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'COMPLEXITY-AWARE' MONITORING AND EVALUATION OF DEVELOPMENT PROGRAMS — ANCHORING THEM IN COMPLEXITY SCIENCE

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As governments and multilateral institutions launch projects and programs to support climate change mitigation and adaptation, the challenge lies in determining their effectiveness. The high complexity of climate-change programs often makes it difficult to determine their effectiveness through standard monitoring and evaluation procedures. 'complexity-aware monitoring' is a qualitative approach to monitoring, recently introduced by international development programs. This increasing awareness of complexity in the evaluation sector opens up a window of opportunity for complexity science to support climate change mitigation and adaptation programs. This paper's contribution is a hands-on methodology for live monitoring and evaluation of development programs. The methodology is rooted in existing literature on social–ecological systems, as pioneered by Ostrom, and in quantitative methods from complexity

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science. To illustrate the methodology, an existing climate mitigation project in Madagascar, funded, monitored and evaluated by the Green Climate Fund, is discussed.

Keywords: Socio-economic systems; mixed-methods; features of complex systems.

1. Introduction

Addressing today's sustainability challenges necessitates a systematic approach that treats social and ecological systems as integrated social–ecological systems (SES). Pioneering work has been done by Elinor Ostrom in conceptualizing SES with the aim of counteracting the, in her view misguided, tendency of "seeking simple solutions to complicated governance problems" [20].[a] These SES are also inherently complex adaptive systems (CAS), and the international development sector increasingly recognizes the importance to account for the complexity of these systems in which they wish to implement change.

Impact evaluations of development programs have become a crucial tool for assessing the causal impacts of policies and programs in areas like climate, health, and economic development. A common approach is to track initiatives according to predefined implementation plans. These typically define outcomes, outputs, and activities and support their achievement with indicators or milestones. An undergirding *theory of change* relates activities, outputs, and outcomes in a theory about causal relationships, showing how objectives should be achieved [27]. Monitoring and evaluation (M&E) frameworks then measure whether the theory of change has effectively reached predefined outputs and outcomes. Such M&E frameworks are designed to track what has been defined prior to implementation. However, in highly complex situations outcomes might only emerge over time, and simple theories of change might not capture the myriad interacting factors that lead to an emergent outcome. This can result in overstated causality attributed to a single intervention or biased reporting of other contributing factors [23, 24, 28].

In 2016, the U.S. Agency for International Development (USAID)[b] introduced 'complexity-aware monitoring' principles as part of their Strategic Program for Analyzing Complexity and Evaluating Systems [16, 26]. In 2018, the Institute for Development of the Swiss Agency for Development and Cooperation presented complexity-aware approaches to a theory of change [11]. In 2019, the Green Climate Fund (GCF)[c] began to develop a complexity approach to evaluation [7] (see also [29]). In 2021, Hertz *et al.* sketched out the elements of a complexity-aware M&E system for international development programs in the area of sustainable development [12]. The conceptual basis on which 'complexity-aware monitoring' is built is the so-called Cynefin framework which defines four types of systems: simple,

[a] Governance problems, here, refer to the "interaction patterns of actors with conflicting objectives and the instruments chosen to steer social and environmental processes within a particular policy area." [19]
[b] USAID dedicated to advance U.S. foreign policy which includes the conservation and stewardship of natural resources.
[c] GCF was set up by the United Nations Framework Convention on Climate Change (UNFCCC) as its operating financial entity in 2010.

(technically or socially) complicated, complex, and chaotic [21, 30]. While this distinction sounds somewhat fuzzy, the underlying ideas are, indeed, in line with concepts from complexity science. For example, USAID recognizes "complexity when diverse elements interact with each other in unanticipated ways to create a new reality."

The above shows that, over the past years, the international development sector has become more and more aware of the necessity to adopt a complex-systems perspective in M&E and in managing development programs. There is also an increasing effort in incorporating complex-systems related concepts and methods in M&E. Cremades *et al.*, for example, present a set of 10 principles to integrate the so-called water-energy-land nexus with climate services [6]. The water-energy-land nexus is a methodological approach to resource management that draws attention to the complex-systems nature of the (limited) resources. This integration of climate services with quantitative modeling and assessment is designed to support the achievement of sustainability targets. Other examples of incorporating complex-systems related concepts and methods in M&E are [3, 12, 21]. Even complexity-science tools begin to percolate through, such as social-network analysis or Markov models, albeit still mostly in a qualitative rather than quantitative form [16].

However, these examples are more the exception, and there is still a disconnect between the literature on development program M&E and the scientific literature on SES and on CAS. The opportunity for complexity science (and the ambition of this paper) is to anchor complexity-aware monitoring of development programs in the concepts and quantitative tools of complexity science. To this end, in this paper we provide a hands-on methodology for M&E which is firmly rooted in the work by Elinor Ostrom and colleagues on SES and in the concepts and mathematical tools of complexity science. The new methodology systematically identifies the drivers and dynamics of a SES from a complex-systems perspective and, as a result, provides an effective guide for monitoring, managing, and evaluating a development program. We illustrate the new methodology with the case study of a mitigation and adaptation project from the portfolio of the GCF.

The scientific contribution of our methodology is a road map toward a quantitative, complexity-science informed tool kit for M&E, including data analysis and computational modeling.

This paper is structured as follows. In Sec. 2, we give a brief introduction to M&E, SES, and CAS and to what extent they have been integrated conceptually in the past. In Sec. 3, we introduce the new methodology for M&E of CASES. In Sec. 4, we illustrate the methodology with a case study of a climate mitigation and adaptation project from the portfolio of the GCF. We end with some concluding remarks in Sec. 5.

2. Background

2.1. *Evaluation & monitoring*

In traditional theory-based evaluation, evaluators create a theory of change that maps out causal links between a project's inputs and outputs. For example, an intervention might aim to establish a causal link between providing vaccines to a community and improving health outcomes. Evaluators then test this hypothesized causal relationship through randomized or quasi-experiments to verify whether the vaccine input results in better health outcomes. However, in highly complex situations, simple theories of change might not capture the myriad interacting factors that lead to an emergent outcome. This can result in overstated causality attributed to a single intervention or biased reporting of other contributing factors [24]. Westhorp proposes that complexity approaches can enhance evaluations in two ways. First, a realist evaluation can incorporate multiple theories of change to reflect a program's complexity while still measuring the outcomes of its subcomponents [28]. To fully understand the context and effectiveness of a complex program, different evaluation approaches may be necessary.

2.2. *Complexity-aware monitoring*

All development programs incorporate performance monitoring and so-called context monitoring. While the aim of performance monitoring is to reveal whether a program is on track and whether expected results are being achieved, the aim of context monitoring is to reveal unintended consequences.

Hertz *et al.* sketch out the elements of a complexity-aware M&E system for international development programs in the area of sustainable development [12]. Their M&E system is meant not just as a tool to track compliance against a pre-determined theory of change. Rather, they intended it as a real-time approach, constantly defining and re-defining narratives for change that help push systems along trajectories of interest. According to Hertz *et al.*, dealing with complexity involves embracing uncertainty; and this challenges established notions of accountability — something which they believe funders and implementers must begin to tackle collectively.

USAID recently adopted a similar perspective and recommends that staff apply "complexity-aware" principles in ongoing monitoring [26, 30]. To them, this means that a monitoring methodology should use leading indicators to gain insights into effects before results are finalized and consider the relationships, perspectives, and boundaries that affect and are affected by changes within the complex system. In 2021, the U.S. Agency for International Development (USAID) — dedicated to advance U.S. foreign policy which includes the conservation and stewardship of natural resources — introduced 'complexity-aware monitoring' principles as part of their Strategic Program for Analyzing Complexity and Evaluating Systems [16].

2.3. *Social–ecological systems*

The SES[d] framework, pioneered by Ostrom [20] for analyzing SES with the aim of counteracting the, in her view misguided, tendency of "seeking simple solutions to

[d] An alternatively term in use for SES is human–environment systems (HES).

complicated governance problems". This framework is perfectly suited to use in situations where one is concerned with how human decisions affect the natural environment. An example is the overharvesting or misuse of ecological resources or, indeed, international development programs and the systems they aim at transforming.

Ostrom's framework is now widely used in the analysis of coupled human-environment systems. Examples include community-based conservation [4], water-management problems [18], and irrigated agriculture and recreational fishery ([13], see also [17] and other contributions to the same special issue).

Due to the coupling of physical processes and social dynamics in SES, both qualitative and quantitative approaches are required. Mitigation and adaptation work on the ground relies on the insights gained through SES modeling, and an effective communication between modelers and decision makers is essential for its success. Elsawah *et al.*[8] identified eight grand challenges in SES modeling, one of them being the communication of the plethora of scientific methodologies and findings to the policy makers and stakeholders that are involved in working toward the UN's Sustainable Development Goals.

2.4. *Complex adaptive systems*

The terms 'complex' and 'complexity' are used frequently, and often in the loose sense of 'complicated', 'difficult to understand' or 'difficult to predict', as we observed, for example, in the above mentioned Cynefin framework. In complexity science, however, these terms have a more specific meaning. And, although there is no uniformly accepted definition, most complexity scientists would agree with the following: A complex system consists of many interactions between many parts and self-organizes into robust structures, often on multiple time and length scales, due to feedback from the components' interactions and openness to the environment. Holland, a computer scientist, began studying systems "that defied accurate simulation by computer" [14, p. 17]. For these systems, that "change and reorganize their component parts to adapt themselves to the problems posed by their surroundings", he coined the term 'complex adaptive system' [14]. Ladyman and Wiesner have identified 10 features that all natural and social complex systems exhibit [15]. These features are the following: large number of parts and interactions, diversity, openness, feedback, nonlinearity, self-organization, robustness and resilience, adaptive behavior, memory, and modularity. The human–climate system — with its major, large-scale components 'climate and ecosystems', 'social systems', and 'economy' — is without a doubt a complex, adaptive system.[e] It contains smaller-scale complex systems that also contain, generally coupled, economic, ecological, and social components.

[e] We use the term 'complex adaptive system', since it is the terminology used in the cited literature on SES. In the conceptualization by Ladyman and Wiesner [15], 'adaptive behavior' is a feature of (functional) complex systems.

2.5. *Linking SES and CAS*

How do concepts from CAS connect to social ecological systems? The resilience perspective by Folke [9], for example, emphasizes the feedbacks within interlinked SES that cause vulnerability and build resilience. Preiser *et al.* [22] also present a CAS perspective to SES. They designed organizing principles to advance research methods on SES. Schlüter *et al.* presented an analytical framework to understand and capture emergent phenomena in SES [25]. Schlüter *et al.*'s framework provides a systematic way to study SES, emphasizing the importance of interactions and feedbacks. The authors emphasize the importance of a detailed dynamical picture in order to understand emergent phenomena in SES such as pattern formation and feedback dynamics between ecological and social actors. It helps researchers and policymakers to better understand complex dynamics and potential outcomes in SES.

The Great Barrier Reef Marine Park case study demonstrates the practical application of acknowledging ecosystems as CAS [19]. Olsson *et al.* provide an adaptive governance framework developed from extensive data and in-depth interviews, identifying strategies like bridging science and policy and facilitating community participation.

In other words, the scientific community engaged in studying SES is already providing a link to the field of CAS. What needs strengthening is the link to the international development sector engaged in transforming CAS on the ground. With our new methodology, introduced in the following section, we contribute to a stronger connection between the fields of SES and CAS and the international development sector, with its very practical needs on monitoring and evaluating interventions into SES on the ground.

3. A Hands-on Methodology to M&E in CAS and SES

We now integrate the above concepts and tools of CAS and SES, which we collectively call CASES in the following. The result is a pragmatic methodology for M&E of climate mitigation and adaptation projects. The methodology proceeds in three steps, as outlined below: in step 1, the user identifies the relevant system components and subcomponents; in step 2, interactions between any two subcomponents are characterized and causal links are identified; in step 3, the system is checked for feedback loops and other indicators of complexity.

3.1. *Step* 1: *Identifying the SES components*

We proceed along the lines of Ostrom's original framework, with the key difference being the requirement for subsystems to be quantifiable, at least in principle. This requirement leads to a slight regrouping of systems and subsystems compared to Ostrom.

We separate a system into four core systems: A *User System* which includes all living beings or groups of living beings such as villages or companies that are part of the system; a *Resource System* that includes ecological and other resources such as ecosystem services or information services; a *Governance System* that is composed of all people or entities that have some form of legal or managerial function over some or all of users and resources; and an *Environment System* which includes everything that is impacting on the other systems but is not impacted by them (immediately and/or significantly), such as the climate or the global economy.

There is an ethical dimension to this classification into core systems. Some would argue that any animal cohort should be part of the User System while others consider them as part of the Resource System. This is not the place to take a stance on these issues, but it is worth pointing out that the methodology allows for both viewpoints to be adopted. Figure 1 visualizes these core components of CASES and potential interactions. The Environment System has no arrows pointing to it, only away from it, by definition. We are interested in the components within these core systems, how they interact, and what their dynamics are. For this purpose, we separate each core system into subsystems and attach to each subsystem a set of properties that are quantifiable, at least in principle. Because we require the properties to be quantifiable, we call them 'variables'. Herein lies one of the main differences to Ostrom's SES framework. For example, the core system User System may contain the subsystem 'local population' which might own the variables 'subsistence' and 'size'. The core system Resource System may contain the subsystem agriculture which might own the variables 'health' and 'yield'. Table 1 lists, for each core system, a possible set of subsystems and for each subsystem a possible set of variables. The list of subsystems and variables is not exhaustive nor is there a minimum list of subsystems and variables that are always present since each CASES will have its own specific composition. The choice of subsystems and variables could (or even should) be guided by an expert elicitation process (see e.g. [1, 2] for more on expert elicitation). For a real-world example of a CASES, see Fig. 2 and the discussion in Sec. 4.

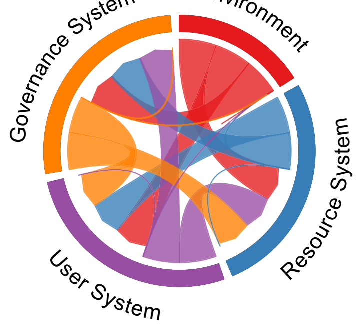

Fig. 1. The core components (on the circumference) of CASES and potential interactions (arrows).

Table 1. Quantifiable variables for different possible subsystems of Resource Systems, User System, Governance Systems, and Environments.

Subsystem	(Quantifiable) Variables that describe the subsystem
Core system: Resource System	
Ecosystem	Growth or replacement rate, economic value, number of units, health of coastal ecosystem, health of ecosystem
Agriculture	Growth or replacement rate, economic value, number of units, agricultural/aquafarming yield
Infrastructure	Economic value, number of units, quality, marine/aviation safety, drinking water supply
Information services	Economic value, number of units, weather predictability, early warning system availability, climate information resources
Financial investments	Growth rate, economic value of public investment, economic value of private investment
Core system: User System	
Enterprise	Number of businesses, number of women-led businesses, profit, sustainability of technology
Local population	Size, knowledge of CASES, profit, sustainability of technology, employment rate, employment of women, health, safety
Core system: Governance System	
Central government	Climate awareness of decision making, climate awareness in ecosystem management, corruption, amount of distributed/ deliberative decision making
Community governance	Climate awareness of decision making, climate awareness in ecosystem management, corruption, amount of distributed/ deliberative decision making
Core system: Environment	
Atmosphere	Global warming, frequency and intensity of extreme weather events, solar irradiation, predictability
Ocean	Acidification, sea level rise, predictability
Global market	Predictability, accessibility

3.2. *Step 2: Identify and classify interactions between subsystems*

Once the relevant subsystems and variables have been specified, the second step is to identify the existing interactions between them. For each pair of variables, the user needs to decide whether they are correlated, whether the correlation is positive or negative, and whether there is an causal relation. The answers can be based, again, on expert elicitation or on statistical analysis if suitable data are available. Take as an example the two variables 'subsistence of the local population' and 'health of the eco-system'. In CASES where the local population is relying on the local ecosystem to provide their food, an interaction is present. The direction of the interaction is from the 'health' to the 'subsistence'. The correlation is positive since an increase in eco-system health causes an increase in subsistence. An example of a negative correlation is given by the two variables 'frequency of extreme weather events' and 'safety of the local population' since an increase in the former causes a decrease in the latter. With core systems, subsystems, variables, and interactions in place, we have assembled a (coarse-grained) description of the CASES.

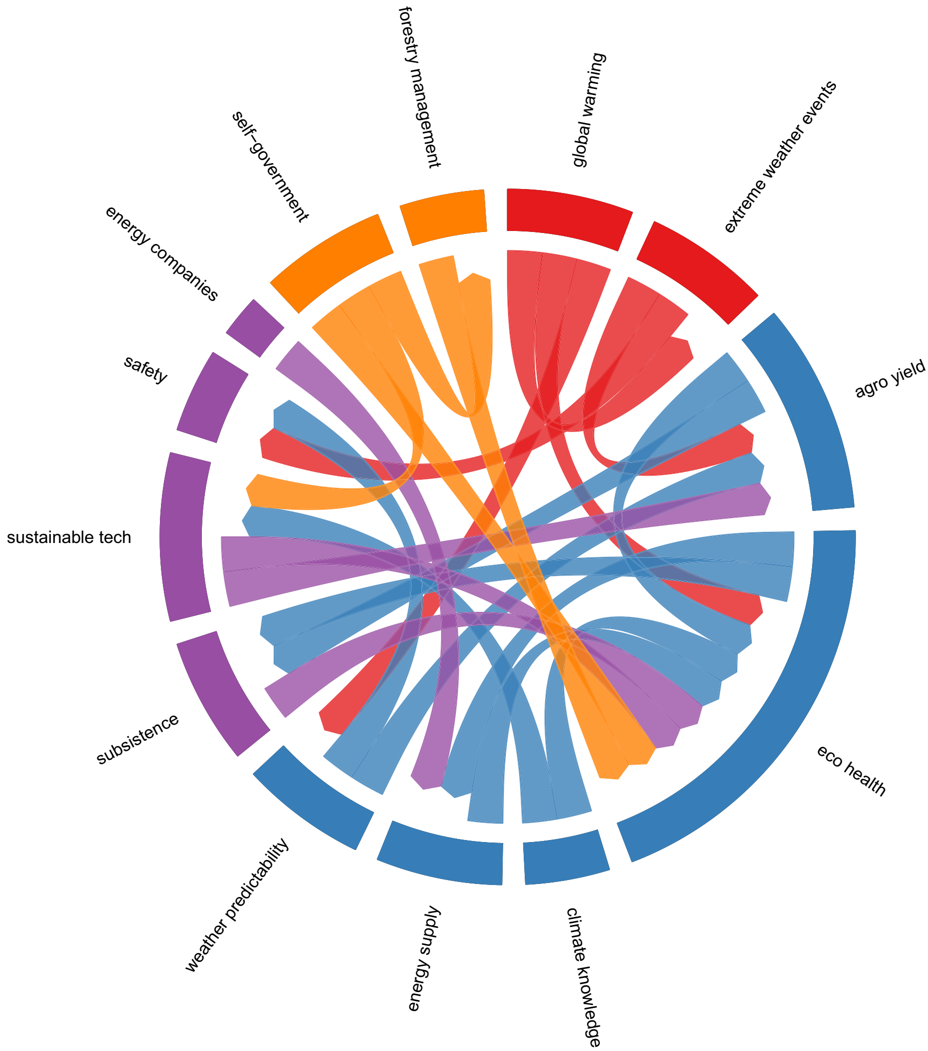

Fig. 2. (Color online) Madagascar CASES, without interventions: variables and causal relations between them according to expert assessment. The core systems are the Environment (red), the Resource System (blue), the User System (purple), and the Governing System (orange).

3.3. *Step 3: Analyzing the complexity of the project*

It is tempting to introduce a scoring of the complexity of a project, and, thus, make programs comparable. Bamberger, Vaessen, and Raimondo, for example, propose a complexity score of development programs [3]. 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. We will resist the

Table 2. The 10 features of complexity and how they are interpreted in CASES.

Feature	CASES property	Assessment
Size	Number of variables (excl. environment)	Stakeholders, resources, ecosystems, etc.
	Number of connections between (nonenvironmental) variables	Interactions between stakeholders, resources, ecosystems, etc.
Diversity	Number of subsystems (excl. environment)	Types of stakeholders, resources, organizations with (dis)similar interests, needs, etc.
Feedback	Number of loops with dynamics on similar timescales	Well-separated timescales versus processes and overlapping timescales
Adaptive behavior	Number of social interactions	Social dynamics irrelevant versus dominant
Nonlinearity	Number of multiple-input nodes	Single linear causal chain versus multiple nonlinear causal relations
Memory	Number of medium and long timescale processes	Relevant dynamics are fast versus slow
Nestedness	Number of multivariable subsystems (excl. environment)	Subsystems have versus have no substructure
Openness	Number of links from the environment	Quite independent of versus very dependent on external influences
	Number of variables in environment	External influences are few versus many

single-number quantification of complexity, since we agree with Gell-Mann's statement that "A variety of different measures would be required to capture all our intuitive ideas about what is meant by complexity." [10] (see also the discussion in [15]). Instead, we will identify the 10 features from Sec. 2.4 for a given CASES and relate it to properties that are relevant for its M&E.

Table 2 lists all the complex-systems features from Sec. 2.4 and how they relate to the representation of CASES such as that in Fig. 2. The first column labels the complex-systems feature that is assessed. The second column describes the property of the representation obtained with steps 1 and 2 above and that is considered a proxy for the complex-systems feature. The last column contains the description of the complexity feature in the context of M&E. This albeit qualitative assessment immediately provides a way to differentiate between the 'complexity' of the program and that of the CASES that is intervened in — simply by doing this step 3 (the complexity assessment) twice. The difference between 'CASES without program interventions' and 'CASES with interventions' is then a proxy for the complexity of the program.

In the following section, we illustrate the new methodology with the case study of a climate mitigation and adaptation project from the portfolio of the GCF.

4. Case Study: Sustainable Landscapes in Eastern Madagascar

The GCF is the financial instrument created by the United Nations as a result of the Copenhagen summit of the IPCC in 2014. An initial funding pledge of US$ 10 billion from member states for the years of 2015–2019 was followed by a pledge of US$

9 billion for the years 2020–2025. The GCF has since initiated and invested in more than 250 projects (and counting) in the developing world to mitigate the effects of climate change on vulnerable communities and to aid adaptation to climate change. The Independent Evaluation Unit of the GCF provided access to data of projects that have been funded since the initiation of the Fund in 2014. One project was selected and is discussed in detail here to illustrate the new methodology. Additional case studies are found in [29].

We have chosen the GCF-funded project 'Sustainable Landscapes in Eastern Madagascar' as our case study. It is the example of a medium complex project, i.e. interesting enough to address with the new methodology, but not too large in size to distract from the methodology. The project addresses the economic and ecological vulnerability of small-holder farmers in two remote areas of Madagascar.[f] Due to climate change, farmers in these areas are exposed to more and more extreme weather events, mostly droughts. Because most farmers rely on their own harvest for survival, such events can be catastrophic and result in periods of starvation for many families. For fuel, the population depends mostly on wood collection. Among the multi-level reasons for this are their remoteness and disconnect from the country's energy supply system. The (at the time of writing still ongoing) GCF project addresses these challenges by a variety of measures, both economic and ecological. For example, the project introduces farmers to sustainable farming techniques and leads information campaigns on climate change; it links local food producers with the national market; it invests in alternative energy supplies and provides financial infrastructure for start-up companies, in particular in the renewable energy sector.

The Madagascar CASES without the interventions is shown in Fig. 2. Variables are listed around the circumference of the circle, and a directed arrow is drawn from one variable to another if the former affects the latter, according to expert assessment. The information whether the causal relation is positive or negative is not included in the figure, for reasons of clarity. The environment, drawn in red, has no incoming arrows, per definition. The dynamics are encoded in these arrows. An arrow indicates a causal relation, which also implies a time scale (not visualized). The time scale (e.g. on this order of hours, days, months) is a measure of how fast effect follows a cause. When variables are part of a closed loop, they are only effectively coupled when the time scales of all involved arrows are of a similar order of magnitude. Otherwise, feedback is unlikely to occur. The list of variables is given in Table 1. The selection of these variables and the assessment of causal relations was carried out in discussion with the project management team.

Until now, we have discussed the example system without the external interventions. We now add in the intervention and discuss the resulting CASES which has grown by the added variables and interactions. Table 3 lists the additional variables introduced by the interventions. The visualization of the complete Madagascar CASES with interventions is shown in Fig. 3.

[f] This is GCF project FP026, https://www.greenclimate.fund/project/fp026.

Table 3. The list of core systems/types/variables for the Madagascar CASES.

Core system	Subsystem	Quantifiable variables
(a) Sustainable Landscapes in Eastern Madagascar — System before intervention		
Environment	Atmosphere	Global warming, frequency and intensity of extreme weather events
User System	Farming sector	Number of farmers using sustainable techniques
	Energy sector	Number of low-emission or renewable-energy businesses
	Local population	Subsistence, knowledge of climate change, safety
Resource System	Ecosystem	Health
	Agricultural land	Yield
	Energy supply	Proportion of low-emission energy supply
(b) Sustainable Landscapes in Eastern Madagascar — Additions to system through intervention		
Resource System	Climate information services	Weather predictability, available information material, available data
Governance System	Community government	Climate-awareness of decision making
	Government forestry services	Climate-awareness of forestry services, availability of forestry-monitoring systems
	Investment sector	Value of public investment, value of private investment, value of trust fund

In Table 4, we assess the complexity before and after the planned interventions.

From this table and Figs. 2 and 3, we make the following initial observations. The exposure of the system to the environment is quite high, with almost half of the variables, excluding the governance variables, being affected. Furthermore, the ecosystem, which plays a central role for the subsistence of the population, is the system most affected by the environment with seven incoming arrows. This suggests that further and detailed modeling of the sum of these interactions might be worth investing in. Further observations are best made in the context of the so-called OECD DAC criteria, as follows.

4.1. *Assessing the complexity of the Madagascar CASES*

In development and climate evaluation, the OECD DAC criteria are the basic criteria used for most evaluations [5]. One of these evaluation criteria is '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. A realistic assessment of efficiency takes into account the difficulty of achieving the desired outcome. Generally, the more complex the system is, which is intervened into, the more difficult it will be to achieve a successful outcome. Reducing 'complexity', to begin with, to the number of elements and the number of interactions in the system before any intervention has taken place, the CASES representation gives a proxy for this complexity and, hence, for the potential difficulty of achieving a successful outcome. We can see from the CASES of the Madagascar project in Fig. 2 that a large number of elements and, even more importantly,

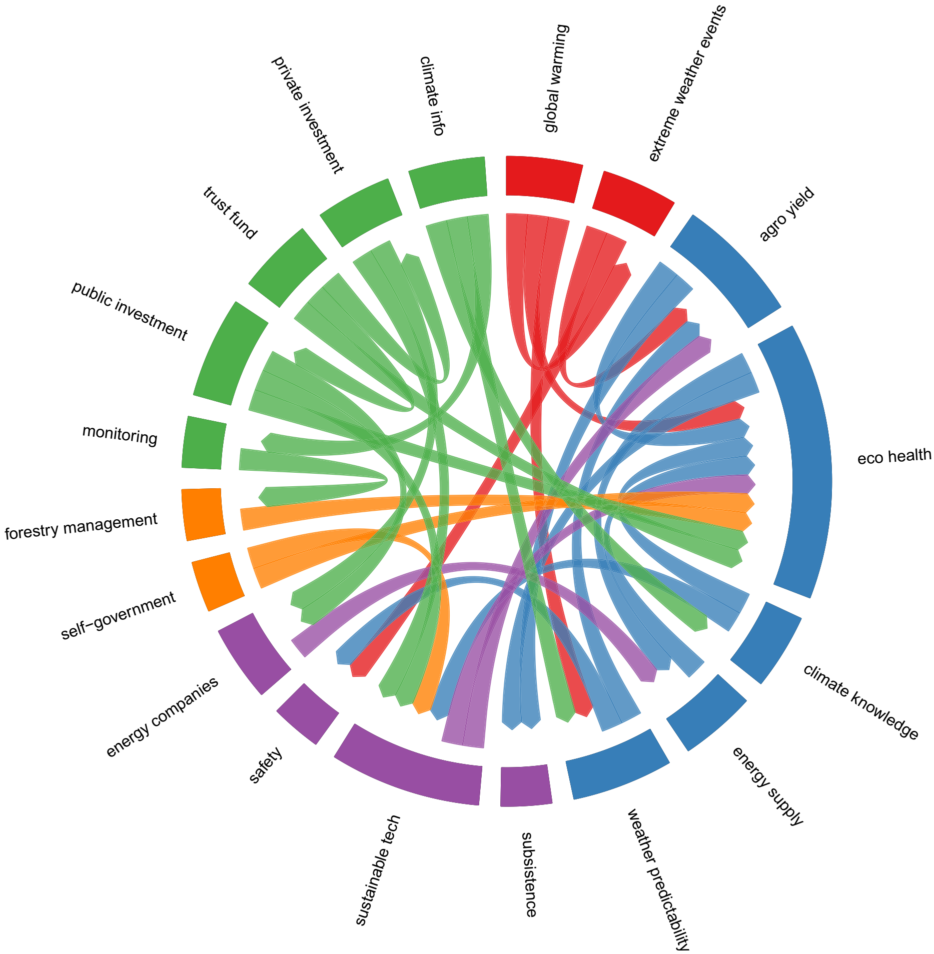

Fig. 3. (Color online) Madagascar SES, with interventions marked in green. The Environment is in red, the Resource System in blue, the User System in purple, and the Governing System in orange.

a large number of interactions exist. This might inform the amount of resources required to achieve a desired outcome and, thus, may influence the assessment of a project's efficiency.

The way the interactions are interlinked also contributes to the assessment of potential difficulty of a project. For example, in Fig. 2 we find a loop from 'eco health' to 'subsistence' and back to 'eco health'. We find another feedback loop between 'eco health' and 'energy supply'. These three variables are very relevant to the outcome of the planned interventions. At the same time, a feedback loop makes a prediction of the system behavior upon intervention nontrivial. In cases like these, a more detailed analysis of the dynamics might be desirable to prevent undesired outcomes due to unpredicted dynamics. For example, the relative time scale of these processes is

Table 4. Complexity assessment of the Madagascar CASES.

Feature	Cases property		Assessment
Size	Number of variables (excl. environment)	12(17)	Many stakeholders, resources, ecosystems, etc.
	Number of connections between (nonenvironmental) variables	16(35)	Intervention introduces many new interactions between subsystems
Diversity	Number of subsystems (excl. environment)	8(9)	Many types of stakeholders, resources, organizations
Feedback	Number of loops with dynamics on similar timescales	0(3)	Intervention introduces potential for feedback
Adaptive behavior	Number of social interactions	13(31)	Social dynamics are very relevant
Nonlinearity	Number of multiple-input nodes	6(11)	Single linear causal chain unlikely to capture dynamics
Memory	Number of medium and long timescale processes	13(31)	Relevant dynamics are medium to slow
Nestedness	Number of multivariable sub-systems (excl. environment)	3(5)	Subsystems become more nested through intervention
Openness	Number of links from the environment	4(4)	Quite exposed to external influences from the start
	Number of variables in environment	2(2)	Environmental influences are twofold

Note: Numbers in the third column refer to the representation in Figs. 2 and 3.

relevant for the scale of the feedback. The CASES representation and the associated measures such as numerosity and feedback give a large-scale view of a climate mitigation and adaptation project and, thus, facilitate decisions on when and where to invest in smaller-scale data gathering, modeling, and assessment.

One factor in the probability of success of a project is the scale of the intervention. A single, smaller intervention is easier to plan and implement successfully than a large number of interventions. The more or less simultaneous execution of several interventions into a complex system can have synergistic effects that may be enhancing or diminishing the desired outcome or even changing it. One indicator for the potential for such synergistic effects is the presence of nonlinearity (one variable being affected by more than one other variable). In Fig. 3, we can see that many variables are prone to nonlinearity, chiefly among them the variables 'eco health' and 'sustainable tech'. Based on Fig. 3, we now discuss two further OECD DAC criteria.

'Impact' is one of the five OECD DAC evaluation criteria. This criterion measures what (and how much) difference the intervention/program makes. This difference can be negative, positive, intended or unintended. The impact can be in many systems — social, physical, environmental, economic and so on. The CASES representation provides useful assistance to assessing impact since its aim is to include all variables that are affected, either directly or indirectly, by an intervention. A variable is said to be affected indirectly if there is no direct link from an intervention but there exists a linkage path via other variables. As a result, the total impact of an intervention might be bigger than is immediately obvious and even more inclusive than originally planned. Take for example, the two variables 'climate info' and 'subsistence' in Fig. 3.

There is no direct link between them since information alone does not grow food. But there is a linkage path from 'climate info' to 'subsistence' via 'weather predictability' and 'agro yield'. Equally, there is no direct link but a path from 'climate info' to 'subsistence' via 'climate knowledge' and 'eco health'. In this case, all links represent positive correlations and thus they enhance each other. There might easily be cases where the effects are opposite, and an assessment is required whether they will cancel each and whether to invest in further data gathering and modeling.

A third OECD DAC evaluation criterion is 'effectiveness'. Effectiveness examines if the program is achieving its intended objectives. The above discussion on the two OECD DAC criteria 'efficiency' and 'impact' illustrates how they are affected by the number of elements and interactions, the feedback loops and the linkage paths in the system. A similar argument can be made for the effectiveness of a project. Should the analysis be carried out during the early project planning phase, effectiveness may be enhanced by identifying variables that may be unintentionally affected while taking away the impact from those that are meant to be targeted. The remaining two OECD DAC criteria are 'relevance' and 'coherence', and their assessment is outside the scope of this paper.

5. Concluding Remarks

Complexity science provides a wide range of mathematical and computational tools, such as network analysis, agent-based modeling, and differential equations to capture the feedback loops, nonlinearities, and other emergent properties that characterize CAS and SES. Linking the concepts and tools of complexity science and the SES framework to complexity-aware monitoring of development programs is essential for addressing the multifaceted challenges inherent in these programs.

Here, we have introduced a hands-on methodology for M&E of climate mitigation and adaptation projects that is firmly rooted both in the literature on development program M&E and the scientific literature on SES and CAS. Our methodology allows an integrated assessment of a program's complexity. In particular, it highlights sources of potential instability and uncertainty. Being aware of these is crucial for a successful adaptive and responsive project management. Our methodology also identifies correspondences between processes on the ground and complex-systems techniques suitable to study them. As such, our methodology opens up directions for future work: bringing more of the quantitative tools of complexity science, such as network science and time series analysis, to M&E of climate programs.

We consider a closer integration of M&E, SES and CAS crucial for successfully tackling some of the grand challenges posed by a more and more interlinked human–climate system.

The financial investments of the international development sector in mitigation of and adaptation to climate change is considerable. The GCF, for example, has an annual budget of \$1–2 billion. The annual budget of USAID is \$50 billion. Supporting the existing development programs with the best existing science is paramount to success in mitigation and adaptation in the face of climate change.

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