Employing a Systems Thinking Approach in **Climate Risk Assessments**

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Center for Study of Science, Technology and Policy
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1. Introduction

The world is witnessing the increasing impacts of climate change at an alarming rate. Wildfires, floods, cyclones, and heatwaves have become uncomfortably common in our present age. Current research in climate sciences tells us that even if we were to completely stop producing greenhouse gases today, we would still face the detrimental impacts of climate change due to historical emissions (Zickfeld et al., 2013). Additionally, the impacts of climate change are not felt in isolation. We are concurrently seeing the collapse of economic systems, wars, pandemics, and political instability, which heighten the impacts of climate change, making adaptation even more difficult.

Climate adaptation is best implemented when there is a scientifically grounded evidence base, such as climate risk assessments, to direct adaptation efforts. However, the complexity of adaptation is not reflected in any of the current risk assessment methods. Our mental models are seemingly still obedient to linear methods of thinking, which do not capture complex realities on the ground. To plug this gap, we have conceived a project titled 'Modelling Complex Climate Change Risks to Systems' to explore the complex dynamics between the drivers of risks. The project uses STELLA 3.0 (systems dynamics modelling software) to visualise the interplay between the drivers of risk for the agriculture production system at a national scale.

This working paper aims to set the context for our work, present our hypothesis to understand climate risks through a systems lens, and present an example of a causal loop diagram (CLD) created for the agriculture production system to highlight the difference between linear and systems thinking.

Section 2 of the paper lays the conceptual foundation for climate risk and adaptation and sets the problem context for this project. Section 3 briefly introduces systems thinking and the methodology employed for this study. Section 4 reviews the literature on systems, complexity, and climate risk, highlighting the current state of research in this domain. Section 5 presents a comprehensive CLD for the agriculture production system, accompanied with a distilled CLD highlighting key reinforcing and balancing loops. Section 6 concludes the paper with observations on the next steps in this project.

2. Climate Change Risk and Adaptation

The Intergovernmental Panel on Climate Change (IPCC, 2022) in the Sixth Assessment Report (AR6), Working Group Report II (WG II), defines climate risk as

The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. (IPCC, 2022, p.5)

The IPCC AR5 provides a framework that quantifies risk as the interaction of three drivers—hazard, exposure, and vulnerability—with each driver affecting the other in complex and dynamic ways, resulting in risk (Figure 1).

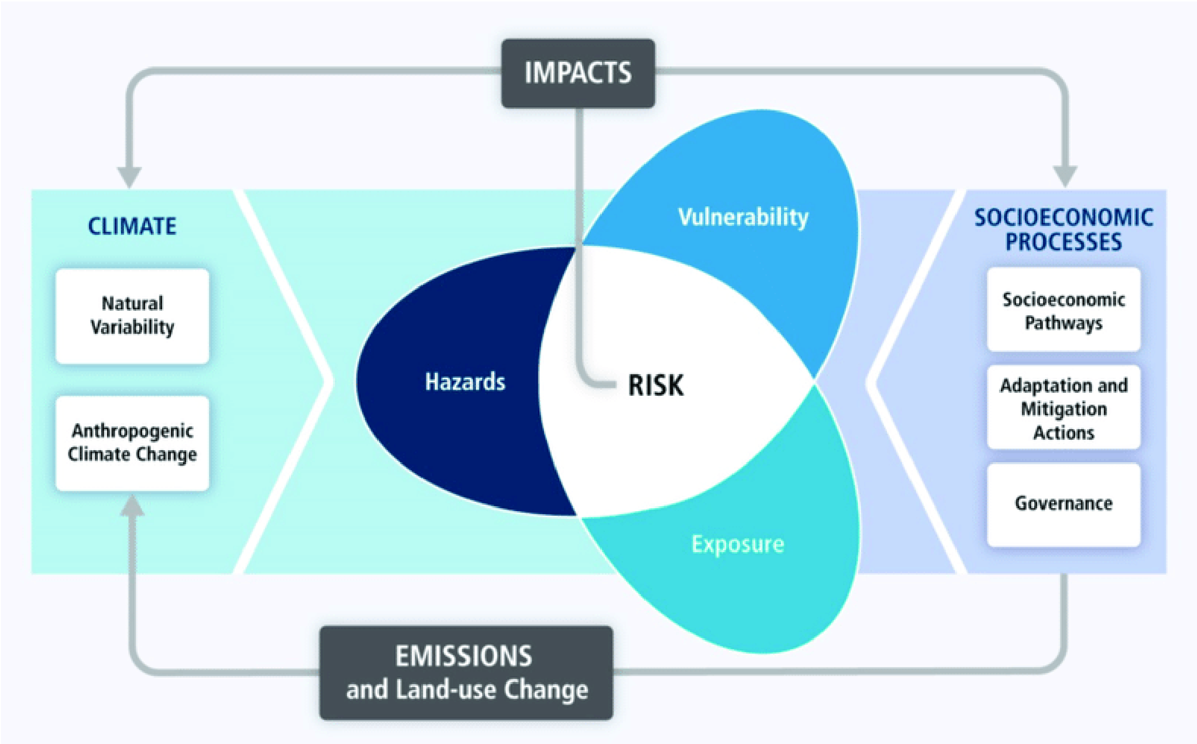

Figure 1: IPCC AR5 Risk Framework

The three drivers of risk are defined by the IPCC (2022) as follows:

Hazard	Exposure	Vulnerability
'The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.'	*The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.'*	*'The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.'*

Risk is computed as the aggregation of hazard, exposure, and vulnerability:

2.1. Contextualising the problem

The goal of a risk assessment is to provide an evidence base to guide actions towards adaptation planning. The IPCC (2022) defines climate adaptation as follows:

In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects. (IPCC, 2022, p.5)

The three drivers of risk can be thought of as policy levers that can be manipulated to lower risk, thus providing a tool for government departments, non-governmental organisations (NGOs), policymakers, and other relevant stakeholders striving to implement adaptation action. While, technically, all the drivers of risk are subject to manipulation, 'hazard' cannot be modified with short- to medium-term policy interventions[1] and, therefore, is not generally considered a lever. Mathematically, each driver is positively related to climate risk; therefore, it follows that climate risk reduction occurs through the reduction of exposure, vulnerability, and hazard, provided the other drivers are constant. The resulting lowered climate risk index indicates that adaptation has occurred (Lempert et al., 2018). However, current literature acknowledges that adaptation processes are not governed by a single judgement at any given point in time (USGCRP, 2018), such as a one-time reduction in exposure or vulnerability, but is a constant process of learning, evaluating, and responding to changes in climate and the system of concern (Vervoort & Gupta, 2018)—an indication of a dynamic system.

In acknowledgement of the above, the IPCC AR6 risk framework has included 'responses' as a new driver of risk (Figure 2), an evolution from its predecessor (Figure 1).

[1] The reduction of a climate hazard can only be achieved through the mitigation of GHGs, which will reflect in the lowering of climate impacts only in the distant future.

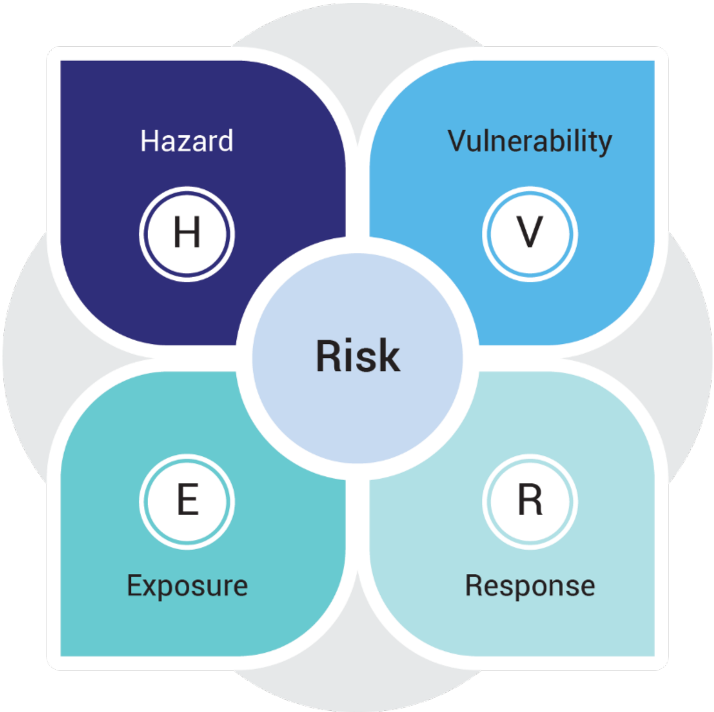

Figure 2: Risk framework including responses, source: Simpson et al. (2021)

Responses are reactions of a community or ecosystem to the impacts of climate change. Short-term responses are better understood as 'coping', which conceptually differs from adaptation (a long-term response). Coping is meant to sustain the basic functioning of a system when an adverse event occurs, whereas adaptation calls for systematic changes in the functioning of the system to resist current and future climate impact (Kattumuri et al., 2017).

To better understand 'responses', let us look at examples. In a village experiencing frequent floods from a nearby river, a typical coping response is for some households to temporarily migrate. Suppose for this same village, local departments construct levees to prevent the river from breaching its boundaries, establish early warning systems, and create a strong local support system, such actions will ensure that the village adapts to current and future floods.

Alternatively, responses can also lead to negative consequences, which is termed 'maladaptation' (Schipper, 2020). In this case, flooding may be exacerbated if the levee were to be constructed without considering geographical features such as slope and vegetation.

The inclusion of responses is, therefore, an acknowledgement of the dynamic nature of climate risk. However, despite complex processes on the ground constantly changing the nature and magnitude of exposure and vulnerability of a system, there are no robust frameworks that can quantify these changes.

To plug this gap, we begin with a review of existing frameworks to assess climate risk and reflect on the 'wicked problem' of climate adaptation (Davoudi et al., 2009; Jordan et al., 2010; Perry, 2015). While, in principle, the concept of adaptation is fairly straightforward (refer to the definition in Section 2.1), complications arise when trying to understand *how* systems adapt, which is primarily because adaptation involves working with complex socio-ecological systems (SES).

In practice, indicators[2] are chosen to represent the drivers, which are in reality abstractions of a complex SES. Changes made to an element of one system will often produce feedback and unintended effects on other elements, leading to non-linear outcomes, which are currently not given enough attention in scholarly and policy domains. The theoretical lowering of risk rests on the assumption that when a driver of risk (exposure or vulnerability) is manipulated, the other driver remains static or constant. But, in reality, a simple reduction in a driver does not necessarily lower climate risk on the ground. This is because risk is dynamic, evolving as exposure and vulnerability change and influence each other.

Research objective

To understand the complex feedback loops that exist between the drivers of risk (hazard, exposure, and vulnerability) and their implication for climate adaptation.

Further, employing a systems thinking approach can offer a possible methodological framework to address the research objective.

[2] 'Operational representation of a characteristic or quality of a system' (Birkmann & Pelling, 2006; Fuchs & Thaler, 2018)

3. Systems Thinking

Donella Meadows (2009) describes a system as 'an interconnected set of elements that is coherently organized in a way that achieves something'. Three key features define a system: elements,[3] interconnections, and function or purpose. Depending on the nature of the system, properties that are adaptive, self-organising, anticipatory, and evolutionary may be exhibited. These emergent properties of a system cannot be understood by only studying the individual elements of a system. For example, in a football team, each player is an individual element of the system performing certain actions during the game. It is impossible to understand the overall strategy of the team by analysing individual players, as it is a cumulative outcome of actions performed by all the players in the team. The cumulative outcome in this case, 'team strategy', is an emergent property of the team that cannot be understood in entirety if individual elements, 'players and their actions', are analysed.

In the climate context, let us look at climate-resilient agriculture. 'Resilience' is a system property. The definition of resilience stresses the ability of a *system* to cope with a hazardous event, trend, or disturbance (IPCC, 2022). For an agricultural system to be resilient, multiple elements—seed variety, timely land preparation and sowing, input application rates, farmer behaviour and well-being, soil health, and so on—are like the players on our football team. It would be impossible to assess or even aid resilience by micro-focusing on any single element. Analogous to the football example, cumulative outcome is a result of a package of agricultural practices aimed at building resilience.

All systems primarily function through cause–effect feedback loops between multiple elements. Such loops ensure the functionality of the system without any strong external governing entity. Meadows (2009) cites poverty, environmental degradation, economic instability, and hunger as issues that have persisted despite decades of targeted programmes to address them. The persistence is because of the system property of these issues. For example, Meadows (2009) asks why poverty still exists despite decades worth of dedicated investment towards poverty reduction. Poverty, like many other persistent issues, exists because of multiple balancing loops (refer to 3.1) across many economic, social, political, and cultural systems.

'No one deliberately creates those problems (poverty), no one wants them to persist, but they persist nonetheless. That is because they are intrinsically systems problems—undesirable behaviours characteristic of the system structures that produce them. They will yield only as we reclaim our intuition, stop casting blame, see the system as the source of its own problems, and find the courage and wisdom to restructure it.' (Meadows, 2009, p.4)

[3] Elements are fundamental units of a system whose interactions make up the system behaviour (Meadows, 2009). This can be trees, shrubs, plants, and animals of a forest, comprising a forest ecosystem or the workers in an organisation, organs in our body, and so on.

3.1. Applying systems thinking

The first step to applying systems thinking is to develop or create the causal loop diagram of the system of concern. Causal loop diagrams describe a cause–effect relationship between two or more variables (Figure 3).

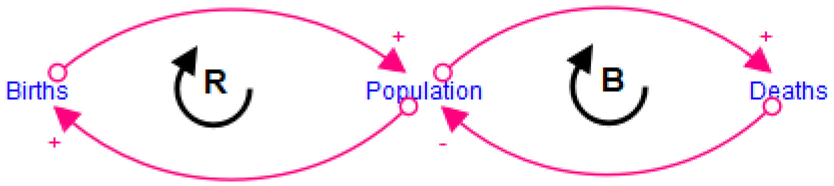

Figure 3: Basic causal loop diagram for population growth and decline

According to Haraldsson (2004), loops can be reinforcing (which can cause the growth or decay of the variables) or balancing (which can check or limit the growth or decay of a variable). In Figure 3, an increase/decrease in births would increase/decrease the population, which would further increase/decrease births, resulting in a reinforcing loop. On the other hand, an increase/decrease in population would increase/decrease deaths, but an increase/decrease in deaths would lead to a decrease/increase in population, thereby limiting the growth or decay of the population, making it a balancing loop.

4. Review of Literature

A literature review was conducted to assess the current state of scholarly research in the broad domain of climate risk assessments, particularly applying systems thinking to climate risk assessments. Given the nascency of the domain, it was important to diversify the search parameters to the largest extent possible. A single search was conducted on Google Scholar on 14 March 2023 with parameters that filtered for complex and interconnected climate risks.

Papers were included for the review based on their relevance in climate risk assessment. Three papers that were not part of the original search results were included in the review, owing to their relevance to the research question.

Our literature review revealed that the inclusion of systems thinking in risk assessment is still at a conceptual and theorisation stage. All of the studies reviewed appreciated the conceptual value and complexity that systems thinking brings into risk assessments (Coetzee et al., 2016). Common to most reviewed studies is the understanding that different sectors are interconnected, and climate can have cascading and complex impacts across SES. Yokohata et al. (2019) have visualised these interconnections between different 'risk items' across the food sector, showing how changes in the climate can affect water, energy, ecosystems, and health, which cascade to impact the food sector. Dawson (2015) has shown that interconnections are not limited to physical sectors and can span social, institutional, and policy interdependencies.

Wassenius and Crona (2022) have explained how complex systems are notorious for non-linear and unpredictable behaviour over time, prompting us to be cautious while conducting climate risk assessments. Future climate risk neglects the inherent randomness in the system, which can lead to the under- or overestimation of climate risk (that manifests because of the dynamics of exposure and vulnerability), potentially resulting in dangerous consequences for adaptation planning.

Finally, Simpson et al. (2021) address the need to include complexity in climate risk assessments by providing a conceptual framework that divides risk assessments into three categories: (1) interactions among single drivers, (2) interactions between multiple drivers, and (3) interacting risks. Category 1 follows the IPCC AR5 assessment that conceptualises risk as the product of the probability of occurrence of hazard, exposure, and vulnerability. Category 2 involves the interactions of drivers between hazard, exposure, and vulnerability—on similar lines as our present hypothesis. Category 3 looks at risks between multiple sectors associated with climate change or other drivers, such as poverty and misgovernance.

Overall, we find that the current literature, while limited, is positively inclined towards the inclusion of systems thinking into risk assessments. This is evident from the fact that none of the papers reviewed showed any significant deviation from our hypothesis. However, the need to advance the present thinking into empirical studies is a gap that this review clearly highlights.

The CLD is a first step towards re-envisioning climate risk assessments through a systems thinking lens. Section 5 applies the systems thinking that we presented earlier. To illustrate our hypothesis, we apply this to an agriculture production system to map the interconnections between exposure, vulnerability, and hazard.

5. Causal Loop Diagram of the Agriculture Production System

We have developed a CLD for the agriculture production system in India to demonstrate the value of applying systems thinking. We have mapped the system such that it is region-neutral as there is very limited understanding and literature on the application of systems thinking for climate risk assessments at this point in time. However, we acknowledge that adaptation should be understood locally. Further, to provide a reasonable bound for our system, we have restricted ourselves to the production process alone, that is, crop cultivation and livestock rearing. Post-production processes such as harvest, storage, packaging, sale, and transport are not considered in the current study but will be included in subsequent iterations of the CLD.

The rationale for the choice of agriculture production system includes the following:

1. Agriculture is a good example of an SES.
2. India being a predominantly agrarian country, there has been extensive research on various components of the agriculture production system, creating a rich repository of secondary literature. This lends itself to a deep understanding of the system and infers all possible feedback loops in the system.
3. The authors have considerable experience working on agriculture-related projects in India.

We consider the agriculture production system to be at risk from three climate hazards: extreme rainfall,[4] drought,[5] and heatwaves.[6] While extreme rainfall and drought are parameters that can be modelled using rainfall as a proxy, temperature is the proxy for heat stress. The system has been further divided into four sub-components:

1. Water
2. Land
3. People
4. Livestock[7]

[4] 'An extreme/heavy precipitation event is an event that is of very high magnitude with a very rare occurrence at a particular place. Types of extreme precipitation may vary depending on its duration, hourly, daily or multi-days (e.g., 5 days), though all of them qualitatively represent high magnitude. The intensity of such events may be defined with a block maxima approach such as annual maxima or with peaks over threshold approach, such as rainfall above the 95th or 99th percentile at a particular place' (IPCC, 2022).

[5] 'Drought' refers to 'hydrologic drought', which is defined as 'a period with large runoff and water deficits in rivers, lakes and reservoirs' (IPCC, 2022).

[6] 'Heatwaves' are defined as 'a period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months. Heatwaves and warm spells have various and, in some cases, overlapping definitions' (IPCC, 2022).

[7] Livestock is technically an agriculture-allied sector. Our experience with Indian agriculture has shown us that most farmers choose to rear livestock as supplementary farm income, and this has warranted its inclusion in our system.

5.1. Description of the CLD

The CLD in Figure 5 (Appendix) is structured to show each sub-component of the agriculture production system separately. Each sub-component has a single variable that serves as the node that is connected to other sub-components. For example, 'Water available (litre/ha)' in the 'Water' sub-component is the variable that connects to 'Land'. Similarly, 'Farm income' in the 'People' component connects to 'Land' via 'Total crop production (tonnes)'.

Figure 5 (Appendix) is a comprehensive representation of the agriculture production system in India. However, to analyse the dynamics of key exposure and vulnerability variables, it is useful to distil the CLD into one that represents key reinforcing and balancing loops (Figure 4).

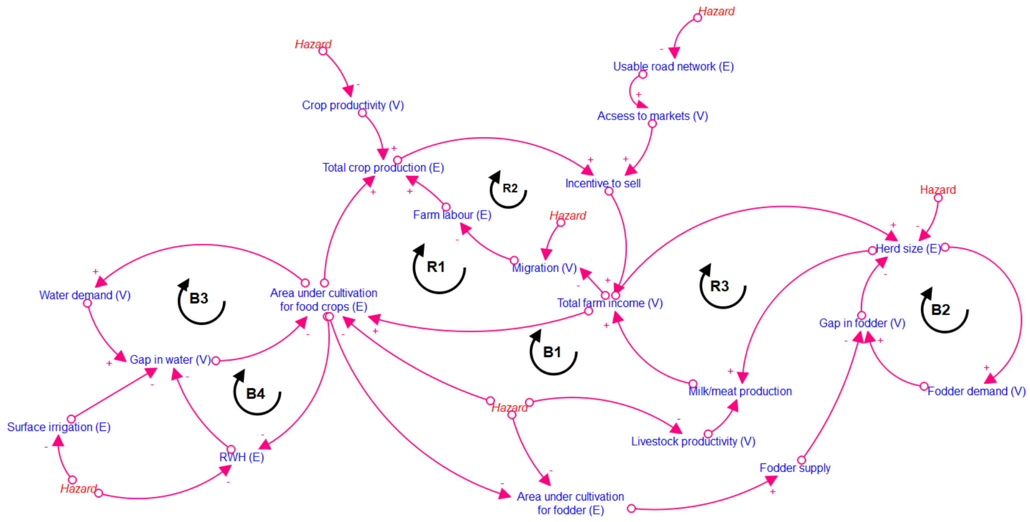

Figure 4: Key reinforcing and balancing feedback loops of the agriculture production system. Accompanying each variable in parentheses is the risk driver that the variable represents: exposure (E) and vulnerability (V).

It is evident that exposure and vulnerability variables are deeply interconnected. To understand the dynamic nature of risk, we present two examples to unpack the concept of balancing and feedback loops.

B1: Balancing loop

Total farm income, which is a cumulative income derived from the sale of crops and milk/meat products, is a vulnerability indicator that is significant in this CLD. One can see that it has the highest number of arrows that are coming in and going out of it, signifying its importance in this sector. B1 tells us that as 'Total farm income (V)' increases, farmers are either able to buy more land or purchase more inputs that allow them to increase the 'Area under cultivation for food crops (E)'. Here, we see a vulnerability indicator influencing exposure. The cultivation of food crops competes with the cultivation of fodder. Hence, as the 'Area under cultivation for food crops (E)' increases, the 'Area under cultivation for fodder (E)' decreases. This decrease reduces the total fodder supply, which increases the 'Gap[8] in fodder (V)'.

The increase in 'Gap in fodder (V)' means that the supply of fodder is decreasing or the demand for fodder is increasing (or both). In this loop, the gap has increased because of the decrease in the supply of fodder. The increasing gap reduces the 'Herd size' because of the lack of food for the

[8] Gap variables represent the gap between the demand and supply of a variable, such as fodder.

sustenance of livestock. Subsequently, 'Milk/meat production' decreases, which translates to lower 'Total farm income (V)'. We had initially started this loop assuming an increase in 'Total farm income (V)'. As this effect cascaded through other related variables, 'Total farm income (V)' has reduced, resulting in a balancing loop.

Under a traditional climate risk assessment, one needs to reduce exposure or vulnerability to reduce risk. B1 shows us that tampering with one or two variables will have cascading effects that will increase or decrease risk non-linearly. This is not a predictable outcome if the IPCC AR5 framework for risk assessment is applied (see Section 2.1).

R1: Reinforcing loop

As the 'Area under cultivation for food crops (E)' increases, the 'Total crop production (E)' increases, which subsequently increases farmers' incentive to sell the crops. The 'incentive' variable is influenced by 'Access to markets (V)' where crops could potentially be sold, which is further influenced by the 'Usable road network (E)'. As this incentive increases, the farmer earns a higher 'Total farm income (V)'. As displayed in *B1*, higher incomes mean farmers can invest in increasing their cropping area. Therefore, an initial increase in 'Area under cultivation for food crops (E)' cascades to further amplify itself.

5.2. Linear versus systems thinking

The agriculture production system CLD presented in Section 5.1 provides an opportunity to briefly discuss the differences that emerge or the issues that go unnoticed or are not captured when linear thinking is applied as opposed to systems thinking.

In traditional linear thinking, we study relationships between two or three variables and assume that they remain constant, ad infinitum. Further, we see these relationships as pure cause–effect. However, in reality, systems comprise multiple variables that are complex, adaptive, and continuously evolving.

If we employ a linear thinking lens for the agriculture production system, we will invariably look at the relationship between a few selected variables at the expense of others. In other words, we miss the forest for the trees. For example, let us consider 'Area under cultivation for food crops (E)', or AUCFC, in Figure 4. This variable influences 'Water demand', 'Total crop production', 'Area under cultivation for fodder', and 'Rainwater harvesting' (RWH).[9] A linear approach would appreciably quantify how a change in AUCFC influences the other mentioned variables. This is a one-way relationship. A cause (change in area under cultivation) has an effect (a change in other variables). In this case, a linear model would quantify how an increase in AUCFC reduces the potential or areas available for RWH; however, loop B4 shows that as RWH reduces, the 'Gap in water' increases, which reduces AUCFC.

A systems perspective goes one step further to understand how these changes can cause feedback. It is not only concerned with how AUCFC affects RWH but also how that change, in turn, affects AUCFC. Similarly, looking at loop R1, linear models can display the positive relationship between AUCFC, 'Total crop production', and 'Total farm income'; however, they do not account for how an increase in farm incomes can have feedback to AUCFC—in all probability, an increase.

[9] Farmers usually set aside a section of their lands to harvest rainwater in the form of farm ponds. Therefore, there is competition between land use for agriculture and the farm ponds. As the area for agriculture increases, there is less area to harvest rainfall.

In this context, it is important to review the IPCC risk framework. As noted in Section 2.1, the purpose of computing climate risk is to aid in adaptation planning. Planning, by definition, means taking steps in the present to achieve some desired goal in the future. In the context of climate change, that goal is to have societies that have successfully adapted to climate impacts. To achieve this, the IPCC risk framework allows researchers and policymakers to project hazard, exposure, and vulnerability into the future to compute future risks from climate change, which would serve as information to guide adaptation planning. However, such projections are normally not dynamic. When exposure, vulnerability, and hazard are projected into the future, they are done independently of each other; that is, future exposure is not dependent on future vulnerability and future hazard and vice versa. These are usually projected using historical trends or through regression analysis. To that end, non-dynamic projections do not capture the complex realities of SES. This may prove detrimental to adaptation planning.

For good adaptation planning, it is important to (some degree) foresee the consequences of our actions today in the future. Here lies the merit in systems thinking and modelling. A systems model allows us to explore multiple future adaptation planning scenarios. These models allow us to tweak exposure and vulnerability variables in the present to visualise their ripple effects across a system in the future. Therefore, one can adjust these variables to visualise the permutations and combinations that give the lowest risk value and, therefore, the highest adaptation outcome. Such information would prove highly valuable to policymakers who need to take concrete actions in the present to achieve significant adaptation in the future.

6. Next Steps

Employing a systems thinking perspective indicates that risk and adaptation are complex domains that require pre-emptive analysis before an intervention is implemented on the ground. Research in agriculture so far has done well to focus on individual elements—farm income, crop productivity, farm labour, and so on—or, at best, a few isolated feedback loops. However, our CLD demonstrates how change in one element can have cascading consequences on other elements in the agriculture production system. Using linear models, we simply are not able to predict the consequences of an intervention on other elements of a system beyond the narrow focus, potentially leading to adverse consequences. This is perhaps why, despite many positive interventions in agriculture, the situation on the ground has not improved significantly. Agriculture in India is not at an industrial scale as in many other Western countries. Here, the social and the biophysical elements are inseparable; they make and remake each other. This makes policy interventions in the sector a challenge.

In the CLD presented, we have not explicitly represented 'response' as a separate driver of risk, as every feedback loop in the system is actually a response. Therefore, the quantification of the CLD would be one of the first attempts within academic literature to successfully quantify response as a driver of risk. If our hypothesis is true, a systems thinking approach can offer a vastly different analysis from traditional linear models. This would greatly alter the overwhelmingly linear mode of thinking employed by researchers and policymakers today for dealing with issues in agriculture. The danger of a linear thinking approach is that it could lead us to believe that risk reduction (in theory) is a simple process. CLDs help us visualise all the interconnections between seemingly disconnected elements of a system.

The next step of this work involves quantifying this CLD by converting it into a stock and flow model on the STELLA 3.0 software. National-level data from sources such as the National Sample Survey of India (NSSO), Census of India, and India Water Resources Information System (WRIS) would be used to supply baseline data to the elements of the CLD. Based on the timescale of the model, we would expect to visualise the dynamics between exposure, hazard, and vulnerability to explore the following research questions:

1. How do dynamics between exposure and vulnerability affect each other over a given timeline? What are the sensitive variables?
2. How does the level of climate risk vary across different agricultural and livestock investment choices?
3. How is the trade-off between the area for crop production and the area for fodder cultivation managed?
4. Are there tipping points in the system? What causes the system to tip?

While these questions are good starting points, we anticipate that as we quantify this system, the questions will be refined further, and perhaps more important questions will be raised. Results from this simulation would prove our hypothesis and establish a conceptual rationale to review our current methods for climate risk assessment.

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8. Appendix

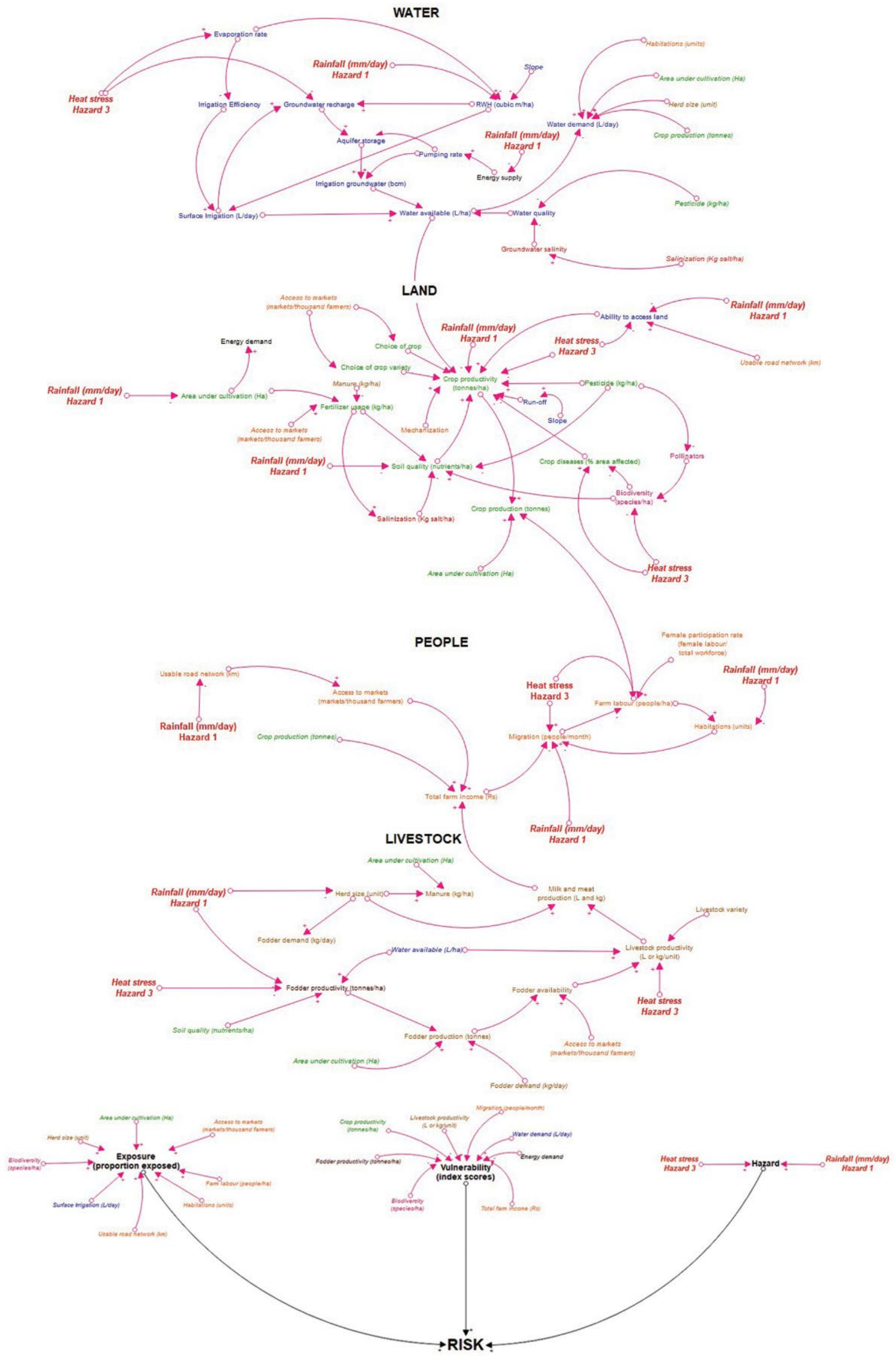

Figure 5: Comprehensive CLD of the agricultural production system

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