IEU LEARNING PAPER

No. 04

NOVEMBER 2020

HOW TO BRIDGE THE GAP BETWEEN COMPLEXITY SCIENCE AND EVALUATION - A NEW ANALYSIS TOOL AS A FIRST STEP

Karoline Wiesner, Jyotsna Puri and Andreas Reumann

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How to bridge the gap between complexity science and evaluation - A new analysis tool as a first step

Karoline Wiesner, Jyotsna Puri and Andreas Reumann

November 2020

175, Art center-daero
Yeonsu-gu, Incheon 22004
Republic of Korea
Tel. (+82) 032-458-6450
Email: ieu@gcfund.org
https://ieu.greenclimate.fund

First Print Edition

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Citation
The suggested citation for this evaluation is:
Wiesner, Karoline, Jyotsna Puri and Andreas Reumann. (2020). How to bridge the gap between complexity science and evaluation – A new analysis tool as a first step. IEU learning paper, No. 04. November 2020. Independent Evaluation Unit, Green Climate Fund. Songdo, South Korea.

Credits
Head of the GCF Independent Evaluation Unit: Dr. Jyotsna Puri (Jo)
Task manager: Andreas Reumann, Principal Evaluation Officer, Independent Evaluation Unit
Editing: Beverley Mitchell, Deborah Hong, Greg Clough, Toby Pearce
Layout and design: Giang Pham
Cover photo: the complex lake pattern in the cross-border nature reserve between Estonia and Latvia, ©Mati Kose

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Printed on eco-friendly paper

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About this IEU Learning Paper

This report builds a bridge between the science of complexity and climate change adaptation activities conducted in the field. It provides an introduction to complexity science, introduces a diagnostic tool for mapping complex human –climate systems, and concludes with lessons that may be learned for designing, managing and evaluating climate projects.

About the author(s)

Dr. Karoline Wiesner is Associate Professor of Complexity Science at the School of Mathematics at the University of Bristol.

Dr. Jyotsna Puri (Jo) is the Head of GCF's Independent Evaluation Unit. She has 23 year's experience in evaluating research in agriculture, environment, health and infrastructure-related poverty alleviation. She has published several books and written extensively. From November 2020, Jo will start as Director, Environment, Climate, Gender, Nutrition, Youth and Social Inclusion, IFAD.

Andreas Reumann is the IEU's Principal Evaluation Officer for the Synthesis, Uptake and Communication work stream. His extensive experience includes designing impact monitoring systems for large research for development projects and developing alternative evaluation methods.

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ACKNOWLEDGEMENTS

The authors would like to thank our colleagues at the GCF Secretariat, in particular both programming divisions, the Division for Mitigation and Adaptation (DMA) and the Private Sector Facility (PSF), for their insights, contributions and engagement. The authors would like to acknowledge in particular the valuable contributions of Mr. Joseph Intsiful, Senior Climate Information and Early Warning Systems Specialist at DMA, Mr. Rajeev Mahajan, Project Finance Manager at PSF, Yves-Patrick Karangwa, Associate Professional at PSF and Mr. Sergio Pombo, Head of Climate Private Equity Funds at PSF, for their insights into current GCF projects in Vanuatu, Madagascar and Chile. The authors would also send their special thanks to Ms. Tina Pasanen, Research Follow at the Overseas Development Institute, for reviewing this paper. We also thank Rob Van den Berg, Technical Adviser to the Head of the IEU, Oswaldo Fienstein and many others at the European Evaluation Society meetings held in Thessaloniki, Greece for excellent conversations and discussions on this topic. All errors are ours.

ABSTRACT

“We should stop striving for simple answers to solve complex problems.” (Elinor Ostrom, 2007).

We are experiencing the reality of climate change in ever stronger terms. Climate and human activity are now firmly coupled. We are seeing one complex system interlinked with another complex system. To solve the problem of climate change and how to live with it, we must learn to explain, predict and act within the complex system that comprises the climate and all human activity. Nothing can be considered in isolation anymore. This human–climate system exhibits all the hallmarks of complexity: non-linear dynamics, sudden transitions, the importance of timescales, and attributes for resilience such as redundancy and modularity. The tools and concepts from complexity science provide a framework that unites the diverse fields of science relevant to tackling the climate crisis in the Anthropocene epoch. This report builds a bridge between the science of complexity and the work in the field to adapt to climate change. It provides an introduction to complexity science, introduces a diagnostic tool for mapping complex human–climate systems, and develops a complexity scoring of interventions into human–climate systems. It concludes with lessons that may be learned from complexity science for designing, managing and evaluating climate projects in a world of climate change.

> “[T]o diagnose the problems and potentialities of linked SES [social–ecological systems] requires serious study of complex, multivariable, nonlinear, cross-scale, and changing systems.” (Elinor Ostrom, 2007).

ABBREVIATIONS

BVR	Bamberger, Vaessen and Raimondo
CIS	Climate information service
GCF	Green Climate Fund
GS	Governance system
IEU	Independent Evaluation Unit
RS	Resource system
RU	Resource Unit
SEEDS	Social–ecological economic dynamic systems
SES	Social–ecological system
US	User system
WHO	World Health Organization

Executive summary

Complexity is the spontaneous emergence of structure and behaviour in decentralized systems composed of many parts and many interactions. The climate is an example of a complex system. A typical climate mitigation and adaptation project designed and implemented by climate finance funders, managing and implementing entities that include governments and/or non-governmental actors has many, if not all, the features of complexity. When such a project is implemented, it interacts with the social and ecological systems that it is placed in and forms a new complex system. However, for investors, this raises large concerns regarding credibility and reporting because cause-and-effect relationships in complex systems are notoriously difficult to identify, even in hindsight. This report introduces a diagnostic tool to map the interaction between the project/investment and the social–ecological system. A complexity rating is derived from this mapping. We propose that the diagnostic tool and the rating together can guide the theory of change, design, management and evaluation of projects by identifying and tracing project components that contribute to non-linear and sudden changes. Tracing such processes can help identify system dynamics that affect feedback and also help measure their strength. We illustrate this with several real-world examples and use these to derive lessons that can help inform the tools used in programme design, implementation and evaluation.

Whom this report is for

This report is aimed at a general audience of evaluation practitioners and the scientifically literate and scientifically interested layperson. The sections have varying levels of background required. The introduction to complexity science (Section E) is accessible to a general audience. Tools and methods of complexity science (Section B) requires some mathematical background; the understanding of the other sections is not affected if Section B is skipped. Sections C and D give the background on social–ecological economic dynamic systems and introduce a diagnostic tool and a complexity score. Together with Section E (Implications of complexity for development programme management and evaluation), they are aimed at a general audience of evaluation practitioners.

Report structure

Section E explains complexity and its significance for climate systems and attendant social, economic and ecological components. Section B reviews some standard tools for the mathematical and computational study of complex systems. Section C introduces a tool for the systematic analysis of social–ecological and economic systems. The tool aids the design, implementation and evaluation of development programmes and investments in complex systems by mapping out its components and their dynamics and correlations. Three GCF-funded projects are presented as examples. Based on this tool, in Section D, a complexity scoring of climate programmes is introduced. GCF-funded projects are used to illustrate this complexity scoring procedure. Section E discusses the consequences of complexity for programme design and evaluation and makes recommendations for successfully integrating complexity into programme management. The Appendices contain further background information. This report is a combination of a literature overview (Sections E, B) and original work (Sections C–E and the Appendices).

A. Short introduction to complexity

People use the terms “complex” and “complexity” regularly in many different contexts. Often, they are used in the loose sense of “complicated”, “difficult to understand” or “difficult to predict”. In science, however, they have a more specific meaning. Complexity is distinct from complicated, unpredictable or chaotic. A complex system can organize itself into a structured state without being controlled from the outside. The order is generated by the many interactions between many parts of the system and feedback from the components' interactions.

Complex systems can transition between ordered states by themselves. Despite never being isolated from its environment, a complex system can maintain its structure. An example is the Earth’s mantle that has, since the planet began to take form, self-organized into land, ocean, tectonic plates and many other geological structures. The timescales relevant to the dynamics of complex systems vary from millions of years, as in this example, to seconds and faster. When a complex system transitions between ordered states, it usually does so suddenly, non-linearly. Such sudden transitions are also called tipping points and have generated significant interest – in particular, in the climate science community (Lenton et al., 2007). An earthquake is such a sudden transition between two stable, ordered states of the tectonic arrangement.

Living complex systems have the additional ability to adapt to changes in their environment and to make decisions using past experience. A standard example of a living complex system is a beehive, which organizes itself into a social system of labour. It also generates order in its environment by building nests and honeycombs, and it adapts its behaviour to changing circumstances such as changing temperature and the presence of invasive fungi (Seeley, 2010). **The “complexity” of a complex system lies in its ability to self-organize into structured states and to maintain this structure over relevant periods of time; in the non-linearity of transitions between different structured states; and, in the case of a living complex system, in the ability to memorize and to adapt its behaviour.** Complexity[1] is ubiquitous in natural, social and socio-technical systems. Other standard examples of complex systems are planetary systems, ant colonies, the brain, ecosystems and cities.

Let us consider an example of a complex system – a lake’s ecosystem – in more detail. A lake’s ecosystem has self-organized over thousands of years and has led to the lakebed's geological structures and its feeding rivers and water basins. Furthermore, the ecology of inhabiting fish species, plants and algae is the result of self-organization on a shorter timescale, usually tens and hundreds of years. Within lake ecosystems, interlinked relations of “who feeds on whom” typically have evolved into a structured web of dependencies, including mutual dependencies, with a hierarchical order of predator and prey (Pimm et al., 1991). Additionally, the lake and its ecosystem are not separate from the environment but are driven by an influx of water, nutrients and solar radiation, and the outflux of water, other matter and heat. The geological and ecological structures of a lake ecosystem are relatively stable despite their interconnections with several systems. The geology of a lake ecosystem undergoes only minor variations on a timescale of thousands or millions of years. The ecosystem is stable over tens of years or more, concerning seasonal changes in temperature and water levels and other external changes. Transitions in the geological structure in this context, such as the formation of new lakes by passing glaciers, are still possible. This example illustrates the various features that constitute the phenomenon of complexity (Ladyman and Wiesner, 2020). All natural and social complex systems exhibit some or all of these features, including **many parts and many interactions, openness, feedback, diversity, non-linearity, self-**

[1] “Complexity” as it is used in the context of this paper is not to be confused with “computational complexity”, which quantifies the length and running time of computer programmes.

organization, robustness, memory and adaptive behaviour. In the following list, these different features of complexity are explained in further detail.

- **Large number of parts and interactions:** The number of parts that constitute the system and the large number of interactions between them are the basic components of any complex system. The number of parts can range from under a few dozen, such as in smaller bee colonies (Seeley, 2010), to 86 billion neurons in the human brain (Azevedo, 2009). Parts, or elements, often interact and with many other parts. Typically, the number of interactions per (relevant) unit of time in a complex system vastly outnumbers the number of parts.
- **Diversity:** Complex systems are heterogeneous in their types of elements and interactions. For example, the atmosphere is composed of a diversity of molecular compounds; the human brain contains many different neuron types; ecosystems host a large variety of species; and village communities comprise a diversity of professions such as farmers, teachers and small-scale entrepreneurs.
- **Openness:** Complex systems are never completely isolated from their environment but are open to external influences. Examples are the constant influx of solar energy into the Earth's climate system and species movement in and out of ecosystems. Drawing the boundary between the system and its environment can be difficult for a complex system and is, to some extent, a choice made by the observer.[2]
- **Feedback:** Feedback is the phenomenon of past interactions influencing future interactions. Feedback loops can be stabilizing (negative) or self-reinforcing (destabilizing, positive). The Earth's climate system, for example, is driven by many feedback processes. An example of stabilizing feedback is the temperature regulation of the land's surface. An increase in temperature due to sunlight leads to surface water evaporation, which causes low-level cloud formation. Clouds reflect a higher proportion of sunlight than clear air. Cloud formation reduces the amount of sunlight reaching the surface, and, as a result, the surface temperature decreases. An example of self-reinforcing feedback is the melting of polar snow cover. An increase in temperature leads to snow melting, which reveals the soil and rock underneath. These have a darker surface than snow and are less reflective, so they absorb more heat. Hence, the snow albedo's cooling effect is lost, and the further increase in temperature causes more snow to melt.

  Feedback in a system makes it challenging to identify causality and often means that causality is no longer a linear chain. This is relevant for the assessment of interventions into ecosystems. The reports of the Millennium Ecosystem Assessment (2005) list many examples of processes that cannot be represented as simple causal chains because of the presence of feedback.
- **Emergence:** This is an umbrella term for a phenomenon that occurs at the aggregate scale of a system while being absent in its constituent parts (Butterfield, 2011). Emergent features are difficult to predict from the properties of the individual parts. Simply put, the term refers to the idea that the system has attributes that are different (and non-additive) from those its individual constituents display. Spirals in chemical reactions are impossible to anticipate from the atomic make-up of the molecules involved. Consciousness, arguably the most extreme example of emergence, is impossible to predict from considering individual neurons. The most tangible form of emergence is the emergence of structure. The coherence in a flock of birds or the

[2] A practical definition of "environment", informed by the notion of environment in physics, is the following: The environment of a complex system influences the system but is not influenced (significantly) by the system. In addition, the spatial scale of an environment is usually much larger than that of the system. What constitutes the environment for one complex system might itself be (part of) another complex system. For example, the environment of a forested area in Madagascar includes the atmosphere, with its temperature profile and greenhouse gases, since the forest is affected by changes in the atmosphere but itself does not affect the atmosphere significantly. This separation breaks down once all existing forested landscapes on Earth are considered together.

fractal structure of broccoli make for captivating videos and images. Features of complexity that "emerge" from the many elements, their interactions and the feedback and openness include non-linearity, self-organization, robustness, memory and adaptive behaviour.

- **Non-linearity:** This is the non-linear dependence of one variable on another variable. An example of non-linearity in a statistical variable is the "power law" found in most countries' wealth statistics[3] (Piketty, 2014). The number of people who own a given amount of wealth is a function of the negative power of the amount of wealth owned (see also Box 2, on the sugarscape model). Another example is the correlation between the number of bird species and the forested area's relative size in their habitat (as modelled by Hansen et al., 2005). In this example, species richness shows a maximum value at an intermediate size of forested area and drops off when the size is below or above this value. In other words, the number of bird species was non-linearly dependent on the size of the forested area in their habitat.
  Sudden transitions, the so-called tipping points mentioned above, are an example of non-linearity in a dynamic variable. The response of a complex system to some external driving force may be non-linear and very sudden. For example, an earthquake is a non-linear response to continuous physical stresses in the Earth's mantle. A stock market crash is a sudden response to ongoing bidding and selling activity. An orderly crowd dynamic can, at a certain threshold of crowd density, turn into panic. The transition between tropical tree cover and a savannah state in the Amazon was shown to be non-linearly dependent on the amount, type and spatial distribution of land-use (Wuyts et al., 2017). Such sudden transitions are difficult to predict, in particular for social systems (Scheffer, 2010).
- **Self-organization:** This is the process by which spatial or dynamic structure is formed by a system through the many interactions between its parts, without a central controller. The spatial structure of the Grand Canyon, for example, is the result of the many interactions between water, rock, soil and microorganisms. Examples of living systems that self-organize are the coherent movement of flocks of birds and the lane formation in pedestrian movement.
- **Robustness** and **resilience:** These terms are often used interchangeably, but they have a somewhat different meaning. Robustness is, technically, the insensitivity to changing conditions and is usually used in the context of modelling assumptions or input to algorithms. In the context of environmental modelling, the robustness of an intervention is discussed with respect to variations in assumptions being made about the system. On the other hand, resilience is a system's ability to withstand or readjust after a perturbation to preserve a function, such as life. Farming communities may increase their resilience to food insecurity, caused by droughts and poor soil fertility, through earnings from relatives employed in urban areas. Ecological systems can exhibit resilience against species loss due to the adaptive behaviour of individual species.
- **Adaptive behaviour:** This is the purposeful change of behaviour of a system in response to changing circumstances while the system maintains a particular function. The US scientist John Holland, who pioneered much of the study of adaptive behaviour, defined systems with adaptive behaviour as "systems [that] change and reorganize their component parts to adapt themselves to the problems posed by their surroundings" (Holland, 1992). The notion of "adaptive behaviour" presupposes a notion of function, predominantly (and for some, exclusively) associated with living things. An example is a honeybee hive adapting to the changing temperature of the environment. The nest's core, where the queen and the brood are located, needs to be kept at a constant temperature. Honeybee hives can keep their nests at a remarkably constant temperature between 34ºC and 36ºC, even though the outside temperature

[3] Real-world wealth distributions are never exact power laws; only parts of the distribution follow an approximate power law.

may vary between -20ºC and +40ºC (Seeley, 2009). Bees achieve this by adapting their behaviour. If the outside is very warm, the bees form ventilation tunnels to increase the nest's air flow. If the outside is very cold, the bees raise their metabolism by flapping their wings, and thus they warm up the nest. The changing formation of a flock of birds following a predator's attack is another example of adaptive behaviour.

- **Memory:** This is the ability of a system to remember and use it for future action beneficially. For example, memory enables a bird to return to the nest site after a day out foraging for food. Memory is essential for the survival of any sophisticated organism. Memory can exist in a group as much as in individuals. The collective memory of foraging trails in an ant colony can go back many years, whereas individual ants have memory spans of only a few days (Gordon, 2010).
- **Modularity:** This is the division of a system into groups or modules performing separate functions. A honeybee hive is modular in its distribution of labour. Different groups of bees perform tasks such as the collection of pollen, nest maintenance or brood care. Modularity is not synonymous with isolated components. On the contrary, bees switch tasks depending on the need at any given moment. The human brain is very modular in its cognitive and motoric functionality. Here, too, parts are not in complete isolation in the sense that neural brain regions can take over tasks from areas that have been damaged. Modularity is associated with function. This is distinct from a clustered structure or the presence of structure within a structure, which is seen in many complex systems. An example is the structure of social groups. Smaller clusters of friends and family form one larger cluster of a local community. Many local communities form the bigger structure of a region or a country.

The features of complexity[4] discussed here are rarely independent of each other and can be mutually reinforcing. For example, species diversity is considered to contribute to an ecosystem's robustness (Page, 2010; McCann, 2010). The economist Andrew Haldane and the scientist Robert May have made specific recommendations to encourage modularity and diversity in the financial sectors to decrease systemic risk (Haldane and May, 2011). Often with complex systems, there is a healthy in-between. Strong local connectivity promotes local resilience because the effects of local perturbations are eliminated quickly. For instance, local damage to a coral reef may be repaired by “mobile link organisms” from nearby reefs, and individual banks may be saved by subsidiary inputs from the larger financial system (Couzin et al., 1999). On the other hand, strong global connectivity can promote vulnerability to collapse due to failure in one part of the system propagating in other parts of the system. Highly connected ecosystems may reach a tipping point where a local perturbation can cause a domino effect cascading into a systemic transition (Dakos et al., 2010). An analogous example in financial systems was the propagation of mortgage defaults in the United States to other economies through the tightly bound and invisible net of credit default swaps (Paul, 2008).

Table 1 lists the features of complexity that were just discussed, each with an example from the lake ecosystem.

[4] Ladyman and Wiesner (2020) additionally list nestedness and history, and they make a distinction between structural and functional robustness.

Table 1. Features of complexity, exemplified by a lake ecosystem

Attribute of complexity[5]	Example from a lake ecosystem
Many elements and many interactions	The many plants, algae and animals, and their mutual dependencies (feeding, predation, symbiosis).
Diversity	The many species of plants, algae and animals.
Feedback	The over-predation of a species and the resulting food shortage for their predator leads to a decrease in predator population and the subsequent recovery of the prey species.
Openness	The lake has an influx of water, nutrients and minerals, solar radiation and an outflux of water, nutrients and minerals and heat.
Self-organization	The flora and fauna species have equilibrated into a network of predator, prey and symbiosis relations.
Non-linearity	The composition of species can undergo sudden (and therefore non-linear) changes when driven across a tipping point by an external force, such as invading species or changes in chemical composition or temperature.
Robustness	The spatial distribution of rock formation, water flows, plant distributions and animal habitats is stable over time. The species composition and predator–prey network is stable over time concerning moderate variation of external factors such as temperature and chemical composition.
Memory	A fish species remembers breeding locations, across generations, that are safe for their offspring.
Adaptive behaviour	Some fish species have learned to use plastic debris to build safe housing.

B. Tools and methods of complexity science

Complexity science builds on and complements standard science. Complexity science, at least under this name, is a relatively young field of scientific investigation. The first research centre explicitly dedicated to the study of complex systems was founded in 1984 in Santa Fe in the United States. Scientific fields that complexity science has built on include non-linear dynamical systems theory, with the subfield of chaotic systems (e.g. Strogatz, 1996); cybernetics, pioneered by Norbert Wiener (1965) in the 1940s and 1950s; and systems theory, developed by Ludwig von Bertalanffy (1968) in the 1960s. The advent and rising power of computational devices has been critical for the development of all these fields. Computational tools continue to be core to the study of complex systems.

The mathematical and computational tools of complexity science have made important contributions to understanding, modelling and predicting complex phenomena in many science areas. The spread of epidemics is now routinely studied with complex network theory by incorporating knowledge concerning physical infrastructure and epidemiology into network models (Colizza et al., 2006; Vespignani, 2012; Brockmann and Helbing, 2013; see also Box 1 on the Severe acute respiratory syndrome [SARS] epidemic). The ecological stability of species, food webs and larger ecosystems is characterized by the mathematics of dynamical systems theory (Scheffer, 2010; Scheffer et al., 2012). Economic stability is often assessed using the theory of statistical mechanics and network theory applied to stock market data or macroeconomic variables (Sornette, 2006; Hausmann et al., 2014; Hidalgo and Hausmann, 2009). Economic behaviour can be modelled with computational agent-based modelling (e.g. Epstein and Axtell, 1996).

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[5] Attributes as identified in Ladyman and Wiesner (2020).

A standard methodology in complexity science is to abstract the particulars of a given system to allow the use of mathematical and computational tools that are independent of the particulars (Torres et al., 2020). An example is the predator–prey relations between animal species in a lake ecosystem. The relations between animal species are abstracted into links between nodes in a graph. This enables the use of analysis tools from graph theory and matrix algebra to study, for example, stability. In the following paragraphs, some examples of this methodology are given with different mathematical and computational tools applied in different science areas.

Fluid dynamics is the mathematical theory of the dynamics of liquids and examines phenomena such as the transition between linear and turbulent flow. Fluid dynamics theory and its numerical techniques are central in representing atmospheric and oceanic processes in climate models. They are also used to understand crowd dynamics, pedestrian flow and the transition from a uniform pedestrian flow to a stampede (Helbing et al., 2007).[6]

The last 20 years have seen the rise of a new type of mathematical model of human society, which has been inspired by analogies between social behaviour and the statistical properties of condensed matter physics. In these models, individuals' opinions or decisions are represented as “states of spin systems”, with interaction forces tailored to mimic the social interactions present in the system. Work in this tradition has come to be known as **sociophysics** (Galam, 2012). Schelling's pioneering work on neighbourhood segregation[7] is an early precursor of sociophysics models (Schelling, 1969). Although the models developed within this discipline are highly idealized, they have provided valuable insights. The model was used, for example, to explain the unexpected outcome in the French referendum on the European constitution (Galam, 2002).[8]

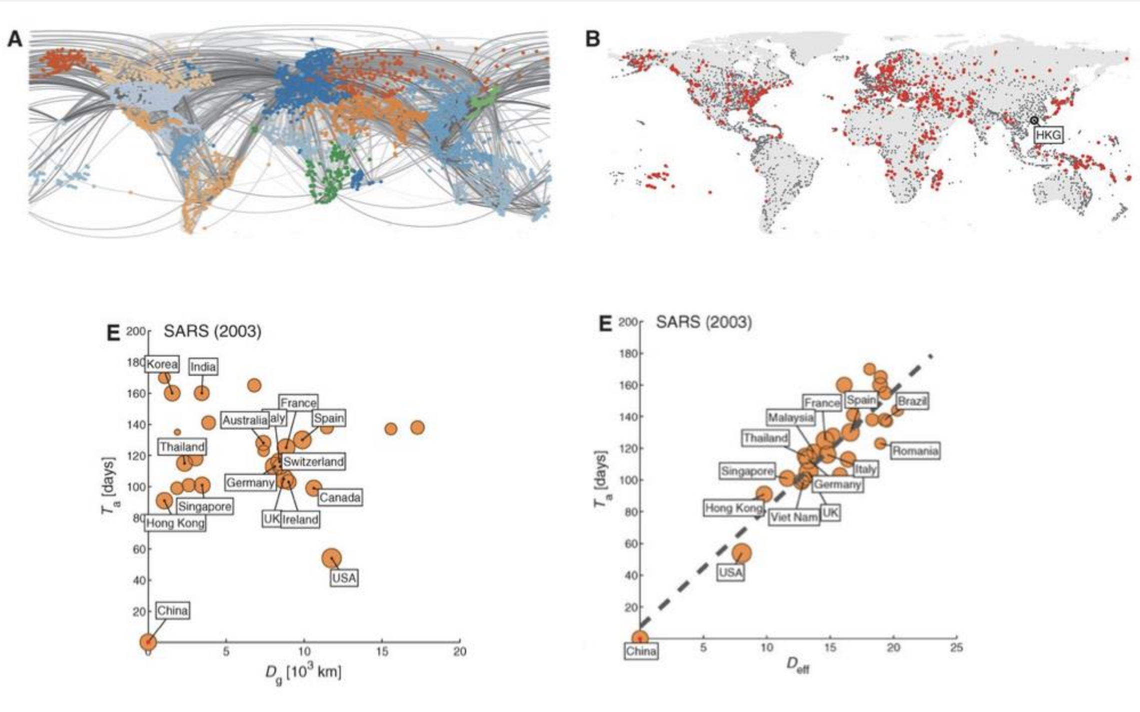
A host of studies have used the **theory of complex networks**, ranging from chemistry and biology to economic and social systems (Newman, 2003). Andrew Haldane, former Executive Director of Financial Stability at the Bank of England, advocated the complex network view as a much-needed new paradigm for financial economics (Haldane, 2009). A complex network view of the economy allows for the transfer of insights from other fields that have used complex network tools for much longer, such as ecology (Battiston et al., 2016). An example in practice is the SARS [Severe acute respiratory syndrome] epidemic in 2003 (see Box 1). SARS was successfully contained by the World Health Organization (WHO) in collaboration with officials, using tools beyond epidemiology, informed by complex network theory, web-based alert systems and air transportation control (Heyman, 2013).

[6] By video recording pedestrian flows in the pilgrim crowd during one of the annual hajj pilgrimages to Mecca and comparing it to the output of a fluid-dynamics model for the given spatial geometry, hotspots were identified where smaller turbulence can turn into stampedes. Subsequent interventions on the ground have made these hotspots less accessible, and in subsequent years the number of deadly incidents due to crowd panic reduced to zero (Spiegel, 2007).
[7] The Schelling model of segregation treats a population and its residences as a lattice of squares, each of which can be populated or not by one of two types of individual (Schelling, 1969). The system evolves according to the rule that individuals move on a given turn, if and only if they are surrounded by fewer individuals of the same type than some specified number. The stable states of such systems are highly segregated, in which most individuals are surrounded by others of the same type.
[8] In 1992, the French President Mitterrand decided to run a referendum on the Maastricht Treaty. While it was expected that a large majority would approve, in the final vote, only 51 per cent approved the Treaty. Schelling’s model predicted that the more people discussed the issue, the more influence a few contrarians would exert on the rest of the population. It was even conjectured that an additional two-week extension of the public debate would have flipped the outcome to a “No”.

Box 1. The SARS epidemic and the use of complex network theory

The **SARS epidemic** began with the first known case of atypical pneumonia in Guangdong Province, China (WHO, 2013). SARS is an infectious and deadly flu-like virus found in small mammals that mutated and infected humans. The speed and scale of the subsequent spread among the human population was enhanced by the global transportation network, which links major cities of the world as if they were neighbourhoods in a single city. The disease spread by air travel via Hong Kong to Vietnam and Canada. Four months after the first reported abnormal case, over 300 people had been infected worldwide and 10 had died. In a rapid response, WHO gave out guidance to travellers and airlines on what to do if someone exhibited symptoms. While infection spread, the number of infected grew exponentially. Six months after the outbreak, a total of 7,761 probable cases in 28 countries had been reported, with 623 deaths. The SARS virus was identified and its RNA sequenced six months after the outbreak began (Marra et al., 2003). Due to international collaboration in prevention measures and laboratory studies, two months later WHO was able to declare the SARS epidemic contained (Heyman, 2013).

The role of transportation networks in spreading the disease is illustrated in the study by Brockmann and Helbing (2013). The speed of the spread (depicted on the lower left-hand side) becomes predictable when the airline network is taken into account (the lower right-hand side shows speed as a function of effective distance, which is not a geometric distance but a function of travel time).



Source: Reproduction of the figures from Brockmann and Helbing (2013), used by permission for the use of AAAS material in a Government Policy Report for Academic/Non-Commercial requestors.

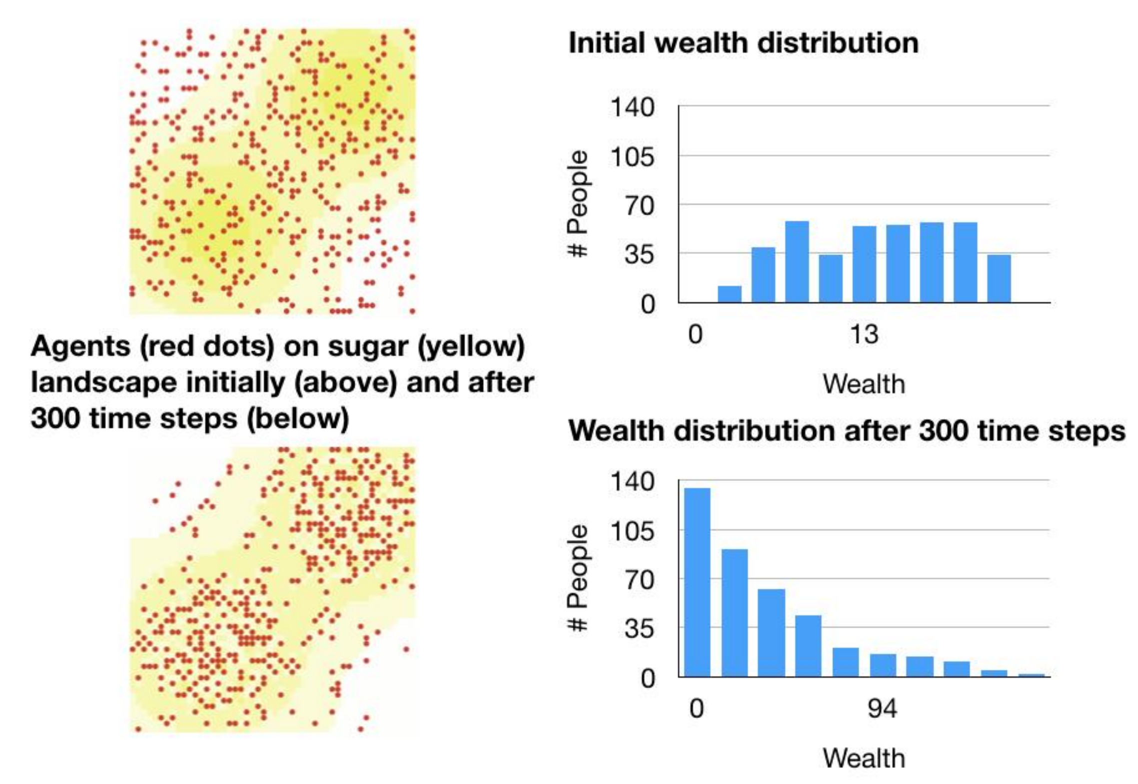
Agent-based models are a widely used tool for studying social dynamics, particularly in economics. These models are computational experiments that, if successful, reproduce the observed pattern of qualitative behaviour. In a computer simulation, a group of agents is equipped with a set of actions that each agent can execute and a set of (usually simple) rules defining the interaction between agents. In any given simulation round, an agent and an action are selected at random and, if the action is allowed for the given agent, executed. One experiment usually consists of many thousands of simulation rounds. One of the first agent-based models was the "sugarscape model", introduced by the American epidemiologist Joshua Epstein and computational, social and political scientist Robert Axtell (1996) (see Box 2).

Agent-based models are frequently used to study feedback in the dynamics of animal groups and to analyse, for example, the flocking of birds or the shoaling of fish. Couzin and Franks (2003) describe observations of army ants in Soberania National Park in Panama. The ants collectively choose a direction to march and form distinct traffic lanes to keep congestion at a minimum. The authors set up an agent-based simulation with simple movement and interaction rules for individual ants that mimic the observed lane formation and the low-level of congestion.

One of the first examples of agent-based models of coupled social–ecological systems (SES) is the Lansing and Kremer (1993) study of Balinese water temples and the emergence of locally organized sustainable and fair water management. Lansing and Kremer showed that the structure of water temple networks could have developed through a process of spontaneous self-organization rather than deliberate planning by engineers. They also showed in their simulation of water temple networks that the emergence of temple networks leads to higher harvest yields and improvement in coping with water shortages. Some more recent approaches to modelling interactions between ecological dynamics and social dynamics using agent-based models are reviewed in Bouquet and Le Page (2004).

Box 2. The sugarscape model

The sugarscape model is one of the first **agent-based models** to illustrate emerging inequality in wealth accumulation. An agent-based model is a grid of cells inhabited by "agents" (depicted as red circles). Some of the cells contain the resource "sugar" (yellow). Agents move on this landscape and "eat" when they find a cell containing sugar. The more sugar they find, the further they can move to find new sugar. Running the simulation with an initially equal distribution of wealth (sugar), this very simple set-up quickly generates a very unequal wealth distribution, where most agents have very few resources and only a handful own most of the resources (see right-hand side, below). Many different and more sophisticated versions exist. All sugarscape models include the agents (inhabitants), the environment (a two-dimensional grid) and the rules governing the interaction of the agents with each other and the environment. The simulation below, with an agent population of 400, was produced with the freely available software NetLogo (http://ccl.northwestern.edu/netlogo/).

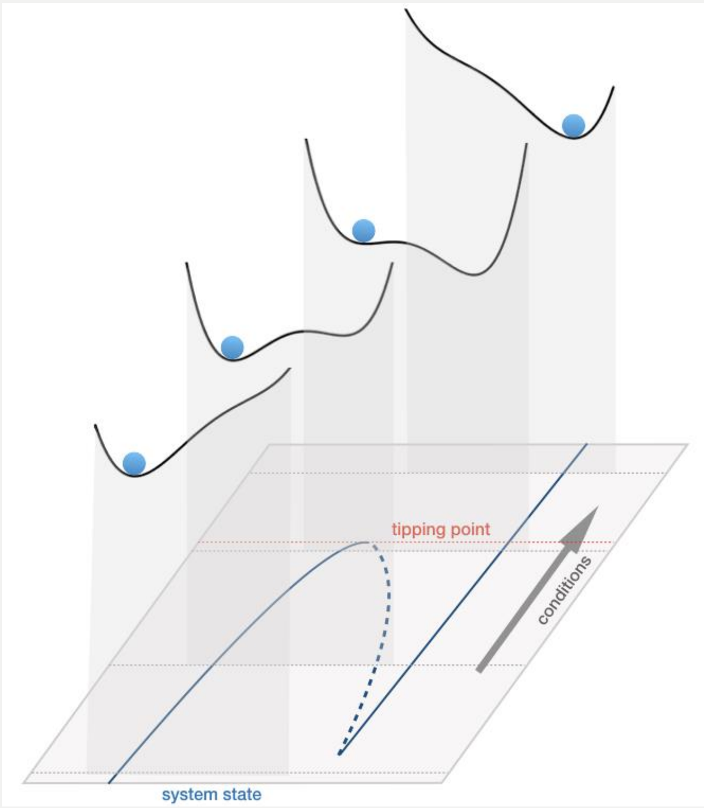


Predicting tipping points (see Box 3) in natural and social systems has received much attention – in particular, in connection to climate dynamics (Scheffer, 2010). Two main mathematical tools in use to study these sudden transitions are the **statistical mechanics** of phase transitions, and **dynamical systems** and bifurcation theory. A classic example of a phase transition in physics is the sudden solidification of water into ice upon a decrease of temperature below 0ºC. The onset of a phase transition is accompanied by an increase in the system's temporal and spatial correlations. The longer these correlations are, the closer the system is to a critical or phase transition. The theory of phase transitions for gases and liquids has found ample application outside of physics. For example, the statistics of earthquakes, stock market busts and other sudden transitions in natural and economic systems have been described by the mathematics of phase transitions (see, for example, Sornette, 2006).[9]

Coupled differential equations (see Box 4) are used to model the temporal evolution of a large variety of complex systems, including ecosystem population dynamics (Holmes et al., 1994) and economic performance (Cristelli et al., 2015). A simple, idealized example is the Lotka–Volterra predator–prey continuous dynamical system used to model the growth and decline of two species populations (Strogatz, 1996).

Box 3. Predicting tipping points

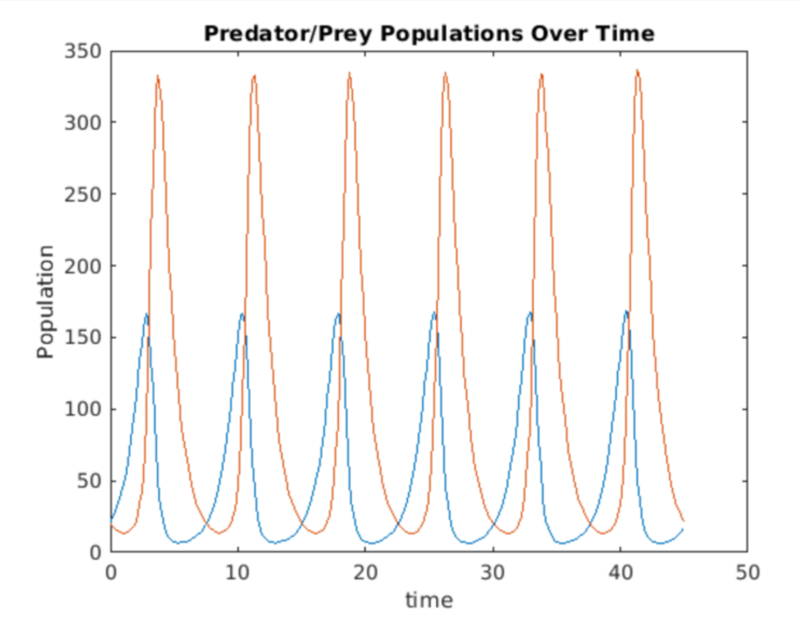
A generic model of tipping points. The system (depicted as ball) sits on a potential (black curve), which has one or two equilibrium states (minima), depending on the parameter setting (conditions). The position and stability of equilibrium states are determined by the (shaded) projection of the potential onto the "system state" curve underneath. Position and stability can suddenly change when conditions are changed across a threshold (tipping point). Imagine the system starts out in the lower left potential, then conditions are changed slowly. As a result, the potential slowly changes shape. The system remains in the left minimum, but at the tipping point the system suddenly changes from the left to the right minimum. The system strongly reacts to small perturbations when it is close to a tipping point.



[9] Related to the theory of phase transitions is bifurcation theory, which is the mathematical theory of qualitative changes in the topology of functions upon the quantitative change of parameters. Bifurcation theory, too, has found applications in complex systems. For example, it has been used to predict the onset of the monsoon in India (Stolbova et al., 2016). Rainfall data of the region and their spatial and temporal variation have proven sufficient to predict the sudden transition from dry weather to monsoon. Another example is a fire-induced bistability of tropical tree cover, which was shown to be caused by anthropogenic use and natural spatial heterogeneity (Wuyts et al., 2017). The instability was predicted to be much less when data of human-unaffected areas were included in the model. The book *Panarchy: Understanding transformations in human and natural systems* (Gunderson, 2001) contains an appendix on a non-linear model of eco-social system interactions.

Box 4. Coupled differential equations

The **Lotka–Volterra equations**, a pair of first-order non-linear differential equations, are frequently used to model the dynamics of biological systems. An example is the dynamics of a population of predator and prey species such as foxes and rabbits. The equations describe the mutually driven growth and decline in population size of two species, the prey x (orange line below) and its predator y (blue line below). There are four parameters, determining the speed of growth of the species.



For certain values of the parameters the numbers of individuals of each species oscillate. The overabundance of predators reduces the number of preys to below the level needed to sustain the predator population. At this point the number of preys begins to recover and the cycle begins anew. For oscillations to be sustained, the timescale of growth must be similar to the timescale of predation.

Viability theory is a combination of non-linear dynamics and control theory (Aubin, 1990, 2009). It is used to model the resilience of complex systems. In viability theory, a given system is represented as a set of coupled differential equations. The response to perturbations is modelled as deviations from stable fixed points in a possibly high-dimensional landscape of attractor basins. A similar, though mostly qualitative, use of the ideas is the representation of tipping points in climate and ecosystems as the transition from one stable manifold onto another due to perturbations of the dynamical system (Scheffer, 2010).

In a recent example, viability theory was used to define a metric for SES's resilience (Béné and Doyen, 2018). The metric was tested on theoretic models of exploitation of renewable resources, such as a non-linear dynamics model with one species harvested by a group of agents. Deffuant and Gilbert (2011) discuss case studies of resilience in ecology and society using viability theory.

Other mathematical approaches to ecology and social dynamics are based on **mathematical game theory** (see Dugatkin and Reeve, 2000). An example is the body of work on coupled SES and the tragedy of the commons by Elinor Ostrom and colleagues (Ostrom, 2015). A different body of work uses game theory to understand sudden transitions in large social groups from peaceful behaviour to political protest. Kuran (1987, 1997) developed such an approach, which was subsequently used to explain why some revolutions were hard to predict. In this approach, open-voting public choice processes are modelled: individuals choose what policy to advocate based on their private preferences, which they would express in a secret ballot. It turns out that they falsify their preferences when the benefits of doing so outweigh the costs. An implication is that a policy advocated for by few people in private might receive strong public support. Kuran concludes from his model that in a given group, the distribution of public preferences may shift significantly in response to a small shift in the distribution of private preferences.

C. SOCIAL–ECOLOGICAL ECONOMIC DYNAMIC SYSTEMS: SEEDS

The human–climate system is a conglomerate formed by human civilization and its planetary environment. Major, large-scale components of the human–climate system are the economy, ecosystems and human activity. Climate change mitigation and adaptation projects are interventions into regions of the human–climate system. These regions are smaller-scale systems that also contain economic, ecological and social components. We call these systems "social–ecological economic dynamic systems" (SEEDS).[10] A multitude of interactions couples their components.

Understanding the complexity of these systems requires an understanding of their composition and of the nature of interactions between the components. In this section, we introduce a diagnostic tool to decompose SEEDS into their components and interactions. The tool is designed to aid the design, management and evaluation of climate projects. Its output clarifies the relevant dynamics and interdependencies of components, and the consequences of feedback, non-linearities and other features of complexity (the complexity of SEEDS is discussed further in Section D). It is important to note the difference between a system's complexity and the complexity of an **intervention in a system.** The tool distinguishes between the SEED system and the project intervention in the system, a distinction that is not made in the relevant literature.[11] The complexity of a project intervention is dependent on the complexity of the system that is being intervened in. Understanding the complexity of an intervention is crucially dependent on this distinction.

In pioneering work, Elinor Ostrom (2007, 2008) introduced a framework for the analysis of SES that is now widely used in the qualitative analysis of community-based conservation (Berkes, 2007), water management problems (Meinzen-Dick, 2007) and similar areas. In its original form, the framework is briefly described in Appendix A. Ostrom, in many writings, cautioned against using simple models of linked SES and against the deduction of general solutions to the overuse of resources from such simple models. Here, we build on her diagnostic approach to increasing the prospects of future sustainable resource use. The result is a diagnostic tool for SEEDS, designed specifically to aid the Green Climate Fund (GCF) in its operation of climate mitigation and adaptation projects. The tool is presented in Section C.1. In Section C.2, three projects funded by the GCF are analysed with the new diagnostic tool. In Section D, an additional tool is introduced that scores the complexity of SEEDS and interventions in SEEDS based on the tool. The scoring tool is dependent on the output from the diagnostic tool.

1. A DIAGNOSTIC TOOL FOR SEEDS

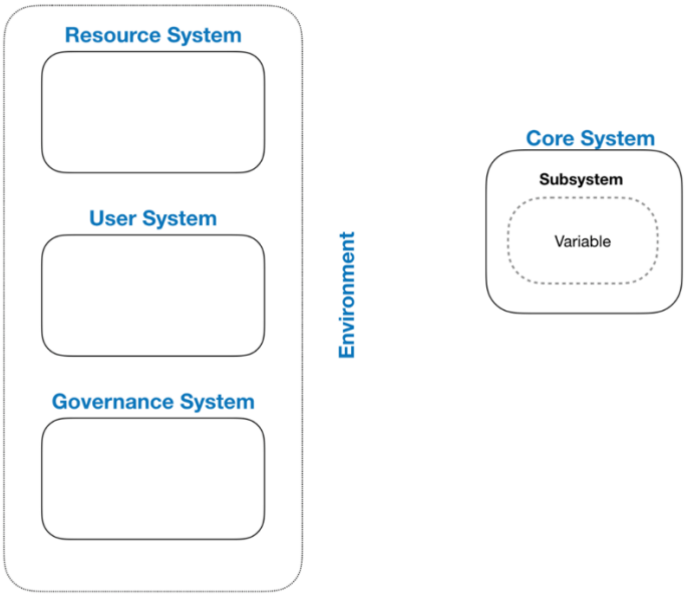
The search for solutions to complex social–ecological problems requires a systematic analysis of SEEDS relevant to the problem. A diagnostic tool is presented in the following section that facilitates a systematic analysis of a human–climate system and its components. These components might be natural resources, such as forest and ocean; social systems, such as villages and companies; and government structures, such as community governments and forestry services. The components

[10] The name illustrates the strong link of the work presented in this section to the work on social–ecological systems by the economist Elinor Ostrom (2007).

[11] The health-care profession, on the other hand, has at least taken notice of this (Shiell et al., 2008).

are coupled in a variety of ways, including through physical and social interactions. The diagnostic tool for SEEDS guides the user through a systematic identification of SEEDS components, their interactions and the processes relevant to their dynamic. The tool proceeds in three steps. The first step is based on Ostrom's conceptual approach to SES and focuses on identifying the system's components and subcomponents.[12] The second (and novel step) is to identify the interactions between the components and their cause-and-effect relations. The third step, also novel, is specific to interventions and identifies the components and interactions introduced to the SEEDS by the intervention. We proceed now to describe the analysis steps in detail.

Figure 1. Basic structure of SEEDS



Note: The three core systems – Resource System, User System and Governance System – are embedded in an environment. Each core system contains one or more subsystems, and each subsystem contains one or more variables.

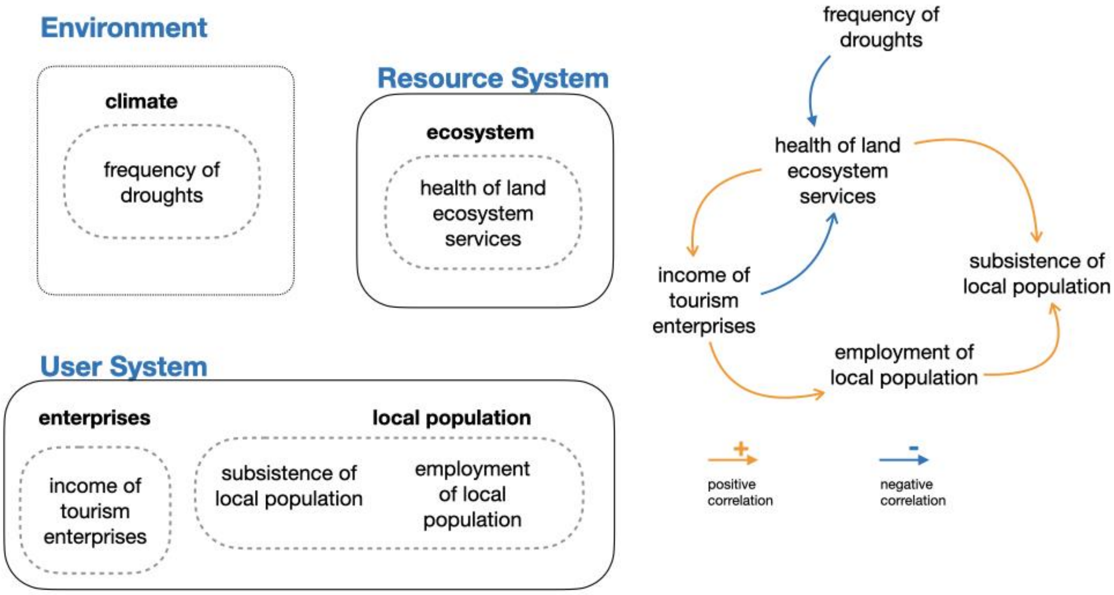
In a first step, the relevant components of a human–climate system are identified and assigned to one of three main components, the "core systems": the Resource System, the User System and the Governance System (Ostrom, 2009). The Resource System contains all the resources, such as fish, parks or renewable energy; the User System contains individuals or groups that use the resources, such as farmers, households and companies; and the Governance System contains all components involved in managing the system. Not all SEEDS contain all three core systems. The existing core systems are embedded in an environment that influences the core systems, such as climate or market conditions, but not itself affected by the core systems (this is the definition of "environment").

Within the environment and each of the core systems, existing and relevant subsystems are identified (Figure 2). For example, the Resource System might contain "ecosystems" and "water supply". The User System might contain "local population" and "tourism industry". Each of these subsystems has one or more variables. This approach only considers variables that are quantifiable or ordinal at the least. This is necessary for causation and correlations to be identifiable (see "second step" below). For example, a variable of the ecosystem might be the "health of the forest ecosystem services", which may be high or low. A variable of the local population might be its "subsistence", which might be increased by an intervention. In Appendix 2, a template list of possible subsystems

[12] This work deviates from Ostrom's original framework in the definition of core systems, subsystems and variables, and in the insistence that variables should be quantifiable.

and variables is given. The list is informed by existing GCF-funded projects and can be extended and modified as needed. Identifying the core systems, subsystems and variables of a SEEDS is not an automated process but results from the analyst's judgment. To reduce bias and omissions in the selection of variables, the SEEDS analysis may be done, for example, using expert elicitation techniques (Aspinall, 2010; Aspinall and Cooke, 2013). All available documentation may be used as the basis of a SEEDS analysis, including interviews and communication with people who are part of the system or involved in the project in some way.

Figure 2. Fictitious example of a SEEDS, with one environment variable, two core systems, three subsystems and four variables



A fictitious example of a SEEDS – a small island with an eco-tourism sector – is shown in Figure 2. This island SEEDS is embedded in an environment with the subsystem "climate" and the variable "drought frequency" and consists of two core systems: a Resource System and a User System. The Resource System contains the subsystem "ecosystem", with the variable "health of land ecosystem services". The User System contains the subsystem "enterprises", with the variable "income of tourism enterprises", and the subsystem "local population", with the variables "subsistence of local population" and "employment of local population".

In a second step, the list of core systems, subsystems and variables is linked into a network of interactions. To begin with, all those variables that "interact" are selected. Two variables are said to be interacting if a change in the former is expected to cause a change in the latter. For example, an increase in the health of the ecosystem has a positive impact on the income from tourism enterprises. Because the increase in one variable causes an increase in the other, this is a positive correlation. Another example is the increase in tourism, which will, in an unsustainable business model, negatively impact the health of the ecosystems. This is a negative correlation because the increase in one variable causes a decrease in the other. Figure 2 (right-hand side) shows the correlations in the fictitious example of the tropical island. The variables are the text labels, and two correlated variables are connected by an arrow that indicates the direction of causality. The arrow is blue if the correlation is negative. It is yellow if the correlation is positive. The environment is, per definition, unaffected by the core systems (otherwise, environment variables would be in one of the core systems instead). Therefore, there are only arrows from the environment to the core systems and never the other way around.

In a third step, the first two steps of the analysis are repeated with any planned interventions included in the SEEDS. For example, it might be planned that a village receives training in sustainable farming. In this case, the subsystem "education" is added to the Resource System, containing the variable "sustainable farming knowledge". Its positive impact on the variable "health of land ecosystem services" is added as an interaction. The SEEDS with the planned interventions included will be larger than the original SEEDS, with more interactions and often more components (subsystems and variables).

Once the two SEEDS representations are assembled, one "without" and one "including" project interventions, a complete overview of the human–climate region is achieved and is available for more quantitative insights. How the SEEDS representations can be used as a basis for a complexity analysis is discussed in the next section. Also, in the next section, we show the results of a SEEDS analysis of GCF-funded projects.

2. GCF PROJECTS AND THEIR SEEDS REPRESENTATIONS

The diagnostic tool introduced in the previous section is applied to three projects that have been funded by the GCF. For each project, a SEEDS representation is extracted from the funding proposal, following the methodology introduced in Section C.1. In discussions with the project management team, the relevant subsystems, variables and interactions have been identified.

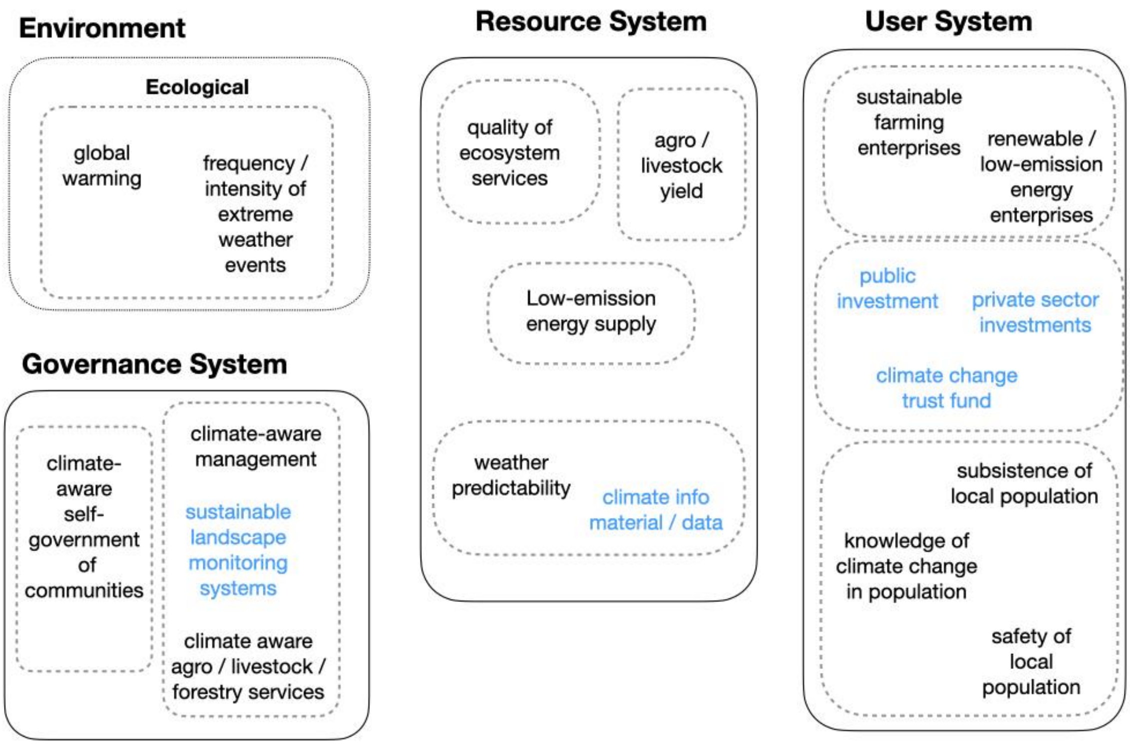
a. Sustainable Landscapes in Eastern Madagascar – GCF project proposal #026

The GCF project #026 (FP026) addresses smallholder farmers' economic and ecological vulnerability in two remote areas of Madagascar. Farmers are exposed to extreme weather events due to climate change; they rely on their harvest for survival and often go through periods of starvation. They have little to no safety net to secure them financially. They depend on local wood collection for fuel, and they are quite isolated from the rest of the country's energy supply and market. The GCF project addresses these issues by introducing sustainable farming techniques, running information campaigns on sustainable farming, linking local food producers with the national market, investing in alternative energy suppliers and providing financial infrastructure for start-up investments.[13]

The Madagascar SEEDS consists of an environment and the three core systems: User System, Resource System and Governance System. The subsystems and variables of the core systems can be seen in Figure 3. The environment contains an ecological component. Figure 4 shows the full SEEDS representation with all interactions identified by the authors in discussion with project managers. For readability, Figure 3 shows the core systems, subsystems and variables, whereas Figure 4 shows only the variables and interactions.

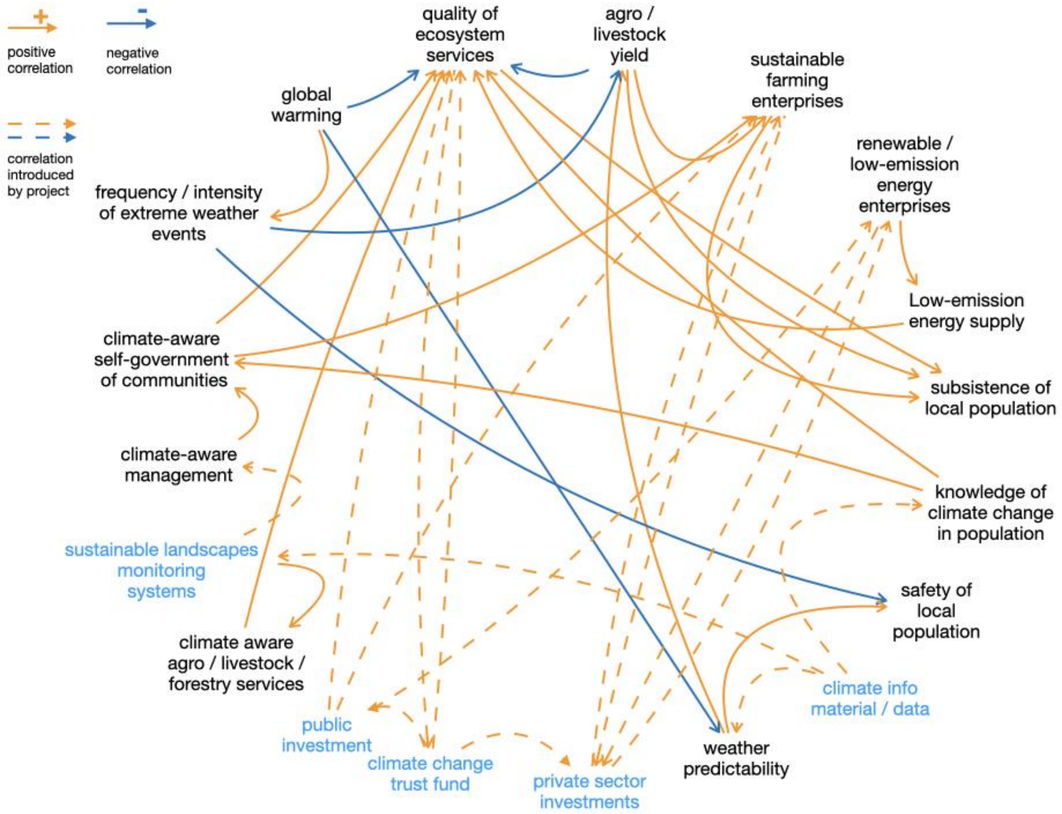
[13] More details on the Madagascar project can be found under https://www.greenclimate.fund/project/fp026.

Figure 3. Components of Madagascar SEEDS



Note: Dashed boxes are subsystems; items in blue are components introduced by the project.

Figure 4. Interactions of Madagascar SEEDS



Note: Items in blue are components introduced by the project. An orange line indicates a positive correlation, and a blue line indicates a negative correlation. Dashed lines indicate interactions that are newly introduced by the project.

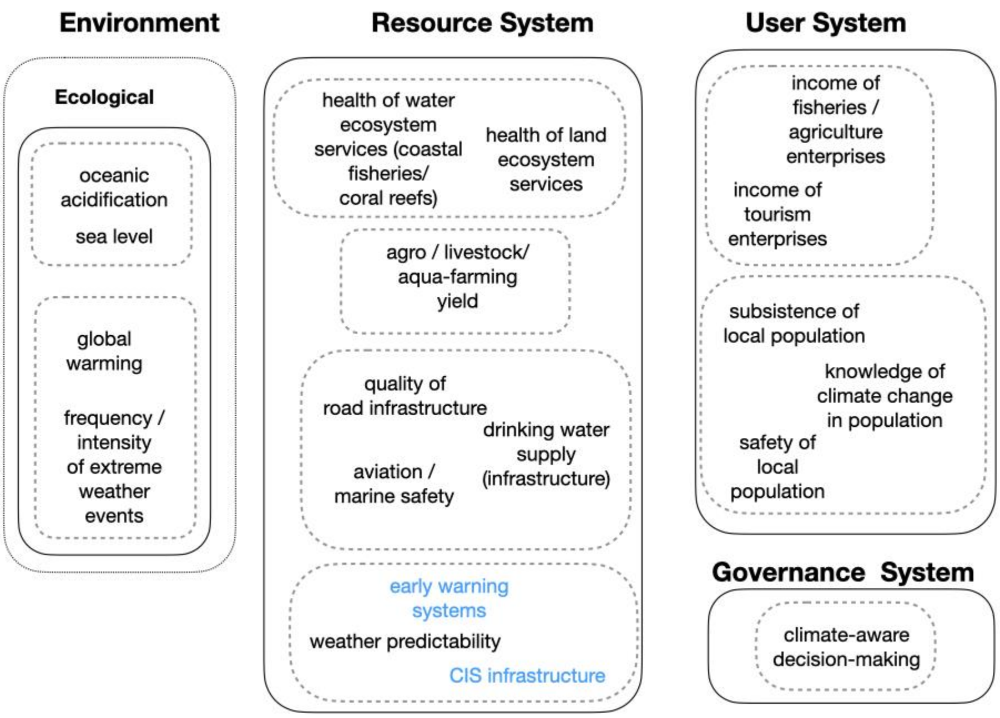
b. Information Services in Vanuatu – GCF project proposal #035

The GCF project #035 (FP035) addresses the extreme vulnerability to climate change of the Pacific island state of Vanuatu. Vanuatu's islands are increasingly exposed to extreme weather events such as cyclones and heavy rainfall, increasing ocean acidity and rising sea levels. Most of the islanders rely on agriculture, fishery or tourism for their income. The islands' road, air, and marine infrastructures are considered inadequately equipped for climate change's current and forecast effects. The proposal is to strengthen the existing climate information services (CIS) by supplying expertise, new equipment, new IT infrastructure and dissemination to the local population and government personnel.[14]

Figure 5and Figure 6 show the Vanuatu SEEDS with the relevant subsystems and interactions.

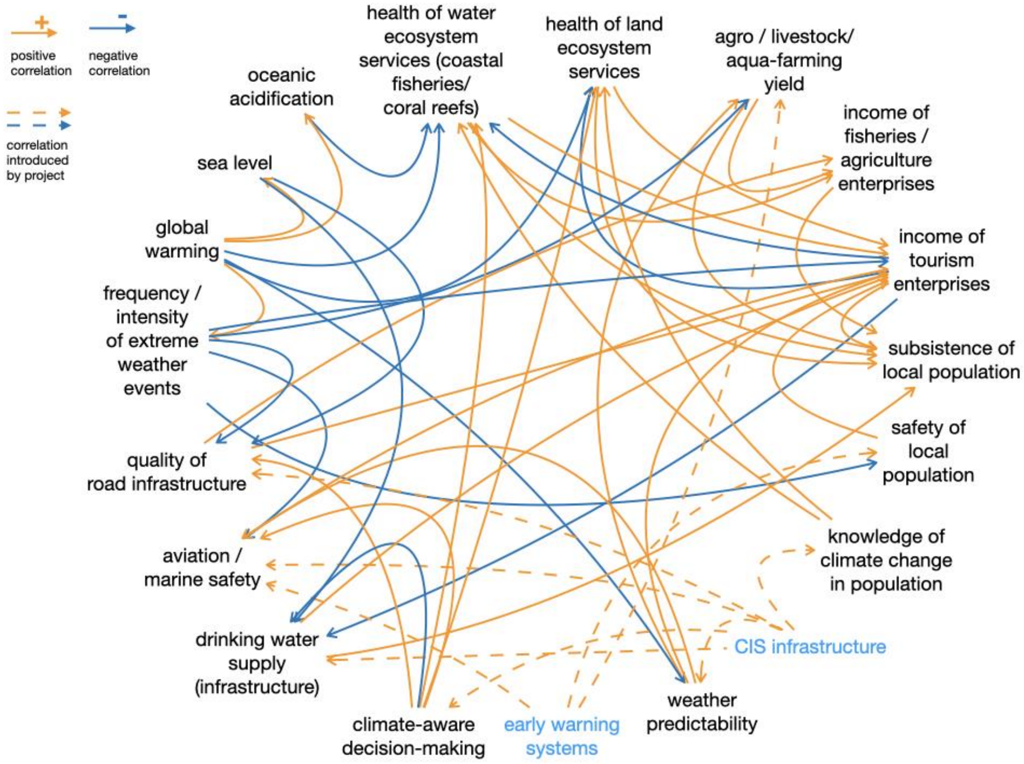
[14] More details on the Vanuatu project can be found under https://www.greenclimate.fund/project/fp035.

Figure 5. Components of the Vanuatu SEEDS



Note: Dashed boxes are subsystems; items in blue are components introduced by the project.

Figure 6. Interactions of the Vanuatu SEEDS

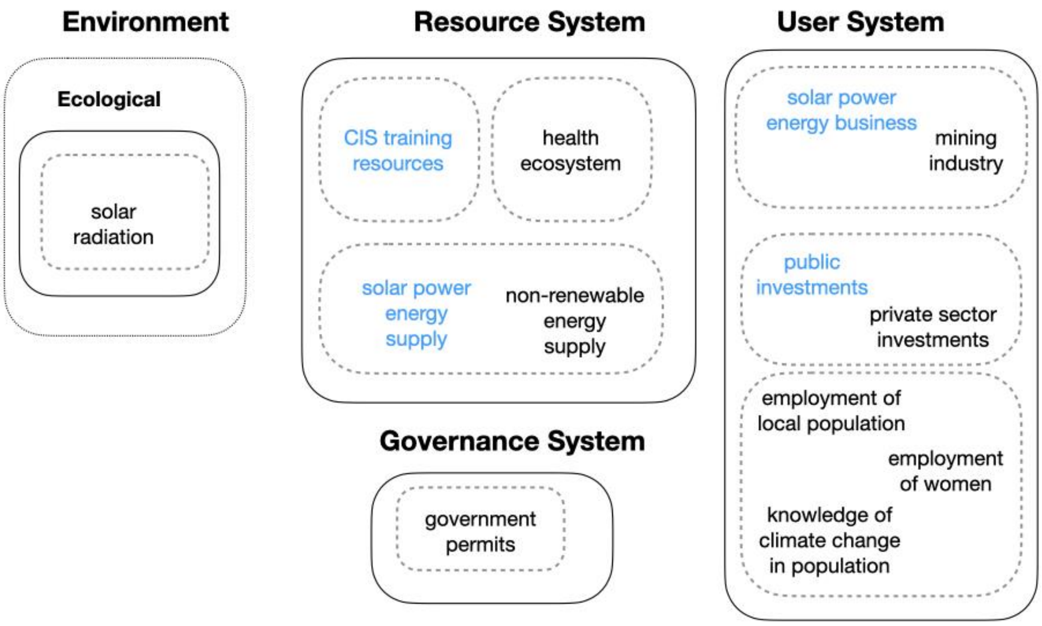


Note: Items in blue are components introduced by the project. An orange line indicates a positive correlation, and a blue line indicates a negative correlation. Dashed lines indicate interactions that are introduced by the project.

c. Climate Action and Solar Energy Development Programme in the Tarapacá Region in Chile – GCF project proposal #017

The GCF project #017 (FP017) addresses the lack of low-emission energy supply in Chile's northern region. The project provides access to loans for renewable energy projects and aims to demonstrate the benefit of investments in renewable energy projects with high upfront capital costs. The low resilience of the local population against climate change is also addressed. In discussion with the project management team, the role of government administration and regulation, such as the provision of energy permits, has also been identified as important. While not given prominence in the funding proposal, it is included as a SEEDS' component, shown in Figure 7.[15]

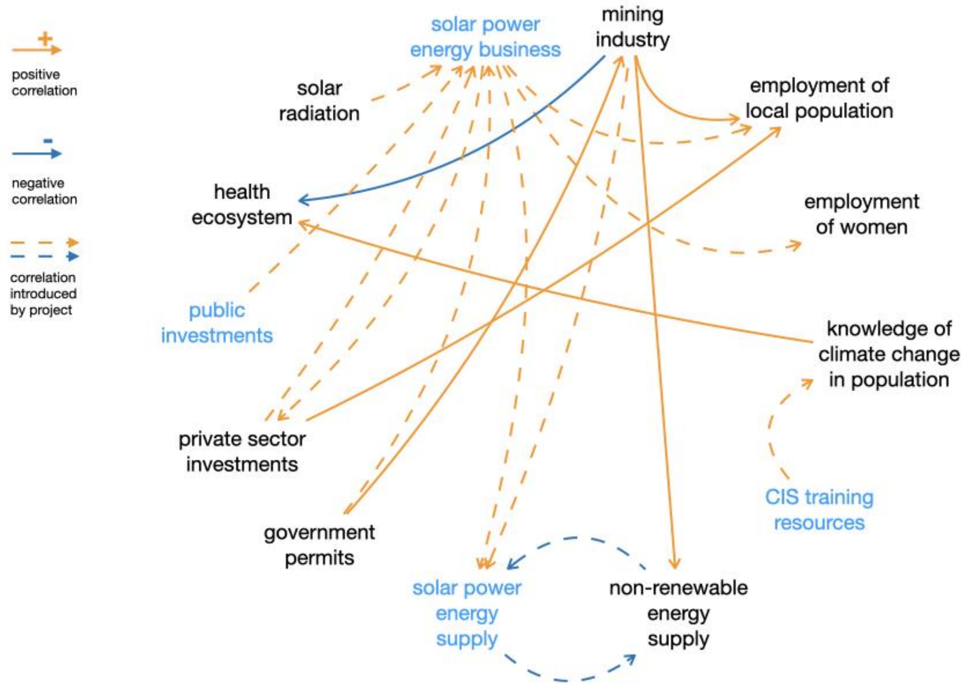
Figure 7. Components of the Chile SEEDS



Note: Dashed boxes are subsystems; items in blue are components introduced by the project.

[15] More details on the Chile project can be found under https://www.greenclimate.fund/project/fp017.

Figure 8. Components and interactions of the Chile SEEDS



Note: Items in blue are components introduced by the project. An orange line indicates a positive correlation, and a blue line indicates a negative correlation. Dashed lines indicate interactions that are introduced by the project.

d. Discussion

From the above representations of the three projects, it becomes clear that the Chile project is the smallest one, with the fewest variables and the fewest interactions. The project in Vanuatu has the most variables and interactions. On the other hand, the number of additional variables in the Vanuatu project is small compared to the number of existing variables. The environment is also strikingly different between the two systems. The relevant environment in the Chile project consists of a single and relatively predictable variable. Vanuatu's situation is very different, with many environmental variables, including many that are difficult to predict. The consequences for the difficulty of project management and evaluation are not easily generalizable but need to be assessed on an individual basis in discussion with project managers and evaluators. The SEEDS representation is a compact yet holistic summary of the project, designed to aid this discussion.

An IEU working paper provides an example of the advantage of a SEEDS representation in terms of variables and interactions:

> Programming on clean cookstoves that ignore household power dynamics are likely to be unsuccessful: Good-quality stoves have substantial health benefits for women who cook but little impact on the men who oversee buying the devices. Cookstove programmes must address financial empowerment and power dynamics within a household to successfully target women’s health (Fiala et al., 2018).

If the variables “male power”, “women’s financial independence” and “women’s health” are identified, their interaction is more likely to be realized.

Table 2 gives some examples of the use of a variable/interaction representation of SEEDS.

Table 2. Examples of SEEDS features and their relevance to climate projects

SEEDS FEATURE	EXAMPLE	RELEVANCE FOR PROJECT
Importance of interactions	The power relation between men and women in a family	Relationships can cause feedback, and hence unexpected dynamics
Importance of variables	Quality of energy grid infrastructure	A single variable can disrupt desired feedback loops
Importance of the environment	Cheap gas supply underbidding solar energy prices	Environment variable may dominate the dynamics
Has the boundary Environment / Core Systems been drawn correctly?	Permit provision by government	Unpredicted feedback loops
Importance of human component (Environment)	Spontaneous shareholder decision to disinvest in market	Source of uncertainty
Importance of human component (User System)	Culture of distrust towards modern technology	Resilience to change

Many more lessons can be drawn from the variable/interaction representation of SEEDS. The goal of this report is to indicate how to learn from these lessons. More work, in collaboration between project managers and evaluators, is needed to draw up a full catalogue of such lessons. For example, the number of variables and the number of interactions is the first item on the list of complexity features (Table 1), but more in-depth analysis is now possible. Feedback loops can be identified, for example. The fictitious example of the tropical island shows one feedback loop, between “health of land ecosystem services” and “income of tourism enterprises”. The dynamics of feedback loops can be highly non-linear, with sudden and drastic changes occurring in a small amount of time. Hence, knowing the existence of feedback loops is important for any project intervention. Their careful monitoring can be crucial for the success of the project. The many ways the SEEDS representation aids the complexity analysis, including a complexity rating, are explained in the next section.

D. MEASURING COMPLEXITY OF SEEDS

While measurement is a core activity of any science, “complexity” cannot be measured as a single quantity since it is an aggregate phenomenon. It is also more fruitful to focus on modelling complex phenomena as opposed to measuring complexity. Many a “complexity measure” has been suggested in the literature. Such measures can only ever assess complexity features and never capture the entire property of complexity. This is because, as we saw in Section A, this property is a composite of many properties. If there was a single measure of complexity, it would, by definition, compress the many features of complexity into a single number (Gell-Mann, 1995; Ladyman et al., 2013; Ladyman and Wiesner, 2020). Examples of measures of individual features of complexity are “species diversity of ecological systems” (Jost, 2006), “stability in ecological dynamical systems” (Scheffer et al., 2012), “risk in financial networks” (Haldane and May, 2011) and “economic diversity of countries” (Tacchella et al., 2012). DeCoste and Puri (2018) made an initial proposal for a complexity assessment of development programmes. Another procedure was introduced by Bamberger et al. (2015). Here, we suggest a procedure for a complexity score fully supported by the complexity science concepts summarized in Section A. The score is an aggregate of 10 features of complexity. A scoring procedure is provided that is based on and requires the variable/interaction representation of SEEDS introduced in the previous section.

1. A COMPLEXITY SCORE

We begin by revisiting eight of the 10 features of complexity from Section A: many elements and many interactions (size), diversity, feedback, adaptive behaviour, non-linearity, memory, nestedness and openness.[16] These features of complexity are now aggregated into a complexity score. While Section B explained how these features are measured in specific sciences, the nature of development programmes is such that none of these measures can be applied directly. However, the mathematical tools of complex networks and non-linear dynamics, for example, are still very useful. Here, they are used to inform measures of complex systems features that apply to development programmes. Each feature can be assessed from the variable/interaction representation of SEEDS as follows:

- **Size:** There are two measures of size: the number of variables and the number of interactions. The number of SEEDS' variables is the combined number of stakeholders involved, the number of decision makers and users, and the number of resources. The number of interactions between these variables is the number of links in the diagram and determines the system's dynamics. It is important to account for both the number of variables and the number of links. Therefore, there are two measures for "size". The environment's variables and interactions are accounted for under a different feature (see "Openness" below).
- **Diversity:** A SEEDS is divided into subsystems, which allows for a distinction between the types of stakeholders, the types of resources and other types of variables. Hence, the number of subsystems is a measure of the diversity of the SEEDS.
- **Feedback:** To capture the amount of feedback in the system, each interaction is assigned a timescale: short (a few weeks), medium (a few months to 1–2 years) and long (years or decades). These timescales are the times in which the relevant dynamics happen. For example, supplying a village with solar power could be completed in a short timespan if it involves only setting up solar panels and batteries. Alternatively, it could take months to build a solar power plant and a local power grid. Generating income for the local population from tourism will be on a medium timescale, whereas the benefit from an early warning system for extreme weather events will have an immediate effect and thus counts as short timescale. Feedback is taking place when processes on similar timescales interact. To measure feedback, the closed loops in the interaction diagram are identified. Those that consist of interactions on the same timescale are counted and act as a proxy for the amount of feedback in the system.
- **Adaptive behaviour:** There is no unique way to quantify adaptive behaviour. But a first proxy is the number of interactions that involve human behaviour. For consistency, we define such an interaction as any interaction that begins or ends with a variable in either the Governance or the User System. The number of these interactions is taken as a proxy for adaptive behaviour. Of course, this is rough and incomplete because, for example, it neglects any adaptive behaviour of the ecosystem.
- **Non-linearity:** Two processes that interact are likely to produce a non-linear change in the variable they affect. Thus, the number of variables with more than one incoming edge is a proxy for the system's non-linearity. For example, suppose the subsistence of a local population depends on the mining industry, the local ecosystem and the solar energy business. In that case, the subsistence might show sudden changes, although any of the influencing processes only change slowly.

[16] The feature "modularity" has been omitted from the set of features for two reasons. First, modularity has been recognized to be difficult to measure (Newman and Girvan, 2004). Second, various approaches by the authors have led to very similar scores for the three example projects. Hence, modularity is likely to be present in all GCF development programmes, and likely to a similar amount. Self-organization is also excluded, since it is the process by which other features arise, such as memory and nestedness.

- **Memory:** Memory in the system is the persistence of states or dynamics over time. A proxy for this is the number of medium- and long-term processes that have been identified previously under “feedback”. The number of interactions on a medium or long-term timescale is taken as a proxy for memory in the system.
- **Nestedness:** All SEEDS consist of at least two levels: the core systems and the subsystems. The number of subsystems with more than one variable is taken as a measure of nestedness.
- **Openness:** Two measures contribute to openness: the number of variables in the environment and the number of interactions between them and the system. Both contribute to the amount of exposure of the system to its environment.

To assess a project's complexity, the complexity assessment is done twice, once scoring the SEEDS of the system without the project interventions and once scoring the SEEDS including the interventions. **The difference in score is a measure of the complexity of the project.**

Table 3 lists all the complexity features just discussed and how they are estimated from the SEEDS representation. The 10 categories that are scored are aggregated into an overall score of a system’s complexity. The first column labels the feature of complexity that is assessed. The second column describes the property of the SEEDS that is a proxy for the feature. The subsequent five columns specify the range for each score, scoring goes from 1 to 5. The last column contains the description of the complexity feature in the context of climate projects. The aggregate complexity score goes from 10 (minimal complexity) to 50 (maximal complexity). The distinction between the system and the intervention, which was emphasized in Section A and above, can be made quantitative using this scheme.

Table 3. The 10 features of complexity that are used for a complexity scoring

Feature	Property	Scoring range					Description of feature
		1	2	3	4	5	
Size (V)	Number of variables (excl. environment)	<5	5–9	10–14	15–20	>20	Few/many stakeholders, resources, ecosystems, etc.
Size (I)	Number of interactions between (non-environmental) variables	<5	5–10	11–20	21–30	>30	Few/many interactions between stakeholders, resources, ecosystems, etc.
Diversity	How many subsystems (excl. environment)	<4	4–8	9–12	13–16	>16	Few/many types of stakeholders, resources, organizations with similar/dissimilar interests, needs, etc.
Feedback	Number of loops with dynamics on similar timescales	0–1	2–3	4–5	6–7	>7	Well-separated timescales / many processes and overlapping timescales
Adaptive behaviour	Number of social interactions	<5	5–10	11–20	21–30	>30	Social dynamics irrelevant/dominant
Non-linearity	Number of multiple-input nodes	<5	5–9	10–14	15–20	>20	Single linear causal chain / multiple non-linear causal relations
Memory	Number of medium and long	<5	5–10	11–20	21–30	>30	Relevant dynamics are fast/slow

FEATURE	PROPERTY	SCORING RANGE					DESCRIPTION OF FEATURE
		1	2	3	4	5	
	timescale processes						
NESTEDNESS	Number of multivariable subsystems (excl. environment)	<4	4–8	9–12	13–16	>16	Subsystems have no / have substructure
OPENNESS (L)	Number of links from the environment	0–1	2–3	4–5	6–7	>7	Quite independent of / very dependent on external influences
OPENNESS (V)	Number of variables in environment	0–1	2–3	4–5	6–7	>7	External influences are few/many

Note: The values in the middle cells give the range of values for each score.

The project intervention's complexity is scored by taking the difference between the SEEDS' score without the intervention and the score including the intervention.

a. Complexity scoring by Bamberger, Vaessen and Raimondo

In Chapter 1 of their book *Dealing with Complexity in Development Evaluation*, Bamberger, Vaessen and Raimondo (2015) (shortened to BVR for this report) propose a complexity score of development programmes. The scoring system comprises four "dimensions", each with a number of variables; there are 25 variables in total. The score for each variable is between (1) low and (5) high. The final complexity score is a weighted average with a minimum of 20 and a maximum of 100.[17] The purpose of the BVR scoring is similar to the purpose of the scoring introduced in this section. Hence, it is briefly discussed here. They differ substantially but do not necessarily contradict each other. Whether and how to merge these two complexity scorings is beyond the scope of this report.

The similarities of the complexity scorings lie in the choice of some of the variables, whereas the main differences are in the assessment procedure. The BVR scoring is obtained through the evaluator's judgment for each variable. The scoring introduced in this section, on the other hand, is based on the SEEDS structure. The SEEDS structure is, to some extent, also based on human judgment rather than objective measurement. However, once the relevant variables and interactions of the SEEDS are agreed on, the complexity scoring follows objectively. The BVR scoring, on the other hand, has independent subjective judgments in every variable.

There are some similarities in the choice of variables that are being scored. For example, BVR use the variable "few or many funding and implementing agencies", which is similar to the first measure of size in Table 3 but ignores the second measure, the number of interactions. The BVR variable "Single vs multiple causal pathways" is similar to the measure of non-linearity. The variable "Stakeholders with similar/diverse interests" is similar to the measure of diversity. The BVR item "Simple/complex processes of behavioural change" is similar to the measure of adaptive behaviour. The BVR variables are grouped into four dimensions of "intervention complexity": (1) the nature of the intervention, (2) interactions among institutions and stakeholders, (3) causality and change, and (4) embeddedness and the nature of the system. Hence, the BVR scoring tries to differentiate between the system and the intervention by separating the variables into two different dimensions, whereas our scoring extracts the difference in a before/after analysis. Arguably, the latter is more in

[17] Bamberger et al. published a revised table on the web after the publication of the book, available here: https://www.unicef.org/evaluation/files/Revised_Complexity_Checklist__.pdf and in Appendix C.

line with the idea that the intervention cannot be separated from the system that is intervened in. Another main difference between the two complexity scorings is that the scoring introduced here is based on the features of complexity as identified by complexity science.

The book by BVR can be seen as complementary to this report. It makes many connections between the concepts of complexity and the practice of evaluation. It draws more heavily from the social science literature on complexity, whereas this report is grounded within the natural science literature on complexity.

In addition to the four dimensions of intervention complexity listed above, BVR consider four dimensions of evaluation complexity: (1) the purpose of the evaluation, (2) the choice of evaluation design, (3) budget and time constraints, and (4) the value orientation of both stakeholders and evaluators and the methodological preferences of the client(s) and other key stakeholders.

It should become clear from these excerpts of the BVR framework that it borrows concepts from complexity science but stays firmly within the discipline of evaluation. On the other hand, the framework presented in this report stops short of giving a complete picture of the evaluation process. There is scope for natural and social scientists and evaluation experts to look for ways to merge these approaches.

In the next section, the three GCF projects discussed in Section C.2 are scored using the variable/interaction representation of the SEEDS and the complexity scoring procedure introduced in Section D.1.

2. GCF PROJECTS AND THEIR COMPLEXITY SCORING

The variable/interaction representation of each SEEDS discussed in Section C is given in tabular form in Appendix 4. All measures introduced in Section D.1 that enter into the complexity scoring of a SEEDS are extracted from its tabular representation. The minimum complexity score is 10, the maximum is 50. Table 4 through Table 6, one for each of the three selected GCF projects, give two scores, one for the system and one for the intervention. For example, the Madagascar project and the Vanuatu project have a similar score, but the intervened system is more complex in the Vanuatu case. The Chile system is a low-complexity system, and with the intervention included, it is of low-to-medium complexity. The consequences for management and evaluation are the subject of future work.

a. Sustainable Landscapes in Eastern Madagascar – GCF project proposal #026

The complexity scorings for the Madagascar SEEDS are given in Table 4. It is worth commenting on the feedback rating. Three feedback loops were identified: one between “quality of ecosystem services” and “climate change trust fund”, a second between “private sector investments” and “sustainable farming enterprises”, and a third between “renewable/low-emission energy enterprises” and “private sector investments”. Loops between more than two variables were not identified, but some loops share one variable, which results in a coupling between them. All feedback loops are self-enhancing, which in the case of this project is by design. All feedback loops involve interactions on a medium timescale.

Table 4. Madagascar complexity rating (without/including intervention)

Feature	Property	Rating	Scoring range					Description of feature
			1	2	3	4	5	
Size	Number of variables (excl. environment)	12 / 17			x	x		Few/many stakeholders, resources, ecosystems, etc.
	Number of interactions between (non-environmental) variables	16 / 35			x		x	Few/many interactions between stakeholders, resources, ecosystems, etc.
Diversity	How many subsystems (excl. environment)	8 / 9		x	x			Few/many types of stakeholders, resources, organizations with similar/dissimilar interests, needs, etc.
Feedback	Number of loops with dynamics on similar timescales	0 / 3	x	x				Well-separated timescales / many processes and overlapping timescales
Adaptive behaviour	Number of social interactions	13 / 31			x		x	Social dynamics irrelevant/dominant
Non-linearity	Number of multiple-input nodes	6 / 11		x	x			Single linear causal chain / multiple non-linear causal relations
Memory	Number of medium and long timescale processes	13 / 31			x		x	Relevant dynamics are fast/slow
Nestedness	Number of multivariable subsystems (excl. environment)	3 / 5	x	x				Subsystems have no / have substructure
Openness	Number of links from the environment	4 / 4			x x			Quite independent of / very dependent on external influences
	Number of variables in the environment	2 / 2		x x				External influences are few/many
Score								23 / 34

b. Information Services in Vanuatu – GCF project proposal #035

The complexity scorings for the Vanuatu SEEDS are shown in Table 5. Here, too, it is worth commenting on the feedback rating. Three feedback loops were identified; all three are stabilizing cycles and were already present before the intervention. One cycle is between "drinking water supply (infrastructure)" and "income of tourism enterprises", the second is between "income of tourism enterprises" and "health of water ecosystem services (coastal fisheries/coral reefs)", and the third is between "health of land ecosystem services" and "income of tourism enterprises". All three involve the variable "income of tourism enterprises". The difference between the system's score without and including the intervention is not that big, an increase of three only. The project adds a large number of links, but it adds them to a system that is already highly linked.

Table 5. Vanuatu complexity rating (without/including intervention)

FEATURE	PROPERTY	RATING	SCORING RANGE					DESCRIPTION OF FEATURE
			1	2	3	4	5	
SIZE	Number of variables (excl. environment)	13 / 15			x	x		Few/many stakeholders, resources, ecosystems, etc.
	Number of interactions between (non-environmental) variables	25 / 34				x	x	Few/many interactions between stakeholders, resources, ecosystems, etc.
DIVERSITY	How many subsystems (excl. environment)	7 / 7		x x				Few/many types of stakeholders, resources, organizations with similar/dissimilar interests, needs etc.
FEEDBACK	Number of loops with dynamics on similar timescales	3 / 3		x x				Well-separated timescales / many processes and overlapping timescales
ADAPTIVE BEHAVIOUR	Number of social interactions	25 / 28				x x		Social dynamics irrelevant/dominant
NON-LINEARITY	Number of multiple-input nodes	8 / 10		x	x			Single linear causal chain / multiple non-linear causal relations
MEMORY	Number of medium and long timescale processes	22 / 27				x x		Relevant dynamics are fast/slow
NESTEDNESS	Number of multivariable subsystems (excl. environment)	4 / 5		x x				Subsystems have no / have substructure
OPENNESS	Number of links from the environment	9 / 9					x x	Quite independent of / very dependent on external influences
	Number of variables in the environment	3 / 3		x x				External influences are few/many
SCORE								30 / 33

c. Climate Action and Solar Energy Development Programme in the Tarapacá Region in Chile – GCF project proposal #017

The Chile SEEDS identifies two feedback loops: the loop "non-renewable energy supply" – "solar power energy supply" is a loop of negative correlations; the loop "solar power energy business" – "private sector investment" is a self-enhancing loop of positive correlations. Both are on a medium timescale and were introduced by the project.

Table 6. Chile complexity rating (without/including intervention)

Feature	Property	Rating	Scoring range					Description of feature
			1	2	3	4	5	
Size	Number of variables (excl. environment)	8 / 12		x	x			Few/many stakeholders, resources, ecosystems, etc.
	Number of interactions between (non-environmental) variables	6 / 17		x	x			Few/many interactions between stakeholders, resources, ecosystems, etc.
Diversity	How many subsystems (excl. environment)	6 / 7		xx				Few/many types of stakeholders, resources, organizations with similar/dissimilar interests, needs etc.
Feedback	Number of loops with dynamics on similar timescales	0 / 2	x	x				Well-separated timescales / many processes and overlapping timescales
Adaptive behaviour	Number of social interactions	17 / 23			x	x		Social dynamics irrelevant/dominant
Non-linearity	Number of multiple-input nodes	2 / 6	x	x				Single linear causal chain / multiple non-linear causal relations
Memory	Number of medium and long timescale processes	3 / 10	x	x				Relevant dynamics are fast/slow
Nestedness	Number of multivariable subsystems (excl. environment)	1 / 4	x	x				Subsystems have no / have substructure
Openness	Number of links from the environment	1 / 1	x x					Quite independent of / very dependent on external influences
	Number of variables in environment	1 / 1	x x					External influences are few/many
Score								15 / 22

E. Implications of complexity for development programme management and evaluation

> Programmes can be simple, but in the real-world of development programming it is more likely that they are or have elements that are complicated or complex. Since TOC [theory of change] products and processes can be used to support all aspects of programme planning and implementation, they need to recognize complexity, and the resulting uncertainty it brings, so that they better reflect the reality of the programme. (Goodier and Apgar, 2018).

While complexity is often perceived as the problem, it also offers solutions. The question is: how do we deal with the increase in uncertainty and unpredictability in complex systems in the context of climate mitigation and adaptation projects? Here, some conclusions are drawn from the previous sections regarding monitoring, managing and evaluating such projects. The Institute for Development of the Swiss Agency for Development and Cooperation is one among few that have begun thinking along these lines (Goodier and Apgar, 2018). Olsson et al. (2004) discuss case studies of unconventional approaches to the management of ecosystems.

For the successful implementation of climate programmes, it is important to realize that the human–climate system that is intervened in and the interventions themselves are interlinked and form a complex system. Since the intervention is not separate from the system, its management also becomes part of the system. In the following paragraphs, some guidelines are suggested for complexity-aware and complexity-based management and evaluation.

The result of self-organization is inherently difficult to predict or control and, even in hindsight, often difficult to explain. In other words, the causal pathways for self-organization and human behaviour are often unknown. Hence, a traditional theory of change is often not applicable to complex systems, especially when they involve human behaviour. If causal pathways are difficult or impossible to construct, a theory of change is necessarily incomplete. Rather than predicting the impossible, a better way to prepare for project implementation is to put in place an adaptive theory of change that is evolving together with the project. Initially unknown developments can be incorporated once they become known, as this example illustrates: “For programmes that may change the price of items in a market, such as the cost of credit or the price of specific inputs such as wood for households, this could lead to an increased take-up in other services that are not climate friendly” (Fiala et al., 2018). The approach needs to be flexible and be prepared for, but not assume, the increased take-up in other climate-unfriendly services. A flexible approach also avoids deploying resources unnecessarily. Finally, while acknowledging that there are feedback loops, most traditional programme design and evaluation systems do not do much in either design or while assessing linkages to recognize this. The framework laid out in this paper provides a first step in this direction.

> Government is an evolving institution, and can evolve in different ways. Complexity policy includes policies that affect government, and the role of government will change with the problems and the current state of the government (Colander and Kupers, 2014, p. 182).

Colander and Kupers think of policy and government in the same way we should think of development projects and complex human–climate systems. A complex system is always evolving and adapting to external change. Accurate prediction of the future dynamics of a complex system and its components is often not possible. Therefore, **a project’s management will benefit from having a structure in place that is adaptive and has decision cycles on a similar timescale to the system’s timescale**. If system elements and relevant management procedures operate on similar timescales, a timely response to an unexpected event is facilitated.

The effects of feedback often become visible only once the programme has started, as in the following example:

> [W]hen clean cookstoves are introduced into communities the demand for wood can decrease, thus decreasing the price of wood. Other households that are not using the clean cookstoves may then increase their own purchases of wood. Rather than reducing the general use of wood, clean cookstoves may have no impact or even a positive (and hence deleterious) effect on total wood usage, and thus no impact on CO_2 emissions (Fiala et al., 2018).

The negative feedback between the price of and demand for wood makes the system resilient against change. In this case, this is an undesirable feedback effect. In other cases, this kind of stability might be helpful. An adaptive management approach is better able to find solutions to unexpectedly occurring feedback.

Centralized control, isolated missions and one-way information flow are often part of traditional management. They are in opposition to the structure and dynamics of complex systems. A complex system is organized into modular parts, which are connected to each other. If one component fails, the others can often adapt without themselves failing. No single central control element exists in a complex system. The food web in the lake ecosystem in Section A is an example of this. **If project management is modular, project implementation is more resilient against failure.**

A complex system is diverse in its elements, which lends it resilience against one specific property's failure or mal-adaptiveness. Management that embraces a diversity of cognitive capability and training is more resilient towards failure to understand system dynamics. A management team that matches the project's diversity is more robust against misinterpreting events and giving too much weight to one component over other equally important ones. It can be beneficial to r**eflect diversity in the SEEDS with diversity in project management.**

There are many uncertainties in the evolution of a complex system, and predicting cause-and-effect relations is difficult, if not impossible. Thus, the project management will likely be faced with unexpected turns of events. While unavoidable, they can be dealt with. Given that unexpected and even extreme events are likely to happen, and given that they are difficult to predict, attempting accurate forecasts may be a waste of resources. Instead, anticipating unknown extreme events and preparing for them is a better use of resources.

In this context, it is relevant to discuss the complexity score's relationship developed in Section D.1 and evaluation practice. In development and climate evaluation, the OECD DAC criteria are the basic criteria used for most evaluations. We discuss these and their linkages with complexity measurement below.

- **Evaluation criterion – relevance:** Relevance relates to understanding whether the programme/investment is doing the right things. In most cases, this is anthropocentric – that is, the relevance criterion examines if the investment is doing the right things for the targeted people or groups of beneficiaries and the extent to which the programme responds to the "needs" of beneficiaries. Assessing the needs of beneficiaries usually requires a "needs assessment". The needs of beneficiaries can be expressed with respect to a diverse set of systems. These can be economic systems, biodiversity systems, social systems and so forth. The diagnostic tool introduced in Section C helps identify relevant systems (the needs assessment work). The complexity score developed in Section D.1 (e.g. the "diversity" and "feedback" attribute of complexity) can help evaluators examine if all of the systems that require a response are being attended to by the programme. The feedback criterion can also help determine if the programme/investment is looping back into any "needed" system.
- **Evaluation criterion – coherence:** Coherence examines if the climate/development programme/investment is compatible with other programmes/interventions in the country/sector/institution. Together, the complexity criteria "nestedness" and "openness" can help assess the extent to which a programme is potentially affected by and affecting other programmes in the sector. By examining the programme interventions' linkages with systems also affected by other programmes and examining the extent to which openness variables are being affected and how many are impacted, evaluators can assess coherence.
- **Evaluation criterion – effectiveness:** Effectiveness examines if the programme is achieving its intended objectives. Almost all complexity attributes such as size (the number of variables and the number of interactions), adaptive behaviour and memory can help assess the scope and, thus, the programme/investment's effectiveness.

- **Evaluation criterion – efficiency:** This indicator measures how well resources are being used. It essentially measures how well funds, capacity, skills, (natural) resources, time and the like are being converted into outputs, outcomes and impacts, as compared to other practical alternatives. In this context, knowing which systems are being affected by the investment/programme, how much they are being affected and the strength of the interaction, and the period within which these interactions are occurring, are useful to then understand and measure this criterion.
- **Evaluation criterion – impact:** This criterion measures what (and how much) difference the intervention/programme makes. This difference can be negative, positive, intended or unintended. The impact can be in many systems – social, physical, environmental, economic and so on. By understanding the linkages and the systems that programmes in complex contexts affect, a first step can be made to set up measurement systems. In turn, this can help understand the strength and, therefore, the impact of the programme/investment.
- **Evaluation criterion – sustainability:** This evaluation criterion measures the extent to which the programme's effects or the investment will continue. By understanding the memory attribute of interventions in complex systems, evaluators can understand this attribute of complex interventions and systems.

Overall, it is important to acknowledge that understanding complexity provides an overall paradigm within which evaluation must occur. The framework introduced in this paper provides an initial outline that is cross-disciplinary to go beyond the traditional and relatively anthropocentric origins of evaluation criteria and encourages us all to think about additional systems. While we believe that visualizing systems as complex and understanding their attributes is a critical way to see development/climate interventions and investments, the question of measurement remains. This is something we invite practitioners to think about expansively and especially in the context of non-human systems – an area that has been relatively ignored until now.

To end this section, we draw some general conclusions for development/climate programmes:

- Human–climate systems are complex; they exhibit self-organization, sudden non-linear changes, feedback and other complexity features. Development programmes need to be aware of this; simple solutions and linear theories of change will be unlikely to succeed.
- Complex systems are impossible to control with simple, singular means; they are constantly adapting to their environment and reacting to past events. Any intervention in a complex system automatically becomes part of the system and, hence, its outcome is difficult to predict. Development programmes need to be aware that any intervention automatically becomes part of the system and its non-linear dynamics.
- Diversity is a strength of complex systems; it facilitates their resilience to disruption. With a diversity of management and implementation approaches, development programmes can increase their robustness and subsequent impact.
- Complex systems involve dynamics on different timescales, some of which are interacting more strongly than others; understanding the timescale of the dynamics and matching it with a management that can react on a similar timescale is beneficial for the success of a programme.
- Complex systems are modular but never the sum of isolated components; this makes them more resilient towards disruption. Similarly, programme implementation could benefit from modularity.
- For evaluation to consider complexity, it may be useful to think of the degree of complexity and to appreciate that highly complex systems will require more advanced methods for

assessing their effectiveness, efficacy, efficiency, impact, sustainability, coherence and relevance, compared to less complex systems.[18]

- Evaluations of complex systems can take advantage of their modularity and parse different parts while recognizing that these are not necessarily additive.

Evaluation methods will need to be tailored depending on the type and changes in emergence size, diversity, feedback loops, memory, non-linearity, nestedness, and systems' openness. This has particular implications for how evaluators consider and measure impact, effectiveness, sustainability and efficiency. Process-tracing methods, most significant change methods and many others recognize these attributes of complex systems. However, these methods will also need to advance themselves to consider the requirement of quantitative/ordinal ranking for evaluation methodology to contribute to decision-making and strategy.

[18] See, for example, the OECD DAC evaluation criteria.

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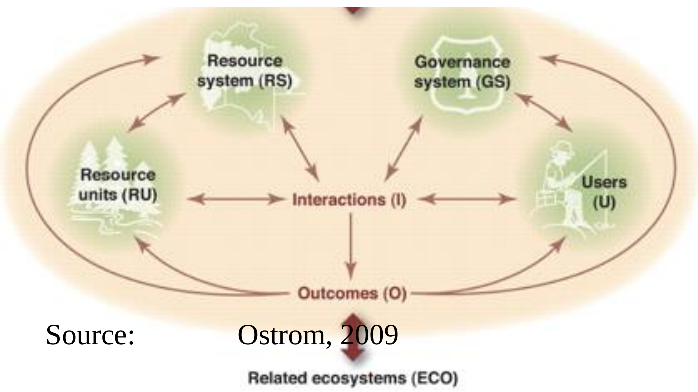
APPENDICES

Appendix 1. Review of Ostrom's framework for structuring social–economic systems

In this appendix, we briefly review the framework introduced by Ostrom and others for describing social–economic systems and their interconnections as a nested set of subsystems (see Ostrom, 2009, for a summary). We make a few modifications for the reasons explained below.

Ostrom deconstructs a social–ecological system (SES) into nested levels of subsystems (see Figure A - 1). The core subsystems forming the top-level of an SES are the Resource System (RS), the Governance System (GS) and the Users (U)[19]. Some examples of each of these are as follows:

Figure A - 1. Sketch of the core systems in the SES framework



Source: Ostrom, 2009

- **(RS)** protected parks and territories, forested areas, farmed land, wildlife and water systems
- **(GS)** the government and other organizations that manage the RSs, specific rules related to the use of the RSs, how these rules are made
- **(U)** individuals who use the RSs in diverse ways (farmers, locals)

These core subsystems are connected to each other and to an environment of political and social (S) and ecological systems (ECO). Each core subsystem has specific properties attached to it and, in turn, consists of its own subsystems.

Resource System. An RS has one or more of the following properties:[20] (RS1) Sector (e.g. water, forests, pasture, fish); (RS2) Clarity of system boundaries; (RS3) Size of resource system; (RS5) Productivity of system; (RS7) Predictability of system dynamics; (RS8) Storage characteristics; and (RS9) Location.

Resource Units. Furthermore, any given RS consists of resource units (RU). RUs are, therefore, the second sublevel in the hierarchy of SES, if we consider the SES itself as level zero.[21] Units and/or properties attached to an RU are (RU1) Resource unit mobility; (RU2) Growth or replacement rate; (RU4) Economic value; (RU5) Number of units; (RU6) Distinctive markings; and (RU7) Spatial and temporal distribution.[22]

Governance System. The different types of GS are (GS1) Sector (government, non-government, community); and (GS2) Type of rules-based system (property-rights systems, operational rules, collective-choice rules, constitutional rules, monitoring and sanctioning processes).[23]

Users. Each User system is assigned a set of attributes. Properties of a User System are (U1) Number of users; (U3) History of use; and (U4) Location.

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[19] We will later relabel this the User System (US) for reasons explained below.
[20] Ostrom, in addition, lists (RS4) Human-constructed facilities and (RS6) Equilibrium properties. RS4 is a type of sector, (hence, part of RS1). RS6 is vague.
[21] In Ostrom (2009), RUs are placed alongside the core systems at the top-level of the SES, although, strictly speaking, they are a subcategory of a resource system.
[22] In Ostrom (2009), (RU3) Interaction among resource units is listed, although this is not a property of a single RU but a type of interaction. It is therefore included in the list of interactions.
[23] The list of GS in Ostrom (2009) also included (GS2) Nongovernment organizations. This was included in GS1, which was relabelled "Sector". (GS3) Network structure was considered to be too vague. The following GS were summarized as GS2, which was relabelled "Type of rule-based system": (GS4) Property-rights systems; (GS5) Operational rules; (GS6) Collective-choice rules; (GS7) Constitutional rules; and (GS8) Monitoring and sanctioning processes.

We decided to introduce a new core system, the User System (US), and put Users on the second sublevel in the SES hierarchy. This mirrors the distinction between Resource System and Resource Units. These modifications leave us with three core systems on sublevel 1: Resource System, Governance System and User System. On the level below, i.e. at sublevel 2, we have Users and Resource Units. These changes are not necessarily in contradiction with Ostrom's ideas since she writes: "Each of the eight broad variables shown in Figure 1 can be unpacked and further unpacked into multiple conceptual tiers." (Ostrom 2007). Table 1 lists the, now, three core systems and their variables with the modifications introduced here.

The sublevel of a User System consists of the users. Users are assigned a set of properties. Whether these are homogeneous across the User System depends on how the group of users is defined: (U2) Socioeconomic attributes of users; (U5) Leadership/entrepreneurship; (U6) Norms/social capital; (U7) Knowledge of SES/mental models; (U8) Importance of resource; and (U9) Technology used.

Environment. The environment of a given SES consists of all systems that influence the SES. It can consist of surrounding ecosystems (ECO) and social and political settings (S): (ECO1) Climate patterns; (ECO2) Pollution patterns; (ECO3) Flows into and out of focal SES; (S1) Economic development; (S2) Demographic trends; (S3) Political constellation;[24] (S4) Government resource policies; (S5) Market incentives; and (S6) Media organization.

To be consistent with the description of the core systems above, one might separate the environment into sectors (climate, political, social, economy, media) with corresponding properties such as stability and predictability. Listing S4 here and not under GS indicates that it is not considered under the SES's influence but separate. Where exactly such boundaries are drawn is likely to be system dependent and intervention dependent.

More variables have been added subsequently. Epstein et al. (2013) and Vogt et al. (2015) pointed out that the ecological component is somewhat neglected in the SES framework, with its emphasis on social and economic considerations in a game-theoretic setting. Vogt et al. (2015) discuss a case study of forest conservation in Indiana, United States, within the SES framework with additional ecological variables.[25] Figure 2 in Vogt (2015) illustrates the application of the extended SES framework to the Yellowwood Lake Watershed forest. Further discussions, extensions and applications of Ostrom's SES analysis framework are found in McGinnis and Ostrom (2014) and Bots et al. (2015), and the references therein.

Ostrom lists several types of interactions that can occur in an SES. Here, in contrast to the original work, these interactions are classified in terms of the interacting parts. Interactions can be within a core subsystem, between subsystems and between a subsystem and the outside. Examples of possible interactions are[26] (I1) Harvesting (US → RS); (I2) Information-sharing among users (US ↔ US); (I3) Deliberation processes (US ↔ US); (I4) Conflicts among users (US ↔ US); (I5) Investment activities (US → RS); (I6) Lobbying activities (US → GS); and (I7 = RU3) Interaction among resource units.

"Investment activities" (I5) might be an interaction initiated by a single user or a group of users. Other forms of interaction that can be added to this list are (I8) Information flow from governance system to users, and (I9) Mitigation from resource system to eco/climate system. Given any particular project, other kinds of interaction can be added to the list.

[24] In Ostrom (2009), S3 is called "Political stability", which is one temporary state of a political system and thus a property of a political system not a sector of the environment.

[25] The authors call their addition an "additional tier-1 subsystem". This is another category mistake. Their addition is merely that of rules to the existing RS.

[26] Ostrom (2009) also lists (I7) Self-organizing activities; and (I8) Networking activities. The former is too vague, and the latter is covered by I2 and I3.

Interactions happen on different timescales and on and between different levels of the nested SES. For example, information-sharing is a process on a short timescale (hours, days), whereas investment activities occur on a longer timescale (months). Information flow from government to user system is an interaction on the level of core systems, whereas conflict among users is on the subsystem level of users.

Table A - 1 lists the main elements of an SES and their potential properties, called "Tier 1". Table A - 2 lists the subsystems of these main systems, called "Tier 2", and their respective properties. See also Table 2 in Vogt (2015), which provides a more detailed explanation of the RS and the RU. A procedure developed by Hinkel et al. (see Table 3 in Hinkel et al., 2015) can help identify components of a given SES.

The list below served as a template for a list of SEEDS subsystems and variables in Section C, tailored to a GCF-funded project's needs.

Table A - 1. Tier 1, top-level systems and their properties

System	Label	Property	Possible values
Resource System	RS1	Sector	Lake, forest, pasture
	RS2	System boundaries	Clear, contested, fractal/disconnected, artificial, ecological
	RS3	Size	Square metre, cubic metre
	RS4	Human constructed facilities inside	Dams, sewage
	RS5	Productivity	Renewable, water/ light/nutrient availability
	RS6	Equilibrium properties	Existence of alternative stable states
	RS7	Dynamics	Predictable, variable, equilibrated
	RS8	Storage characteristics	Carbon, water, nutrient source-sink dynamics, spatial and temporal distribution
	RS9	Location	Inlands, connected to other resource systems
	RS10	Ecosystem history	Geologic history, natural disaster history, human use and disturbance history
Governance System	GS1	Sector	(Non-)government organization, community
	GS2	Structure	Network, hierarchy
	GS3	Rule system	Property-rights system, operational rules, collective-choice rules, constitutional rules, policies
	GS4	Monitoring & sanctioning processes	Centrally organized, non-existent
User System	US1	Sector	Private, communal
	US2	Number of users	
	US3	History or past experiences	Exploitation, conservation, no use
	US4	Location	Concentrated, dispersed, local
	US5	Norms / social capital	Non-existent
	US6	Knowledge of SES/mental models	

System	Label	Property	Possible values
	US7	Importance of resource	Profit, survival
	US8	Technology used	Primitive, traditional, sustainable
Environment	E1	Sector / type	Demographic, media, political, economic, ecological
	E2	Dynamics	Stable, predictable, cyclic, equilibrated

Notes: User System does not exist in the original classification. User variables (U), which have been assigned to the User Systems have been relabelled as US. US3, US6, US7 and US8 are also properties of individual users, which might or might not be homogeneous across the User System.
RS10 is an additional variable introduced in Vogt (2015).
GS1 combines the original GS1 and GS2 to eliminate the original confusion between property variable and possible values.
GS2 generalizes the original GS3, which was a possible value of a property rather than a property variable.
GS3 is the property variable merging the original GS4–GS7, which were all possible values of that property.
GS4 is the original GS8 and S4.
U1 in the original framework.
U3 in the original framework.
U4 in the original framework.
U6 in the original framework.
U7 in the original framework.
U8 in the original framework.
U9 in the original framework.
E1 combining S1, S2, S3, S5 and ECO from the original framework.
E2 including S3, ECO1 and ECO2 from the original framework.

Table A - 2. Tier 2, elements of top-level systems and their properties

Element	Label	Property	Possible values
Resource Units	RU1	Type	Trees, fish, water
	RU2	Mobility[27]	Immobile
	RU3	Growth or replacement rate[28]	Annual, non-renewable
	RU4	Economic value	High, local
	RU5	Number of units	
	RU6	Distinctive markings	Colour, patterns
	RU7	Spatial & temporal distribution	Heterogenous, cyclic
Users	U1	Socioeconomic attributes[29]	Farmer, high education
	U2	Leadership/entrepreneurship[30]	Present

Examples of possible interactions are listed in Table A - 3.

[27] RU1 in the original framework.
[28] RU2 in the original framework.
[29] U2 in the original framework.
[30] U5 in the original framework.

Table A - 3. Possible interactions within/between tiers of SES (labels in Table A - 1 and Table A - 2)

LABEL	DESCRIPTOR	INTERACTION BETWEEN
(Potential) Interactions[31]		
I1	Harvesting	U(S) → RS
I2	Information-sharing	U ↔ U
I3	Deliberation processes	U ↔ U
I4	Conflicts among users	U ↔ U
I5	Investment activities	U(S) → RS, U(S) → E
I6	Lobbying activities	US → GS
I7	Interaction among resource units	RU ↔ RU
I8	Information flow from governance system to user system	GS → US
I9	Mitigation from resource system to eco / climate system	RS → E

[31] I7, I8 and I9 are not mentioned in original framework. Ostrom (2009) also lists (I7) Self-organizing activities; and (I8) Networking activities. The former is too vague, the latter is similar to I2 and I3.

Appendix 2. A TEMPLATE LIST OF SEEDS SUBSYSTEMS AND VARIABLES

Here, a template list of subsystems and variables is given, compiled from GCF-funded projects. This list can be extended as needed. In its current form, the list is an extension and modification of variables found in Ostrom (2009), Epstein et al. (2013) and Vogt et al. (2015). For more explanation, see the main text.

ENVIRONMENT

atmosphere

- global warming
- frequency and intensity of extreme weather events
- solar radiation

ocean

- acidification of ocean
- sea level
- ...

RESOURCE SYSTEM

ecosystem

- health of coastal ecosystem
- health of land ecosystem
- ...

farming

- agricultural yield
- aqua-farming yield
- ...

financial investments

- public investments
- private investments
- ...

infrastructure

- quality of road infrastructure
- marine/aviation safety
- drinking water supply
- low-emission energy supply
- non-renewable energy supply
- ...

information services

- weather predictability
- early warning system availability
- climate information resources
- ...

USER SYSTEM

enterprise

- income of (sustainable) agriculture enterprises
- income of (sustainable) aqua-farming enterprises
- income of (sustainable) tourism enterprises
- number of low-emission energy providers
- income of women-led enterprises
- income of mining industry
- ...

local population

- subsistence of local population
- employment of women
- employment of locals
- health of local population
- safety of local population
- knowledge of climate change
- ...

GOVERNANCE SYSTEM

central government

- climate-aware decision-making

community government

- climate-aware agro/livestock/forestry services
- …
- climate-aware community self-government
- ...

Appendix 3. BAMBERGER, VAESSEN & RAIMONDO CHECKLIST FOR ASSESSING THE LEVEL OF COMPLEXITY OF A PROGRAMME

In Chapter 1 of their book *Dealing with Complexity in Development Evaluation*, Bamberger, Vaessen and Raimondo (2015) propose a complexity score of development programmes. The scoring system is composed of four "dimensions", each with a number of variables; there are 25 variables in total. The score for each variable is between (1) low and (5) high. The final complexity score is a weighted average with a minimum of 20 and a maximum of 100.

Checklist for assessing the level of complexity of a program							
	Low						High
		Complexity rating					
Dimensions		1	2	3	4	5	
DIMENSION 1: THE NATURE OF THE INTERVENTION							
1. Objectives	Few and relatively clearly defined						Multiple, broad and often not clearly defined
2. Nature of the problem	Well understood/ high level of agreement						Not well understood/ high level of disagreement
3. Size	Affecting small population						Affecting large population
4. Stability of program design	Relatively stable						Emergent design
5 Implementation procedures	Clearly defined in project design						Often not clearly defined and changing
6. Services or components	Relatively few						Large number
7 Technical complexity	Low						High
8. Social complexity	Low						High
9. Duration	Clear start and end date						No clear end date and sometimes no clear start date
10. Is the program design well tested	Well tested and used many times						Relatively new and untested
	Total dimensions score [N/2]						
DIMENSION 2: INTERACTIONS AMONG INSTITUTIONS AND STAKEHOLDERS							
11. Budget	The use of the funds is clearly defined						General budget support with no clear definition of services to be funded
12. Funding and implementing agencies	Relatively few						Large number
13. Stakeholders	Relatively few and with similar interests						Many and diverse
14. Consensus on objectives/ approach	High level of consensus						Low level of consensus
15. Level of cohesion among stakeholders	High level of cohesion						Low cohesion and/or competition and conflict
	Total dimension score						

A revised table was published on the web after the publication of the book. The table is copied here, from *https://www.unicef.org/evaluation/files/Revised_Complexity_Checklist__.pdf*

DIMENSION 3: CAUSALITY AND CHANGE							
16. Causal pathways	Single and linear causal pathway						Multiple causal pathways (non-linear, interconnected, recursive feedback loops)
17. Certainty on outcomes	Relatively high degree of certainty						Low degree of certainty
18. Agreement on appropriate actions to address problems	Relatively high agreement						Relatively low agreement
19. Emergence	Program design and implementation relatively stable over time						Program design and implementation experience significant changes over time
20. Processes of behavioral change	behavioral change process simple/easy to measure						Complex and difficult to understand
	Total dimension score						
Dimension 4: Embeddedness and the nature of the system							
	Value	1	2	3	4	5	
21. Agreement on key contextual factors	High level of agreement and factors easy to identify						Disagreement and/or difficult to identify
22. Context and embeddedness	Program relatively independent of context						Contextual factors significantly affect program
23. Interactions among contextual factors	Little interaction among factors						Significant interactions among different factors
24. Stability of program environment	Stable program environment						Unstable and changing program environment
25. Ease of identification of factors	Contextual factors easy to identify and measure						Contextual factors difficult to identify and measure
	Total dimension score						
		TOTAL SCORE					

How to calculate scores:
There are a total of 25 items [10 for Dimension 1 and 5 for Dimensions 2,3 and 4]. Each item is rated on the 5 point complexity score ranging from very low to very high complexity. Each Dimension has a maximum score of 25 points so that the maximum possible complexity score is 100 and the minimum is 20. As Dimension 1 has more elements that must be assessed, this dimension has 10 indicators, while the other Dimensions each have 5 indicators. In order to ensure that each Dimension has the same total of 25 points, the total score for Dimension 1 is divided by 2.

Steps for calculating the complexity scores

Step 1: Review each indicator and put a check indicating whether the indicator has a very low, low, medium, high or very high level of complexity.

Step 2: For each dimension the value to be assigned to each position is indicated. For example, a "very low" complexity rating is given a value of "1" for Dimensions 2,3 and 4. Similarly a "very high" complexity rating for these 3 dimensions would be given a value of "5".

Step 3: For each Dimension add the values for each indicator and put the "total dimension score" in the corresponding box. The minimum possible score for each Dimension is 5, and the maximum is 25.

Step 4: Add the total scores for each dimension and put the total in the "Total Score Box"

Step 5 When interpreting the scores, remember that the scores are combining different kinds of indictors so that the values are ordinal so that the totals only provide a rough estimate and should not be treated as interval variables that can be manipulated statistically

Source: Bamberger, Vaessen and Raimondo (2016) Chapter 1. Bamberger and Raimondo 2018 update for EES Workshop

Appendix 4. TABULAR REPRESENTATION OF SEEDS INTERACTIONS FOR THE THREE GCF PROJECTS DISCUSSED IN THIS REPORT

Table A - 4. Madagascar SEEDS: matrix representation of interactions

	quality of ecosystem services	agro / livestock yield	low-emission energy supply	weather predictability	climate info material / data	sustainable farming enterprises	renewable / low-emission energy businesses	subsistence of local population	safety local population	knowledge of climate change in local population	climate-aware management	climate-aware agro / livestock / forestry services	sustainable landscape monitoring systems	climate-aware self-government of communities	climate change trust fund	public investment	private sector investment	global warming	frequency / intensity of extreme weather events
quality of ecosystem services								1m							1m				
agro / livestock yield	-1m					1m		1m											
low-emission energy supply	1 l																		
weather predictability		1s							1s										
climate info material / data				1s						1m	1m	1m	1s	1m					
sustainable farming enterprises								1m								1m			
renewable / low-emission energy businesses	1m		1s														1m		
subsistence of local population																			
safety local population																			
knowledge of climate change in local population	1 l													1m					
climate-aware management														1m					
climate-aware agro / livestock / forestry services	1m																		
sustainable landscape monitoring systems											1m	1m							
climate-aware self-government of communities	1m					1m													
climate change trust fund	1m															1m	1m		
public investment	1m					1m	1m												
private sector investment						1m	1m												
global warming	-1 l			-1 l															1 l
frequency / intensity of extreme weather events		-1s							-1s										

Note: Interactions added by project are in blue. The labels indicate the timescale: (s) short, (m) medium, (l) long.

Table A - 5.   Vanuatu SEEDS: matrix representation of interactions

	health of water ecosyst. services	health of land eco-system services	agro / livestock/ aqua farming yield	quality of road infra-structure	aviation / marine safety	drinking water supply (infra-structure)	income of fisheries / agriculture enterprises	income of fisheries / agriculture enterprises	subsistence of local population	safety of local population	knowledge of climate change in population	climate-aware decision making	weather predictability	EWS	CIS	oceanic acidification	sea level	global warming	frequency / intensity of extreme weather events
health of water ecosyst. services								1m	1m										
health of land eco-system services								1m	1m										
agro / livestock / aqua farming yield							1m												
quality of road infra-structure							1m	1m											
aviation / marine safety								1m											
drinking water supply (infra-structure)								1m	1s										
income of fisheries / agriculture enterprises									1s										
income of tourism enterprises	-1m	-1m				-1m			1s										
subsistence of local population						-1l													
safety of local population								1m											
knowledge of climate change in population	1m	1m																	
climate-aware decision making	1m	1m		1m	1m	1m													
weather predictability					1s			1m											
EWS			1s		1s					1s									
CIS				1m	1m	1m					1m	1m	1s						
oceanic acidification	-1l																		
sea level						-1l													
global warming	-1l	-1l											-1m			1l	1l		1l
frequency / intensity of extreme weather events			-1s	-1s	-1s			-1m											

Note: Interactions added by project are in blue. The labels indicate the timescale: (s) short, (m) medium, (l) long.

Table A - 6. Chile SEEDS: matrix representation of interactions

	health ecosystem	solar power energy supply	non-renewable energy supply	solar power energy business	mining industry	public investments	private sector investments	employment of local population	employment of women	knowledge of climate change in population	government permits	CIS training resources	solar irradiation
health ecosystem													
solar power energy supply			-1m		1m								
non-renewable energy supply		-1m			1m								
solar power energy business		1s					1m	1s	1s				
mining industry	-1 l							1s					
public investments				1m									
private sector investments				1m				1s					
employment of local population													
employment of women													
knowledge of climate change in population	1m												
government permits		1s	1s										
CIS training resources										1m			
solar irradiation		1s											

Note: Interactions added by project are in blue. The labels indicate the timescale: (s) short, (m) medium, (l) long.

Independent Evaluation Unit
Green Climate Fund
175 Art center-daero, Yeonsu-gu
Incheon 22004, Republic of Korea
Tel. (+82) 032-458-6450
ieu@gcfund.org
https://ieu.greenclimate.fund

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