract high-level problems rather than shorter-term more applied issues (Bazilian et al., 2011). Some prominent IAMs include GCAM (http://www.globalchange.umd.edu/gcam/), IMAGE (models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation), and WITCH (https://www.witchmodel.org/).

As an example of IAM application, Bijl et al. (2017) use the IMAGE model to assess the long-term water demand in the electricity, industrial, and household sectors. They show that water withdrawals and consumption are both expected to increase globally; however, highly aggressive measures to improve water use efficiency can lead to water use reductions. Such aggressive measures are not expected to be reasonable globally, however. Similarly, Admiraal et al. (2016) also use the IMAGE modeling framework to assess how the costs and benefits of climate mitigation strategies may change depending on the timing of their implementation. The study suggests that gradual change is most effective in terms of costs and net benefits, rather than delayed or early action; however, results are affected strongly by assumptions in the financial discount rates applied.

3. Indices for WEF nexus performance assessment (analysis)

The definition of outputs and indicators of success is of paramount importance in the development of models and tools associated with sustainability. Model outputs must be relevant in that they must provide requisite evidence to researchers, NGOs, policy- and decision-makers, and other stakeholders. The timeliness of the outcomes is also essential because the modeling results must provide information and knowledge to address critical current issues. This information can be generated by means of data, indicators, indices, and qualitative and quantitative studies (such as the models described earlier in this chapter), as demonstrated in Fig. 5.7.

To understand the level of attainment of specific sustainability goals, various indicators have been developed and monitored. These are necessary to benchmark a province, state, nation or region, or the state of a system. They are also invaluable for ascertaining progress and trends and identifying focus areas for policy or development interventions. These indicators are typically recorded on a basin, subnational, or national level, in accordance with an internationally

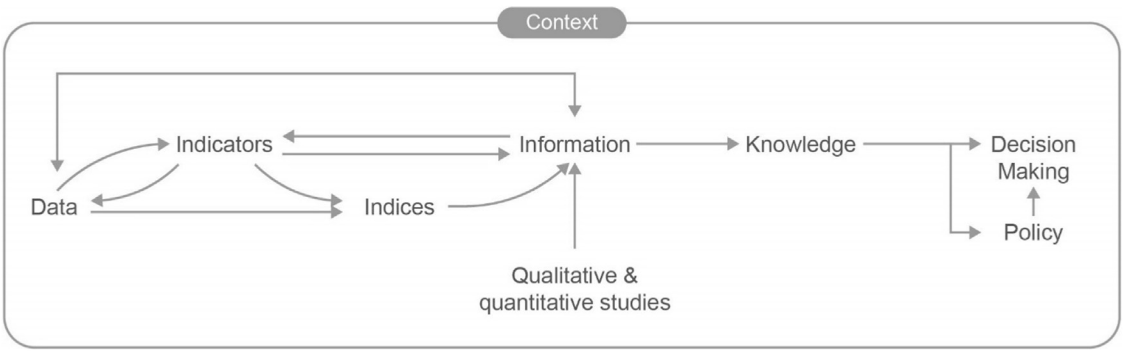


FIGURE 5.7

From data to decision-making. *Modified from Segnestam, L., 2002. Indicators of Environment and Sustainable Development: Theories and Practical Experience. The World Bank Environment Department (Environmental Economics Series. Paper No. 89). Waas T., Hugé J., Block T., Wright T., Benitez-Capistros F., Verbruggen A., 2014. Sustainability assessment and indicators: tools in a decision-making strategy for sustainable development. Sustainability 6, 5512—5534. in Simpson G.B., Jewitt G.P.W., Becker W., Badenhorst J., Neves AR., 2020. The Water-Energy-Food Nexus Index: A Tool for Integrated Resource Management and Sustainable Development. OSF Preprints.*

agreed-upon methodology. The indicator values, together with the underlying data, are subsequently audited by international bodies such as the World Bank, United Nations, International Energy Agency (IEA), or Food and Agriculture Organization (FAO) of the United Nations. In terms of the WEF nexus, indicators relevant to access to, and availability of, water, energy, and food are of particular interest.

Following from the development of individual indicators, composite indicators were developed to enable the understanding of complex concepts such as competitiveness, industrialization, and sustainability. This was necessary because of the difficulty in assessing, and drawing conclusions from, a myriad of indicators. Fig. 5.7 presents the complementary role that indices can fulfill in generating information and knowledge for policy- and decision-makers. A composite indicator is formed "when individual indicators are compiled into a single index on the basis of an underlying model" (OECD, 2008). Some actors, for example, advocacy groups, view composite indicators as a valuable tool to further their causes. Others, such as cautious professional statisticians, are wary of composite indicators due to the potentially subjective nature of the selection of the constituent indicators, the method of aggregation, and the weighting of the indicators. Because composite indicators are not universally accepted, they must be developed transparently and used responsibly.

3.1 Human development index

In 1990, the Human Development Index (HDI) was developed by Pakistani economist Mahbub ul Haq to provide a more comprehensive representation of wellbeing than the GDP. He included health and education indicators with the natural logarithm of the gross national income (GNI) per capita. The HDI was based on the premise that human development should focus on the three essential elements of human life, namely, longevity, knowledge, and decent living standards (UNDP, 1990). Although the method of calculating the HDI has changed with time, it has served as a valuable tool for the United Nations Development Programme (UNDP) and other organizations in evaluating developmental progress in many countries and regions under their jurisdiction.

3.2 Environmental sustainability index

Some composite indicators, in contrast to the HDI, are relatively complex. The Environmental Sustainability Index (ESI) integrates 76 data sets into 21 indicators, which are subsequently condensed into a single index (Esty et al., 2005). The ESI serves as a policy tool for identifying issues that require focused attention within national environmental protection programs and across societies more generally (Esty et al., 2005).

3.3 Sustainability development goals

At the beginning of 2016, the Sustainable Development Goals (SDGs) were launched. Associated with these goals are 230 individual indicators to monitor the 17 SDGs and 169 targets of the SDGs. Included in these goals are SDGs 2 (Zero Hunger), 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), 12 (Sustainable Consumption and Production), and 13 (Climate Action), which are relevant to resource security and distributional justice associated with these resources. These goals are termed SDGs, and not simply development goals, because of the pervasive negative impact of humanity on the planet, and some such as access to electricity are not ends in themselves. How electricity is generated is, ultimately, of comparable importance to its availability. SDG 7 is, therefore, to "Ensure access to affordable, reliable, *sustainable* and *modern* energy for all." Similarly, SDG 13 requires that humanity must "Take urgent action to combat climate change and its impacts," while SDG 12 stresses the sustainable production and consumption of the materials and services we consume.

When these SDGs of the *2030 Agenda for Sustainable Development* were adopted, the United Nations stated that:

> "Indicators will be the backbone of monitoring progress towards the SDGs at the local, national, regional, and global levels. A sound indicator framework will turn the SDGs and their targets into a management tool to help countries develop implementation strategies and allocate resources accordingly, as well as a report card to measure progress towards sustainable development and help ensure the accountability of all stakeholders for achieving the SDGs".
>
> **(UN, 2015)**

Because of the large number of indicators associated with the 17 SDGs, an SDG Index was developed (Sachs et al., 2016, 2018; Schmidt-Traub et al., 2017). The SDG Index reports on 156 countries' progress toward all 17 goals and indicates areas where more rapid progress is required. All countries are ranked according to their percentage of achievement on the same group of indicators, and a dashboard has been generated to facilitate comparison between and within countries. Several indicators within the SDG Index are existing composite indicators, such as follows:

- Ocean Health Index
- Sustainable Nitrogen Management Index
- Universal Health Coverage Tracer Index
- Logistics performance index
- Climate Change Vulnerability Monitor

- Red List Index of species survival
- Corruption Perception Index
- Financial Secrecy Score
- Global Slavery Index
- PISA (Programme for International Student Assessment) score

The SDG Index and the associated dashboard apply equal weighting to each indicator and for each goal since all SDGs are considered to have equal importance in the 2030 Agenda (Sachs et al., 2019). Experts attempted to determine different weightings for some indicators at an earlier developmental stage of the SDG Index. However, a consensus on assigning different weights to the indicators could not be reached. The SDG Index values indicate that "no country is completely on track to achieve all SDGs" (Sachs et al., 2018). It also demonstrates that much work remains if equitable and sustainable global access to economic-enabling resources is to be realised.

3.4 WEF nexus index

Following the attention that the WEF nexus has garnered since 2011, various attempts have been made to define, conceptualize, model, and operationalize it, especially for policy- and decision-making. The challenge in obtaining a unified assessment of the WEF nexus is that the three resource sectors are measured in different units, e.g., percentage access, cubic meters, precipitation depth, metric tons of CO_2, kWh, kg per hectare, and international dollars per capita. To provide a coherent quantitative measure of the WEF nexus, a composite indicator that utilizes this framework as its guiding context was developed. The WEF Nexus Index was developed following an assessment of 87 globally available and relevant indicators. Utilizing the methodology espoused by the JRC's *Competence Centre on Composite Indicators and Scoreboards*, 21 indicators were selected to constitute this multicentric index. The WEF Nexus Index, together with its visualization website (www.wefnexusindex.org), provides a lens for assessing integrated resource management and security.

Does the SDG Index, which incorporates (among others) SDGs 2, 6, and 7, render the WEF Nexus Index redundant? El Costa (2015) suggested that since the SDGs seek to incorporate multiple development goals, identifying targets *at the nexus* of various sectors will be instrumental in yielding a more straightforward SDG framework. There is, therefore, a compelling argument in favor of developing an indicator framework for a *subsystem* within the SDGs, such as the WEF nexus. Boas et al. (2016) agree, arguing that "novel ways of cross-sectoral institutionalization" are required if the *2030 Agenda for Sustainable Development* is to be attained.

4. Conclusions

The WEF nexus is an extraordinarily complex system that operates at scales from local to global, and where the three resource sectors interact not just with themselves, but also with exogeneous drivers such as climate change, socioeconomic developments, and policy directions. Coherently modeling the nexus therefore poses a challenge, as numerous sectors, units, underlying philosophies, and data sets should be combined into an integrated framework. As such, there is no one-size-fits-all model capable of modeling and assessing the entire WEF nexus. This is also in part due to the vast diversity in nexus challenges, spatial and temporal scales, and foci of different (research) investigations. However, a number of modeling approaches are available, some of the more prominent of which are introduced in this chapter. Ultimately, it is up to the practitioner to select the tool best suited to the nature of the study being undertaken, and the examples given here offer a glimpse into some of the most used possibilities and their limitations. This chapter also introduces a number of composite indicators, which are developed to report on the performance of the WEF nexus as a whole, but which can also be interrogated to give sectoral (or "pillar")-level information. This information can in turn be used to track progress toward the SDGs or toward nationally or locally determined WEF-related policy objectives.

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