Integration of Resilience Markers framework into Socio-Ecological System: Case Study of Agriculture in Dadeldhura, Nepal

Abstract

The concept of Resilience Markers (RM) (Back et al., 2008) has been commonly applied in organizational sciences to identify beneficial markers, behavior or actions that enhance the resilience of a system. However, such frameworks have yet been applied in a Socio-Ecological System (SES) framework (Ostrom, 2009) as an formal investigation of system resilience in an SES context. Herein, we explore how RM can be integrated into an SES system by applying it the case study of the recent shift in agricultural trends in Dadeldhura, Nepal. Through system dynamics modelling, we reveal the provision of irrigation systems to only support profitable, yet drought-vulnerable, vegetable production results an over-reliance on growing cash crops. To mitigate the effects of climate change on the resilience of the agricultural system, we recommend policies in support of the production of diverse drought-resistant cereals crops and promotion of ecological awareness.

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INTRODUCTION

Traditional livelihoods in Asian countries are interconnected to agrarian societies, in which agriculture plays a vital role in sustaining the local population with a stable supply of food for self-subsistence. In the 21st century, many Asian countries have attempted to make the transition from subsistence farming to commercial farming, thus impelling the production of more cash crops for export to generate economic growth (Hart et al., 1989). One of the most prominent countries that have undergone this transition is Nepal. Since the 1990s, Nepal's agricultural policies, particularly the Agricultural Perspective Plan (Mellor, 1995), has advocated the growth of more cash crops, particularly vegetables, to generate more Household Income for small farmers (Joshi et al., 2007, DiCarlo et al., 2018). While this transition towards a market-orientated agriculture has catalyzed the growth of Nepal's economy, it has also precipitated new challenges such as the increased vulnerability to the adverse effects of climate change and a loss of biodiversity in the ecological environment (Mahendra Dev, 2012).

Geographically, Nepal is prone to various natural disasters, especially droughts that renders its agricultural sector susceptible to supply shocks (Adhikari et al., 2020). According to the Food and Agriculture Organization (FAO), vegetables such as cabbage are highly sensitive to the impact of water shortages caused by droughts, whereas cereals such as millet and wheat are less drought-sensitive (Brouwer et al., 1989). Additionally, the effect of climate change further exacerbated the impact and frequency of droughts in Nepal, which can potentially lead to significant losses in the Household Income of Nepalese farmers (Dahal et al., 2016). With these challenges in mind, our research attempts to explore the impact of such transition and its policy implications in ecologically fragile spaces of Asia such as the Himalayan landscape, with a particular focus on the case study of "Shift from Cereal Crops to Cash Crops" in Dadeldhura district in the Himalayan country of Nepal. Through our study, we show how the concept of resilience markers (RM) framework (Furniss et al., 2011, Back et al., 2008) – an approach to identify sustainable practices for engineering reliability in system that is commonly applied in organization and management – can be integrated in an nuanced social-ecological system (SES) context (Preiser et al., 2018). In doing so, we show how RM can help us to rethink how policies can be tailored to facilitate resilience in SES, as an extension of previous works on this topic (Herrera and Kopainsky, 2020).

LITERATURE REVIEW

To examine our integration of the RM framework in an SES context, our literature review is organized to first introduce the notion of SES as a standalone concept, followed by a discussion on how we conceptualize the application of RM framework in an SES system, and finally we outline the objectives of our present work.

Social-ecological systems (SES)

Social-ecological systems is defined as a complex, constantly adapting system where social, economic, ecological, and other components are strongly interconnected (Young et al., 2006). Agriculture can be categorised as a complex SES where human and environmental factors interact and co-evolve continuously with a high degree of uncertainty (Rivera-Ferre et al., 2013). Nobel Laureate Elinor Ostrom proposed the SES framework to analyse interactions between government, economic resources, and social factors to understand issues of resource crisis (Vogt et al., 2015). The framework comprises of Resources Systems, Governance Systems, Resources Units and Actors that interact in complex and context-specific ways to generate emergent outcomes (see **Appendix S1** for the scheme of SES framework).

While the SES framework has been widely utilised to study Agriculture in Latin America (Castro-Díaz et al., 2019), there is a dearth of literature applying the SES framework in agricultural contexts of Asia communities. Thus, our research in agriculture in Nepal provides a novel opportunity for the application of the SES framework in Asian societies. Additionally, despite its extensive applications to study human-nature systems (Fitzhugh et al., 2019, Dean et al., 2021), there are methodological disparities in the application of the SES framework across authors in different fields. For instance, studies utilising the SES framework have employed a wide array of techniques in data collection and data analysis, each with its own analytical frameworks and unique set of vocabulary to communicate ideas. Therefore, we postulate that the future research on the SES framework still requires a common language to build upon knowledge from one another.

Although the SES framework provides a conceptual lens to investigate interlinkages between society and eco-systems, there are obstacles in translating the knowledge accumulated through this framework to policymaking. SES framework strives to go beyond indicator-based studies and tries to look at social-ecological issues more longitudinally. However, without a common language for policy communication, SES studies largely remain academic without policy uptake (Gallopín, 2006). Notable works by Kopainsky and colleagues have made progress by incorporating system dynamics (SD) modelling for resilience assessment (Herrera and Kopainsky, 2020) and generating tailored policies for enhancing the resilience of SES systems (Herrera de Leon and Kopainsky, 2019). Herein, our work aims to extend the conceptual framework of Resilience Markers (RM) and seeks opportunities to integrate it within the SES framework. In doing so, we aim to understand how the RM framework can be applied to re-think how resilience policies can be shaped to enhance the resilience of an SES.

Integrating Resilience Markers within SES

Resilience, as defined in the social-ecological systems literature, is the ability of the system to recover from unexpected disturbances and the extent of its capacity to adapt and maintain its original functionalities (Hosseini et al., 2016). The RM framework is based on literature in Resilience Engineering, which helps to provide an organized structure for identifying and communicating strategies to manage the resilience of a system. It is a hierarchical structure comprising of Markers, Strategy and Observation levels organized from the highest level of generalizability to the lowest as shown in **Figure 1** (Back et al., 2008). The highest level is the *Resilience Marker*, which are generalizable system features, indicators, or procedures that enhance the resilience of the system that can be generalized across different domains. In the middle is the *Resilience strategy*, which are tangible and specific implementations of the markers in particular context that reinforces system resilience. The lowest level is the *observation of* resilience which manifests in individual behaviors and actions, whereby action undertaken by individuals in the system are shown to be influenced by the implementation of the strategies.

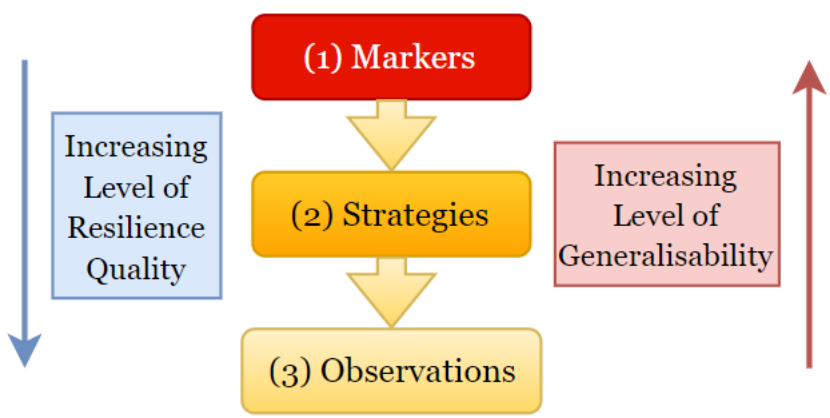

Figure 1. Resilience Markers Framework, adapted from (Back et al., 2008).

The purpose of the RM framework is to establish an easily identifiable connection between abstract theory and specific observations and operationalize resilience for real-world policymaking. This hierarchical framework can be applied to generate more concrete proposals for improving system resilience and provide a basis to compare policies of high generalizability across different sectors and contexts, particularly in small teams across organizations (Furniss et al., 2011). Herein, our research proposes the integration of Resilience Markers into the existing SES framework for novel policy insights, by exploring the inter-linkages across society and ecosystem and operationalize the integration of the RM framework into SES, systems thinking, and systems dynamics modelling will be applied as a methodology.

Objectives of research

Our research aims for the following objectives: (1) to explore the dynamic interlinkages between social and ecological factors shaping the shift in agricultural pattern in Dadeldhura district, in Sudurpashchim Province of Nepal, using systems thinking; (2) to investigate the impact of hazard situations in Dadeldhura using a scenario building exercise through system dynamics modelling; and (3) test plausible policy strategies in the system dynamics model and discuss them through the RM framework for policy communication and application.

METHODS

In order to build our system thinking and dynamics models, we first develop a Causal Loop Diagram (CLD) to visualize the causal-effect relationships between different variables in a system. A set of Reference Modes are generated from field data provided by researchers from the International Centre for Integrated Mountain Development (ICIMOD) (Lipy Adhikari, 2020), which are used to explore the trend of the problem and validate our model. Subsequently, the Stock and Flow Diagram (SFD) is formulated to model our problem. The 5-step modelling framework introduced by Sterman is utilized in the modelling of the system dynamics (Sterman, 2002). All of our modelling works are conducted using Vensim Software developed byVendetta Systems (Eberlein and Peterson, 1992).

Reference Mode

Two reference modes are constructed based on the area of land used for vegetable and cereal crop production in Dadeldhura District. The data is obtained from the Government of Nepal Ministry of Agriculture and Livestock Development (2019). Graphs for “Area for Vegetables” and “Area for Cereals” are as shown in **Figure 2** and **3**, respectively.

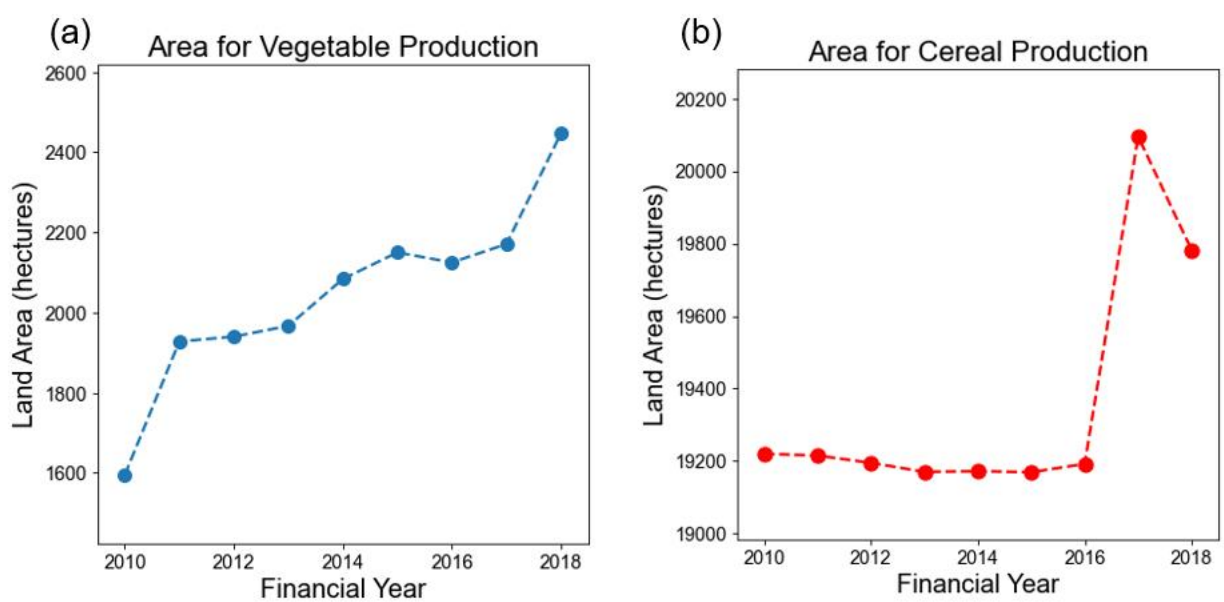

Figure 2. Area of land used for vegetable production from 2010 to 2018 (a), Area of land used for Cereal Crop production from 2010 to 2018 (b). Note that the x-axes are scaled differently.

In addition, we obtained the field data on the vegetable production in Dadeldhura District from researchers from ICIMOD (Lipy Adhikari, 2020). Although the availability of our data is limited from year 2010 to 2015, we are able to observe a slight increasing trend in vegetable production as shown in **Figure 3**.

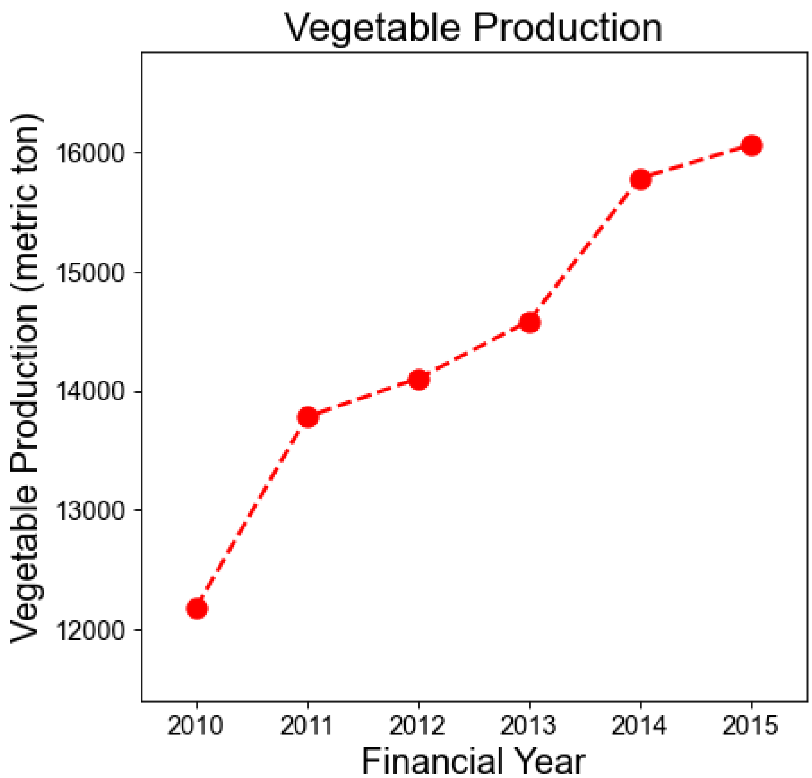

Figure 3. Reference mode for Vegetable Production

From our reference mode, there is a significant increase in the land utilized for Vegetable Production from 2010/2011 onwards. On the other hand, the land use for Cereal Crops remained relatively stagnant from year 2010/2011 to 2018/2019. These changes illustrate the increasing preference of farmers to cultivate vegetable crops that are sold to the market for profit, compared to Cereal Crops that are historically cultivated for self-subsistence. According to the ICIMOD's field report, the four main causes of this trend are increasing Market Demand for vegetables, increased Government Subsidies for vegetables, less occurrence of Wildlife Intrusion on vegetable crops and Male Outmigration. We will make use of these four variables and explore the inter-linkages in the system using our CLD.

Causal Loop Diagram

Based on the reference mode, our CLD is constructed using Vensim™ as shown in **Figure 4**. The key variables in the feedback loops are indicated in *italics* and concepts that can be influenced by policies in **Bold**. The rationale behind our CLD is provided in the following section.

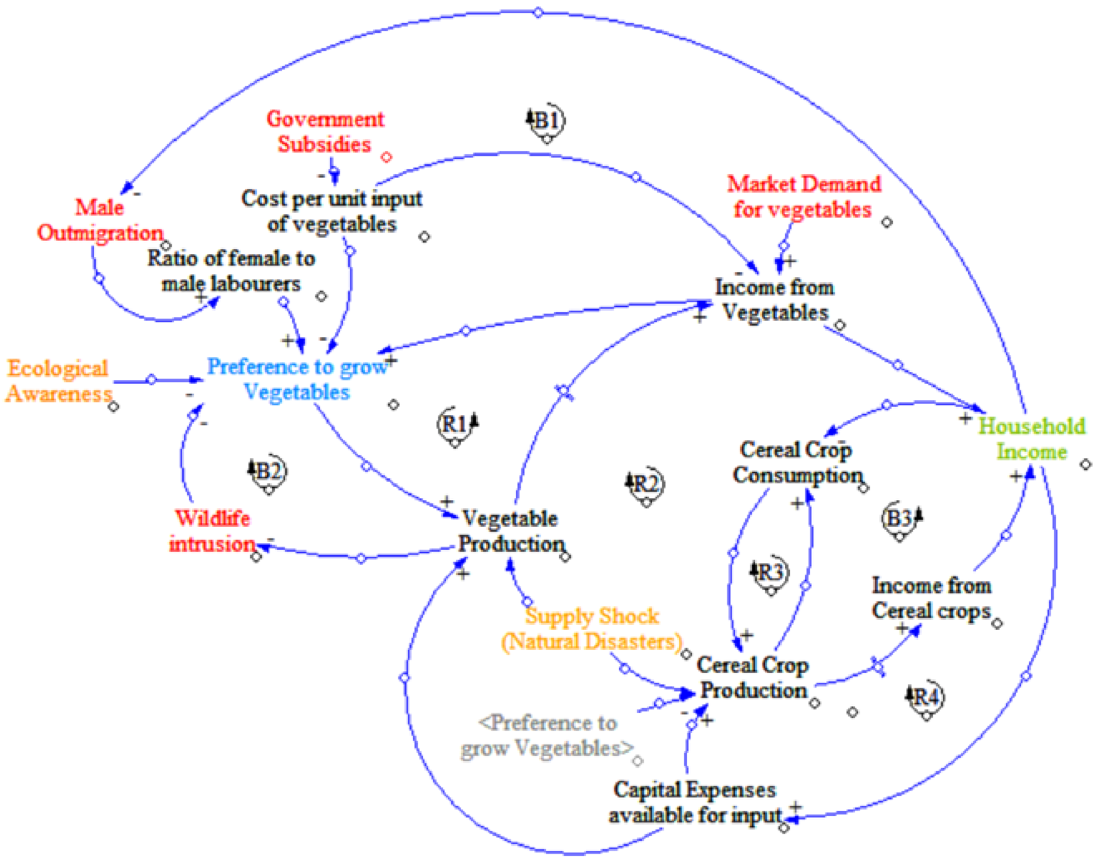

Figure 4. Causal Loop Diagram developed for our system dynamics model.

We start by examining the key reinforcing feedback loop **R1**. In **R1**, we attribute an increase in *Preference to grow vegetables* to lead to an increase in *vegetable production*, this causes an increase in *income from vegetables* and eventually a *greater Preference to grow vegetables* again. The impact of exogenous variables, namely **Government Support** and **Market Demand,** has led to a further increase in *Income from vegetables*.

We theorized that **R2** is a dominant reinforcing loop that would result in an increase in *vegetable production*. As *Income from vegetables* increase, the generated *Household Income* will increase. This will lead to more *Capital Expenses available for input* in the next crop season, which will result in greater *vegetable production*.

On the other hand, the balancing loop **B1** arises from **Male Outmigration.** When *male out-migration* increase, there is a greater *ratio of female-to-male* labourer, leading to an increase in *Preference to grow vegetables*. This will cause an increase in *vegetable production* and *Household Income.* A rise in *Household Income* will result in a decrease in *male outmigration* as there is less incentive to migrate to seek alternative sources of income.

Another balancing loop **B2** is influenced by **Wildlife Intrusions.** As *wildlife intrusions* increase, there is a greater *Preference to grow vegetables*. This will lead to an increase in *vegetable production*, and subsequently a fall in *wildlife intrusion*.

Taking the combined effects of **R1** and **R2**, the behaviour of *Vegetable Production* will show an initial exponential increase, then the increase gradually plateaus with characteristics of a goal-seeking behaviour as **B1** and **B2** take into effect. In theory, this will create an S-shaped curve (i.e., a logistic growth). However, we hypothesize that **R1** is the most dominant feedback loop as Nepalese farmers are most concerned about the increased income generated by *Vegetable Production* (Lipy Adhikari, 2020). Thus, we postulate that the graph of *Vegetable Production* will resemble an exponential growth behaviour more than a goal-seeking behaviour. The increase in *Vegetable Production* is projected to result in a gradual increase at the start, followed by an exponential increase in the long run.

To quantify the welfare of the Nepalese farmers, *Household Income* will be our major indicator of the welfare of the Nepalese farmers. We will be testing the effect of Natural Disasters, particularly Droughts on *Vegetable Production* and *Cereal Crop Production*. This, in turn, will allow us to investigate the effect of the feedback loops on *Household Income.*

Stock and Flow Diagrams

The CLD provides a basis for generating our SFD in our system dynamics simulation model. We provide the full SFD in **Appendix S2**, as well as the documentation for the SFD in **Appendix S3**. We calibrate our model to follow the reference modes for behavioral validation of the model. In general, validation is the suitability of the model for the purpose of the research (Senge and Forrester, 1980). Subsequently, we conducted sensitivity analysis by changing the values of relevant parameters for scenario construction and testing the efficacy of policy interventions in the model.

Since some of the variables have different order of magnitudes and units, a Scaling Factor of 10−20 is introduced to calibrate the variables influencing Preference to grow vegetables such as Wildlife Intrusion and Ecological Awareness. In our model, the Preference to grow vegetables is a value that lies between 0 and 1. If Preference to grow vegetables is equal to 1, all of the Capital Expenses for Crop Production will be allocated towards Vegetable Production and vice versa. The major event for scenario testing is "Natural Disasters", which is modelled by a Poisson Distribution following many researchers in systems dynamics literature such as in modelling disturbances to food security (Herrera de Leon and Kopainsky, 2019). We provide further details of how we model the frequency of droughts in **Appendix S4**.

In the SFD, the parameters Shift, Stretch, Frequency are the parameters used in the Poisson Distribution function as shown in **Figure 5**. The Impact of Natural Disasters refers to the magnitude of damage sustained by the crop production in units of metric tons.

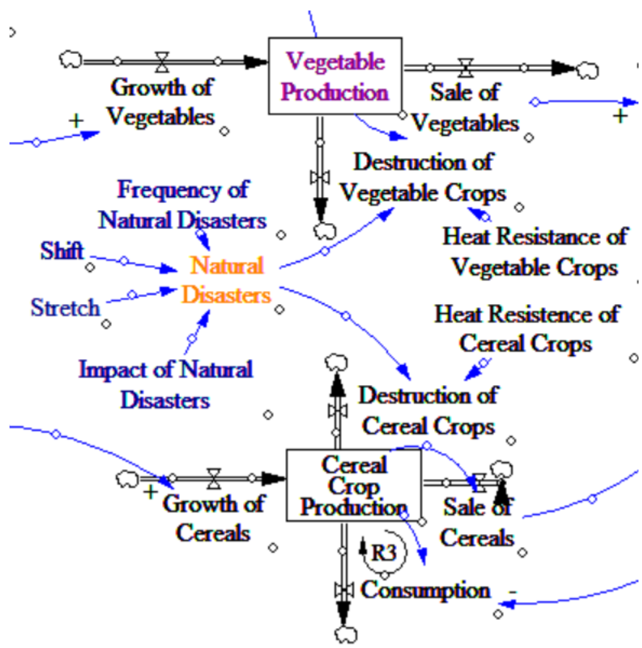

Figure 5. Sub-System on Natural Disasters

Other key variables added to the SFD model are the Heat-Resistance of Vegetables and the Heat-Resistance of Cereals. According to Food and Agricultural Organization (FAO), traditional cereals such as Millet and Wheat are in the low and low-medium sensitivity range to the impact of water shortages, while vegetables especially potatoes and fresh greens are highly sensitive (see **Appendix S5**).

Since the majority of vegetables are in the medium-high sensitivity range, this indicates that most Vegetables are less heat resistant compared to Cereal Crops. Thus, we postulate that the constant Heat Resistance of Vegetables is lower at 40% than the constant Heat Resistance of Cereal Crops at 80%. This means that in the event of a drought, Vegetable Production will suffer a decline of 60% of the Impact of drought, while Cereal Crops Production will only decline by 20% of the Impact of drought.

Sensitivity Analysis

Sensitivity analysis is performed to observe how increasing the Frequency of Droughts in different scenarios would affect the Household Income. The Frequency of Droughts represents the Mean frequency (λ) in the Poisson Distribution. The parameters of other variables in the Poisson Distribution such as the Shift and Stretch are kept constant as shown in **Appendix S4**.

Policy Intervention

Two policy interventions are tested using our simulation model. The first policy is to increase Ecological Awareness. The second policy is to increase Irrigation Support, which encompasses either Irrigation Support for Cereals or Irrigation Support for Vegetables. We provide further details on how we model the effects of these policies in the following section.

Policy 1. Improving Ecological Awareness

In this context, Ecological Awareness refers to how well-informed Nepalese farmers are to the increased vulnerability of growing heat sensitive vegetables. As shown in our subsystem in **Figure 6** below, an increase in Ecological Awareness leads to a decrease in Preference to grow vegetables.

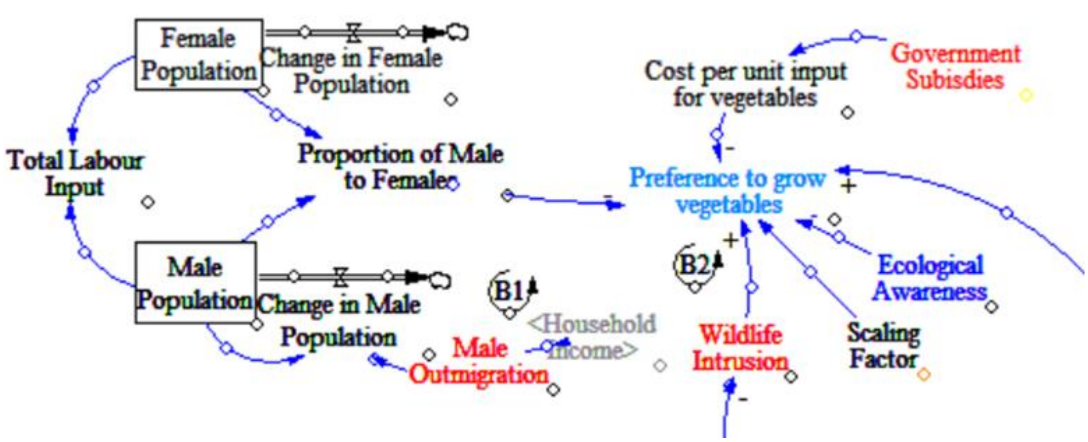

Figure 6. Sub-System on Ecological Awareness

The effect of Ecological Awareness on Preference to grow vegetables is modelled by a shifting Logistics Function following the diffusion theory of ideas and information (Rogers et al., 2014). As the Ecological Awareness increases, preference for vegetables will increase at a slower rate and the maximum possible value of preference for vegetables (between 0 to 1) is also decreased. Further details on this section are provided in **Appendix S6**.

A policy that increases ecological awareness will reduces the effect of reinforcing loop **R1** and **R2** as discussed previously. The reduction in Preference to grow vegetables will result in a more balanced allocation of Capital Expense allocated towards Vegetables and Cereals Crops. By reducing their reliance on heat-sensitive Vegetables, Nepalese farmers will reduce their losses in Household Income in the event of droughts.

Policy 2. Providing Irrigation Support for Vegetables and Cereal Crops

The Nepalese government provides additional Irrigation Support for Vegetables by supplying irrigation systems and water tanks to promote vegetable production as shown in **Figure 7**. This increases the Total Factor Input for Vegetable Production, leading to more Vegetable Production. Although there is currently negligible government support for Cereal Crops, we propose that providing some support like Irrigation Support for Cereals is another viable policy intervention to increase the growth of cereals that are more heat-resistant in the event of droughts. In our scenarios, we will be testing the effectiveness of these Irrigation Support schemes for stabilising Household Income in the event of drought and climate change. In this context, Household Income refers to the collective household income of all the farmers in the Dadeldhura district.

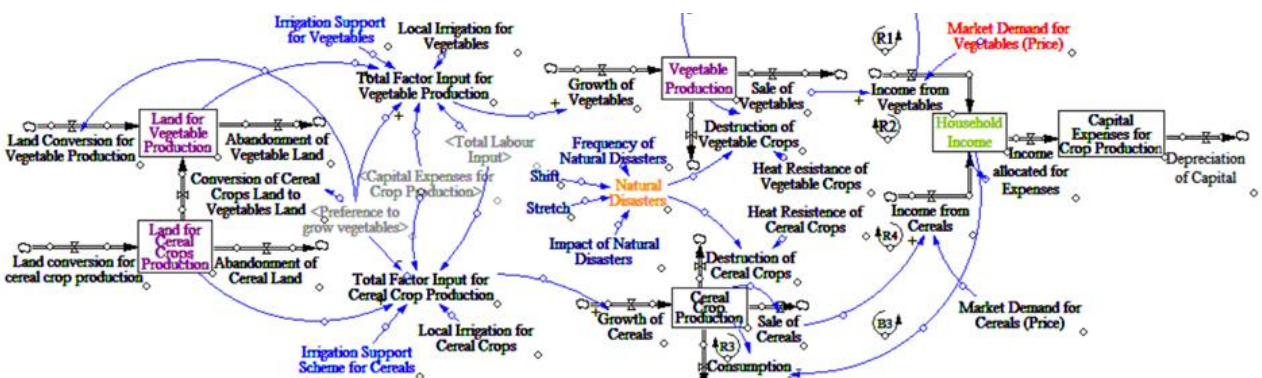

Figure 7. Portion of SFD on Irrigation Support

Policy 3. Providing Irrigation Support and increasing Ecological Awareness simultaneously

Additionally, we will investigate the effect of changing both Ecological Awareness and Irrigation Support simultaneously in the event of Climate Change. This allows us to observe if there is a synergistic effect between the two policies in reducing the impact of Droughts. The cost of providing substantial irrigation support could be very high both in terms of government expenditure as well as the excessive consumption of water resource itself. Hence, it will be worthwhile to investigate a balance between increasing Ecological Awareness and the extent of Irrigation Support required to allow Household Income to recover. This prevents an excess strain on government expenses in providing Irrigation Support Schemes in an attempt to rise Vegetable Production, and consequently the Household Income.

RESULTS

The simulation results generated from the SFD to investigate the dynamics of the system under different Scenarios. We first simulate Baseline and Disaster Scenarios (under subsection 1) to explain the simulation graphs of Baseline and Disaster scenarios in the absence of policy intervention, namely Baseline Scenario, Scenario with Drought in business-as-usual and Scenario with Droughts in a Climate Change World. Subsequently, under Policy Testing (subsection 2), we will investigate the simulation results of different policies in the Scenario of Droughts in a Climate Change World.

Scenario 1. Baseline and Disaster Scenarios

1.1. Baseline Scenario - Base Case without Droughts

The results from baseline simulation are provided in **Appendix S7**, which shows a gradual increase in the Land for Vegetable Production, while the Land for Cereal Crops Production remains relatively constant. Our model also show that the Production of Vegetables resembles an increasing exponential behaviour, which is outlines a key assumption of our model behaviour. In the short-term (i.e., 1-5 years), this assumption may be valid, but in the long run (possibly more than 10 to 20 years), a survival curve is perhaps a better baseline model than exponential growth as we expect resources such as fertilizers, labour and land become more limited. Nevertheless, we believe that our model behaviour are still appropriate for the purpose of analysis for the next 10 years.

Initially, from year 1 to year 4, there is an initial decline in Vegetable Production due to the effects of Balancing Loops **B1** and **B2** as discussed above. However, from year 4 onwards the reinforcing loop **R1** and **R2** dominates and caused Vegetable Production to rise exponentially. The exponential increase in Vegetable Production led to an exponential increase in Households Income from year 4 onwards.

1.2.Disaster Scenario 1 - Droughts in business-as-usual

The results from the simulation in the scenario of droughts without Climate Change are as shown in Figure 12 and 13. The mean frequency of droughts is $\lambda = 0.364$ as there are 16 major droughts from 1972 to 2016 in central Nepal. 19 The impact of droughts is a calibrated constant at 19000 metric tons of damage. The effect of droughts results in an exponential decay of Vegetable Production, this is due to the coupled effect of the reinforcing loops **R1** and **R2** and the balancing loops **B1** and **B2**. On the other hand, the Cereal Production decline initially but recovers after year 4 due to the effect of reinforcing loop **R4**. This allows the Household Income to recover in year 8 after its decline from year 2 to year 8. Thus, we can affirm that preserving the production of more heat-resistant Cereal Crops is imperative in ensuring the stability of the SES system in drought-prone countries.

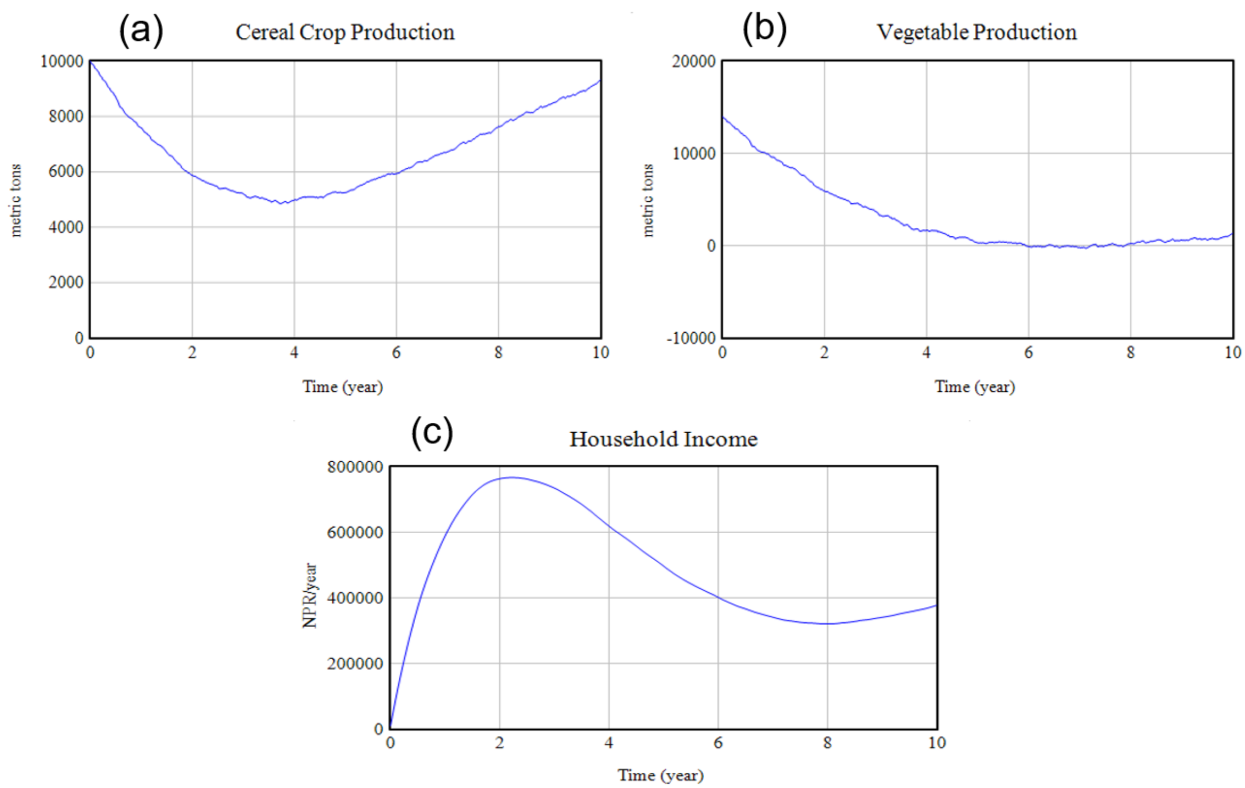

Figure 8. Income from vegetables (a) and cereals (b) in metric tons during drought and household income (c) in NPR/year for Disaster Scenario 1 (Droughts w/o Climate Change).

1.3. Disaster Scenario 2 - Droughts during Climate Change

Climate Change has caused an increased frequency of natural disasters, particularly droughts in Nepal. 20 In our simulation, we increased the frequency of droughts to $\lambda = 0.45$ and kept the impact of droughts and other variables to be constant. This resulted in a collapse in Household Income as shown in Figure 15. Both Vegetable Production and Cereal Crop Production showed behaviour resembling an exponential decay in Figure 14. This indicates that Household Income is especially vulnerable to the impact of extreme cases of climate change and increasing frequency of droughts due to the presence of reinforcing feedback loops R2 for Vegetable Production. Hence, Nepalese farmers may underestimate the additional vulnerability that growing more heat-sensitive vegetable could cause, which can adversely affect their livelihoods if climate change exacerbates the frequency and intensity of droughts in Nepal.

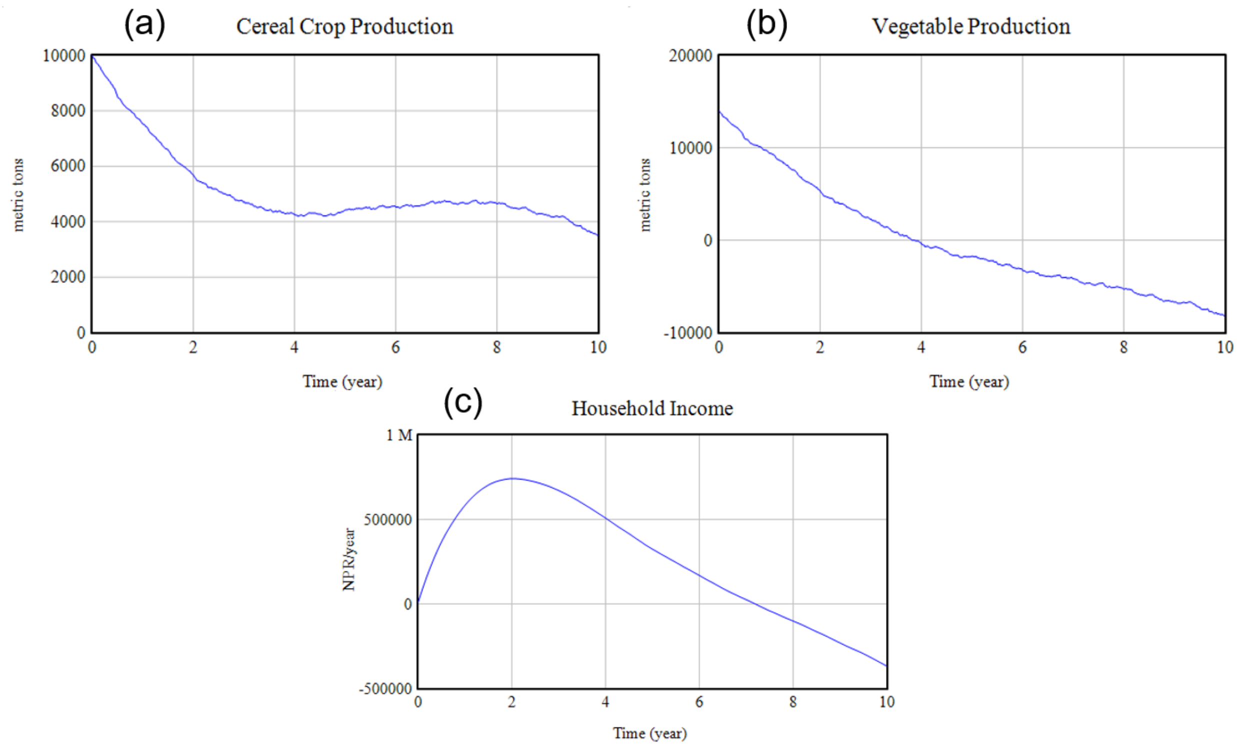

Figure 9. Income from vegetables (a) and cereals (b) in metric tons during drought and household income (c) in NPR/year for Disaster Scenario 2 (Droughts with Climate Change).

Scenario 2. Testing Climate Change Scenario with Policy Intervention

The effect of the two individual policies on the Household Income in the scenarios of Climate Changes will be investigated in Policy Test 1 and 2. In Policy Test 3, the effect of increasing both Ecological Awareness and Irrigation Support simultaneously are also investigated.

2.1. Policy Test 1: Increasing Irrigation Support policy for Vegetables only.

One possible policy intervention is to increase Irrigation Support for Vegetables in anticipation of the potential damages of climate change. The Irrigation Support for Vegetables is increased from 100% to 150% to 200% as shown in the Figures below.

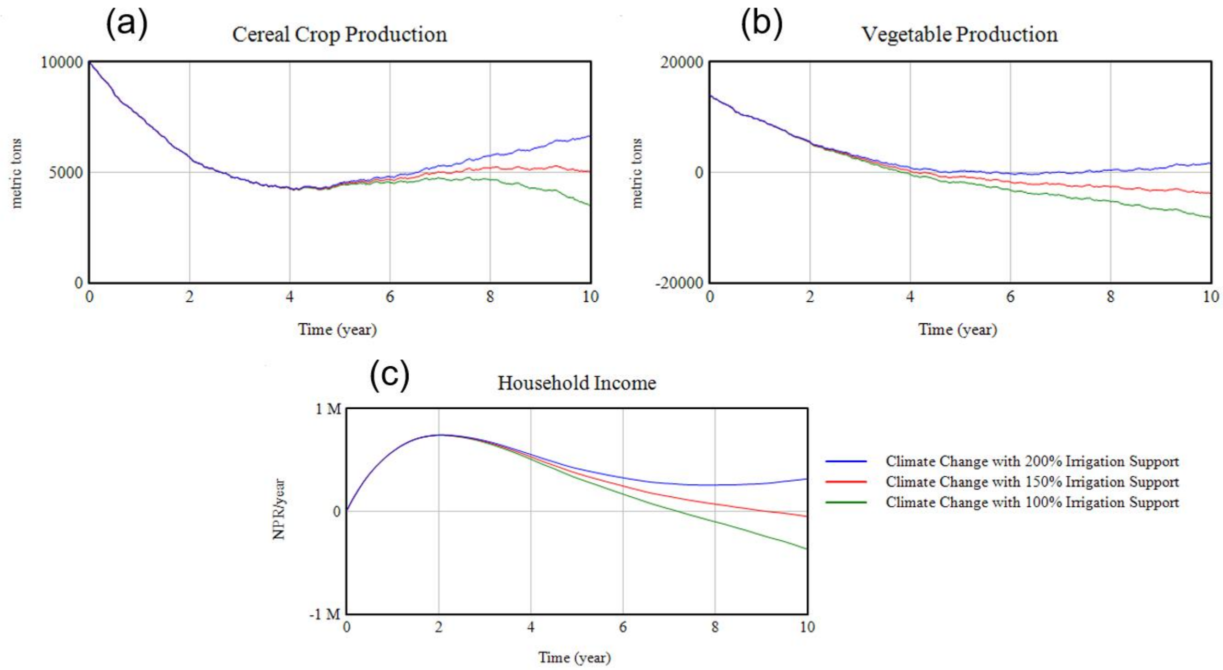

Figure 10. Income from vegetables (a) and cereals (b) in metric tons during drought and household income (c) in NPR/year for Policy 1 (Irrigation Support for Vegetables at different intensity).

The increase in Irrigation Support for Vegetables allowed the Vegetable Production to recover from its usual exponential decay behaviour, thus stabilising the Household Income and prevent it from going into a collapse behaviour. Additionally, providing Irrigation Support for Vegetables also increases Cereal Crop Production as the Household Income does not decrease drastically, leading to more Capital Expenses for Crop Production in the reinforcing loop **R4** in our SFD diagram. However, even though increasing Irrigation Support for Vegetables by 200% prevents the collapse of the system in the event of severe climate change, it may not be a viable policy it incurs a significant increase in government expenditure. Hence, due to cost constraints, the government prefer to increase Ecological Awareness to complement an Irrigation Support Scheme to help the system recover from extreme cases of Climate Change.

2.2. Policy Test 2 - Increasing Ecological Awareness only.

Even though increasing Ecological Awareness from 1 to 5 is insufficient in preventing the Household Income from collapsing, it has resulted in a slight recovery of Household Income as shown in Figure 19. Increasing Ecological Awareness results in a decrease in Preference to grow vegetables, thus resulting in more Capital Expenses allocated towards Cereal Crops Production, thus increasing the effect of reinforcing loop R4. However, the increase in Cereal Crops Production is insufficient in sustaining the Household Income from collapsing due to the decrease in Vegetable Production as shown in Figure 18. Hence, increasing Ecological Awareness needs to be complemented with Irrigation Support.

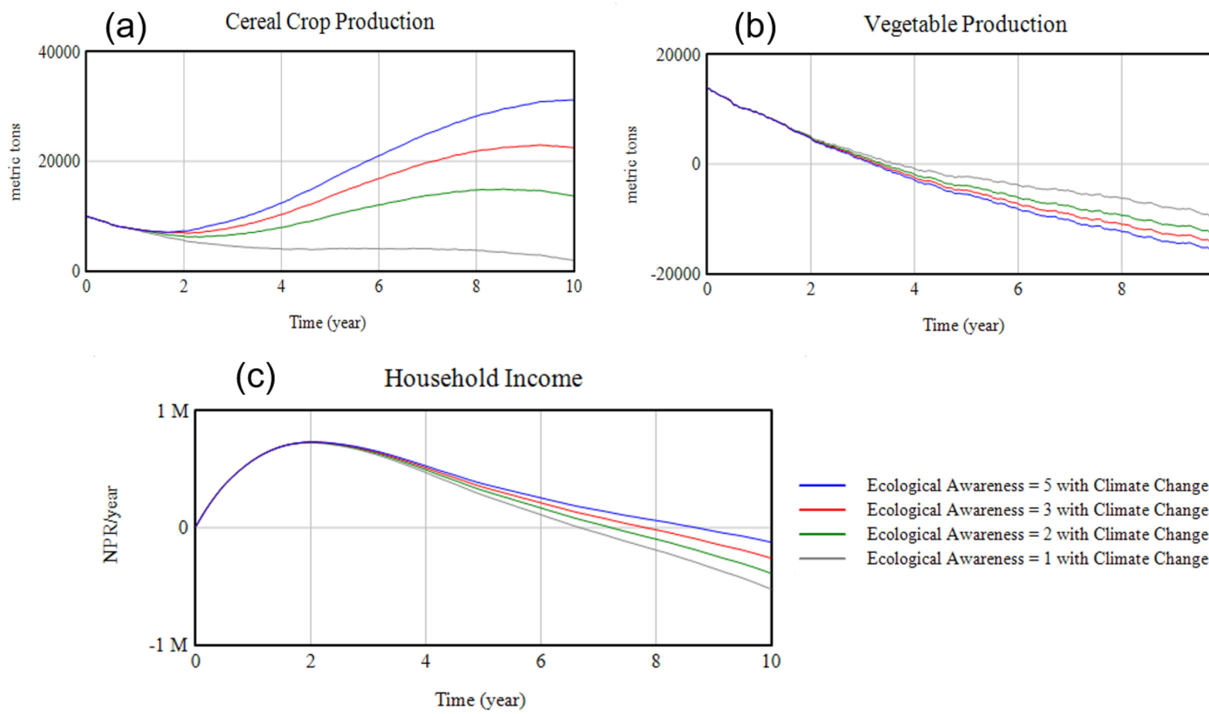

Figure 11. Income from vegetables (a) and cereals (b) in metric tons during drought and household income (c) in NPR/year for Policy 2 (Different extents of promoting Ecological Awareness).

2.3. Policy Test 3 - Increasing Ecological Awareness and providing Irrigation Support

The final scenario is tested by increasing Ecological Awareness and increasing the Irrigation Support for either Cereals or Vegetables as shown in **Figure 12**. The increase in Irrigation Support for Vegetables by 100% and 200% has led to a small rebound in Household Income, whereas increasing Irrigation Support for Cereals by 10% and 20% has led to a drastic increase in Household Income. This is because increasing Ecological Awareness has led to a greater increase in Cereal Crop Production compared to Vegetable Production, thus the Household Income is now more sensitive to an increase in Cereal Crop Production. Furthermore, only a small increase of 10% in Irrigation Support for Cereals is enough for the system to withstand the impact of droughts in the extreme scenario of Climate Change, thus allowing for significant savings on government expenditure compared to increasing Irrigation Support for Vegetables only as illustrated in our previous scenario. Thus, policy to increase Ecological Awareness and increase the Irrigation Support for Cereals has a synergistic effect in increase the resilience of the system. Thus, reducing the potential impact of droughts in a world with Climate Change on the Household Income and the livelihood of the Nepalese farmers.

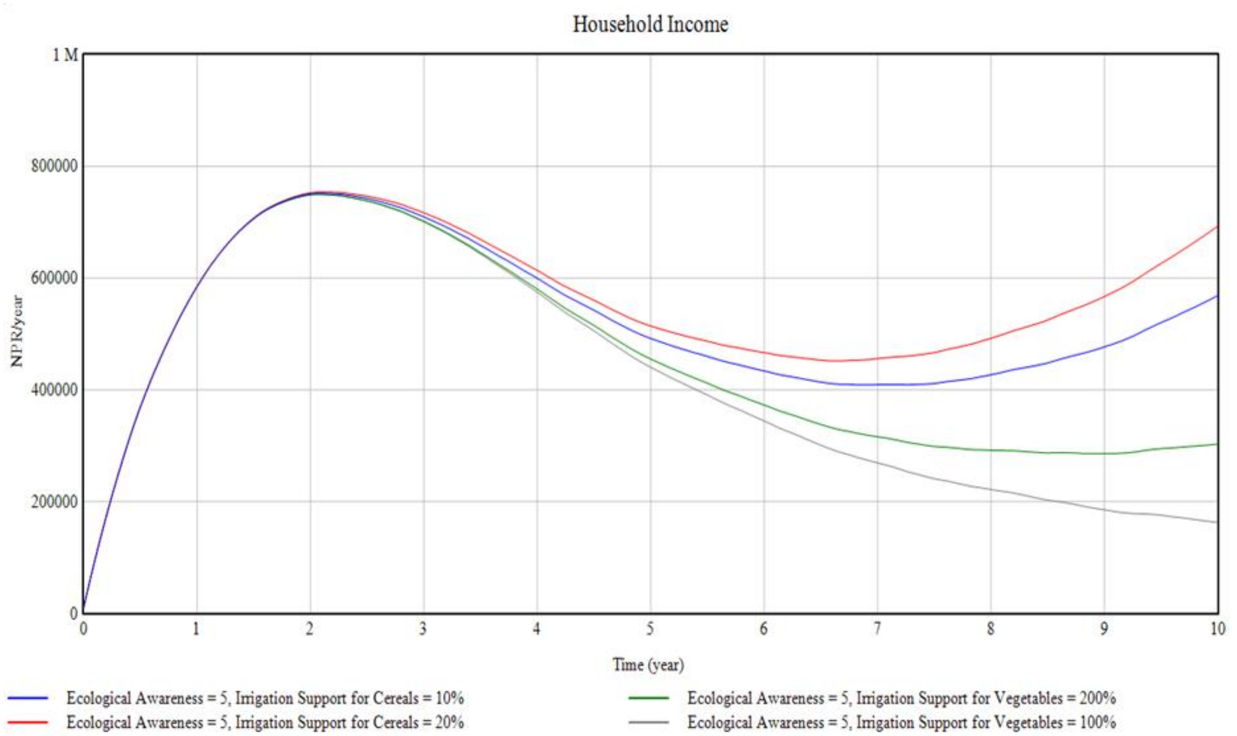

Figure 12. Changes in Household Income with varying values of Irrigation Support for Vegetables and Irrigation Support for Cereals.

DICUSSION - Strategizing and communicating through Resilience Markers.

We can infer from the scenario of "Droughts in business as usual" that there may not be any need for policy intervention as the Household Income recovers from its initial decline. However, this scenario is tested using the mean frequency of droughts that have occurred in the past. In the advent of Climate Change, we can expect an increased frequency of natural hazards occurring in more extreme climate conditions in the future. This may result in the misdiagnosis of drought risks, thus creating a false sense of security among policymakers and farmers in Nepal.

As illustrated in our "Droughts during Climate Change" scenario, if Nepalese farmers continue overestimating the capacity of vegetable production for prosperity, the household income may collapse if the frequency of droughts increases. Hence, it is important to think about means of managing the diversity in the farm system through increasing Ecological Awareness and initiate support for Irrigation of Traditional Crops in drought-prone regions in Asia. Such traditional crops that may be more drought-tolerant can potentially offer a safety net to sustain Household Income during periods of extreme droughts. Thus, a balance has to be managed between growing profitable cash crops and drought-tolerant traditional cereals that are less lucrative. In the following paragraph, we attempt to apply the Resilience Markers framework in our case study. The three levels of resilience are illustrated in Bold front and the description of the elements are underlined.

Following the Resilience Marker framework, the **Observation Level** of resilience in this context will be for farmers to "be aware of the drought-tolerance levels of cereal and traditional crops". This ensures that farmers would not shift towards growing lucrative yet drought-sensitive cash crops such as vegetables as their sole source of income. The **Strategy level** for Nepalese policymakers will be to initiate policy programs to "increase ecological awareness and provide support systems for heat-resistant crops". For instance, the Nepalese government can provide adequate amount of irrigation support for traditional crops, for instance by bundling discounts for water supply with purchase of fertilizers for traditional crops. Thus, incentivising farmers with lower raw material costs to continue growing traditional crops. Additionally, capacity development programs can be introduced to emphasize the benefits of cultivating traditional crops, which can be designed to include consultations with farmers to understand their practical needs and concerns (e.g., fertilizers, water supplies and harvesting logistics) to continue cultivating traditional crops. The **Marker level** of resilience identified in this Social-Ecological System will be to "preserve diversity in production" to reduce over-reliance on a sole source of production. In this context, maintaining a healthy balance between the production of both cereal crops and vegetable crops reduces the risk of farmers from suffering significant losses in their household income if climate conditions do not favour the production of vegetables. Thus, through our research, we argue that the provision of irrigation systems (e.g., through over providence of subsidies and water tanks) to only support Vegetable Production can result in the unintentional consequence of developing over-reliance on growing cash crops, particularly vegetables with a fast period of growth can yield quick and lucrative returns. We recommend that there should be support for maintaining the production of drought-resistant cereals crops to facilitate the diversification of crop production. This, coupled with capacity development programs to increase Ecological Awareness, would facilitate better management of resilience of drought-prone SES systems. We also postulate that the application of Resilience Markers will help not only in the design and communication of policies but also to come up with indicators to monitor and evaluate policy.

Concluding remarks

This study is limited to two types of crops, namely vegetables and cereals. However, other types of crops such as fruits and seeds are not included in the scope of our work. For instance, there is a possibility in declining production of fruits such as orange and sweet limetta for export (Adhikari and GC, 2020), potentially due to increasing temperature and changing climate in Himalayan regions in Nepal (Karki and Gurung, 2012), leading to a loss of Household Income of farmers growing fruits. For a more comprehensive discourse on the application of Resilience Markers in Nepal, we recommend that future work can include more variety of crops and case studies of other districts in Nepal, with our work being focused on Dadeldhura district. Another possible rectification to improve our system dynamics model would be to curate a more data-centric approach is needed such as the use of local precipitation data and downscaled future climate projections, possibly through spatial analytics to account for the geographical aspects of the district itself. Our parameter for "Heat-Tolerance" can also be further elaborated to explore in-depth relationships between different crops precipitation levels and the temperature of the region. While our current model is useful for novel policy insights and initiate discussion on Resilience Markers, we believe that future work can be further combine our concept with geo-agricultural and climate, thus extending this investigation to be more robust and richer in context.

Conflict of interest

No conflict of interest.

Data Availability/Supporting information

Additional supporting information may be found in the online version of this article at the publisher's website presented in the **Appendix S1-S7**.

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