How Participatory and Computer Modeling Enhances Climate Resilience Policy Design in Data-Scarce Social-Ecological Systems: Lessons from the Ikel Watershed

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Abstract

Climate resilience policy design in data-scarce environments is complex and challenging. This research explores how participatory modeling can enhance policy-making by integrating local knowledge and system dynamics (SD). We developed a computer model (Ikel CliRes) using community based SD modeling to overcome the challenges of policy design in a data scarce environment. Focusing on the Ikel watershed in the Republic of Moldova as a case study we engaged stakeholders to identify key vulnerabilities, such as crop yield decline, groundwater depletion, and loss of bioproductive land. By means of the Ikel CliRes simulation model, we were able to test the effectiveness of various resilience-building policies under several climate scenarios. The results show that the most successful strategy involves a combination of extensive reforestation, adoption of water-efficient crops, improved soil conservation, and sustainable agricultural practices, tailored to local demographic conditions. These policies, reinforced by stakeholder engagement, address the specific needs of the community while compensating for data scarcity. The research demonstrates the pivotal role of participatory modeling in guiding policy decisions, validating models, and building stakeholder confidence in data-scarce social-ecological systems (SES).

Research highlights:

- Crop yield, groundwater, biodiversity are key variables of concern for stakeholders.
- A computer model is developed using community based system dynamics modeling.
- It is used as decision-support tool to analyze policies within a resilience framework.
- Not all adaptation policies lead to desired outcomes of resilience building.
- A systemic climate resilience policy is more complex than a policy for individual components.

1. Introduction

The global community expects with high confidence that the average global temperature between 2030 and 2052 is likely to be equal or more than 1.5°C above pre-industrial levels under all emission scenarios (IPCC, 2018). The implications of this change are manifold for the natural and human systems alike. Of the 7.7 billion people worldwide, ca 80% live in the developing countries, and the number is set to increase by 2050. In addition to their reliance on climatic resources, these countries also face the challenge of data scarcity. Choosing and implementing appropriate resilience policies in these communities is equally important and challenging because of the size of the population affected, the widespread data scarcity that limits the decision-makers' capacity to take data-based action, the complexity of relations within the social-ecological systems (SES) interacting at different spatial-temporal scales (Thomsen et al., 2012), and the incapability of human institutions to deal with those interactions (Sterman, 2000; Underdal, 2010).

These limitations often lead to maladaptation arising from reductionist approaches (McEvoy and Wilder, 2012). One such example is the use of extensive agriculture as a measure to compensate for reduced crop yields. Land is a finite resource in a region, a country, and on the planet. New arable land is generated from converting other types of land use, such as meadows, forests or marshlands. Deforestation in the Amazon Forest is a well-known example of such conversion. Natural types of land use play multiple and important roles in ecosystem balance. Their conversion into arable land might solve the short-term problem of food shortage or revenue to corporate and state budget while weakening the system's ability to withstand climate change impacts in the long term. This example highlights the risk of seeing climate change adaptation of individual economic sectors as a definitive solution to challenges posed by climate change impacts. It also illustrates the need for building resilience of the system rather than to manage the system for certain isolated purposes.

In this research, we employ participatory model building to develop and analyze Ikel CliRes – a computer simulation model that acts as a decision support tool for Ikel watershed SES in the Republic of Moldova. By analyzing it within a resilience framework, it helps decision- and policymakers arrive at effective policy conclusions that can yield better performance patterns for several issues of major regional concern. Consequently, it can contribute towards building resilience of this specific SES to climate change impacts.

1.1. The challenge of data scarcity in developing countries

Data scarcity in developing countries hinders the accurate assessment of their resilience (Ndzabandzaba, 2015; UNDP, 2017) to adverse effects of climate change on agricultural systems, making it likely for millions of people in these countries to suffer much greater losses than in the developed countries. Attempts to address this challenge include initiatives that tackle the possibility to do policy- and decision-making in data scarce conditions. One common example of such initiatives is harnessing expert knowledge (Scholten et al., 2013; Shen et al., 2015; Sayyad et al., 2015). The involvement of stakeholder groups in research has been shown to have multiple benefits, such as prioritizing topics for research, providing pragmatic feedback, closing the gap between research outcomes and their use or promoting research impact (Cottrell et al., 2014; Boaz et al., 2018).

1.2. The situation in the Republic of Moldova

The Republic of Moldova (RM) is a landlocked country in Eastern Europe. Agriculture is a major source of income for a large part of the population of the country. Agricultural land covers more than 60% of the country's territory. Over half of its population lives in rural areas.

About a third of the workforce is employed in agriculture, while about 85% of rural households currently own agricultural lands. Most farms (ca. 400 thousand) are small-sized (1.6-1.8 ha) (Ministry of Environment, 2015).

It is one of the poorest countries in Europe. Mass out-migration that started at the end of the 1990s is still a major problem in the country. The UN Department of Economic and Social Affairs (2019) makes several projections for the population of R. Moldova, according to which the trend in declining population is expected to continue in the years to come. Like many other countries, RM is being visibly affected by consequences of climate change. Water scarcity associated with increase in average annual temperature are anticipated to be a major problem in the future especially in the country's central and southern regions. The most important impacts are expected to be on agricultural productivity and human health. National Report on Human Development (UNDP, 2016) foresees that in the upcoming decades the economic, social and environmental impacts of climate change will intensify.

Water-based social-ecological systems are known to be particularly vulnerable to climate change (Cosens and Fremier, 2014). If no adaptation measures are taken, the estimated decrease in agricultural productivity by 2080s' compared to the recent 1981-2010 is expected to significantly decrease in, for example, maize grain (varying between 49% and 74%), winter wheat (38-71%), and other cultivated crops (Ministry of Environment, 2015). Ministries implement various activities at the sectorial level, which are considered as having higher priority than climate change adaptation and resilience. This in turn leads to a competition over the limited state budget (highly dependent on remittances and agricultural production), and often to conflicting policies and interventions in different economic sectors.

1.3. The social-ecological system of Ikel watershed

Ikel watershed is a small watershed, part of the larger transboundary Dniester River basin (Figure 1 in Appendix). It is located in the central region of RM and exposed to climate change impacts. The watershed is shared by 64 administrative units (villages, communes and towns) and inhabited by roughly 120,000 people. As in the case of most of Moldovan small towns and villages, the main occupation of people living in Ikel watershed for many years has been agriculture – either subsistence or commercial farming. Since 1990, the area has been going through strong demographic changes, low economic production, a drain of the workforce (Stemmer, 2011), population aging, and high rates of unemployment and migration among economically active population. Among those who live in rural areas, agricultural activities remain an important occupation, whereas remittances from abroad remain the prevalent income source (Ministry of Agriculture, 2013; National Bank, 2019).

Water is a key resource in agriculture, because its availability affects the evapotranspiration and hence the growth of plants. Evapotranspiration depends on both available soil water, and on the potential evapotranspiration (PET) specific to each type of vegetation, while soil water is directly dependent on precipitation. There are two main sources of water in Ikel SES: surface water (including the subsurface water flows), which is directly dependent on precipitation, and the groundwater in the confined aquifer. The latter is only partly replenished by local precipitation through percolation, while being mostly recharged by the underground inflow. This deep, confined groundwater aquifer within the limits of Ikel watershed, is located in the Baden-Sarmatian bedrock layer at an average depth of 100-200 m below surface (Teleuta et al., 2004), and is also replenished by groundwater inflows from upstream.

Average annual precipitation in the central region of R. Moldova between 1960 and 2019 was 551 mm (UNEP, 2018; NBS, 2020), while for the period 2000 to 2019 it was 542.2 mm. Decline in precipitation and degradation of land and water resources are expected to have implications on agricultural productivity, ecosystem services, income of local people, on local and national budget and on public health (Ministry of Environment, 2015). Analyzed individually, the impacts of climate change on various components of the Ikel watershed are relatively easy to anticipate. But when complex interactions between a number of variables changing at different rates are considered, implications for the sustainability of Ikel watershed as a social-ecological system are hard to grasp. The thresholds, the possible future behavior of the system, the leverage points for interventions to prevent the system from switching to an undesired state are even harder to grasp in the absence of a suitable approach to analyze those complex interactions and systemic feedbacks.

1.4. Key vulnerabilities in Ikel SES and policy proposals

To identify vulnerabilities and priority areas for intervention in building Ikel SES resilience to climate change impacts, a participatory process was undertaken between 2016 and 2021. We engaged multiple stakeholders through coupled use of two sequential processes: social–ecological inventory and group model building (GMB). The process, described in detail in Ciobanu and Saysel (2021), provided a set of priority areas, i.e. key variables, and desired outcomes, i.e. resilience objectives. It also yielded a conceptual model describing the dynamic hypothesis, i.e. the structure of the system that gives rise to the problematic behavior of the SES in focus (see Figure 2 in Appendix) and preliminary suggestions for policy design. The problem, resilience objectives, and policy proposals are described and their effectiveness is presented and discussed in the sections below.

2. Problem

Stakeholders proposed that average crop yield, level of groundwater table, and the area of bioproductive land are the key variables that define Ikel watershed as a SES for the scope of this research. GMB participants have expressed that the objective for Ikel SES in the face of looming climate change impacts is at least the conservation and at best the increase in all key variables between 2016 and 2050 (Figure 1).

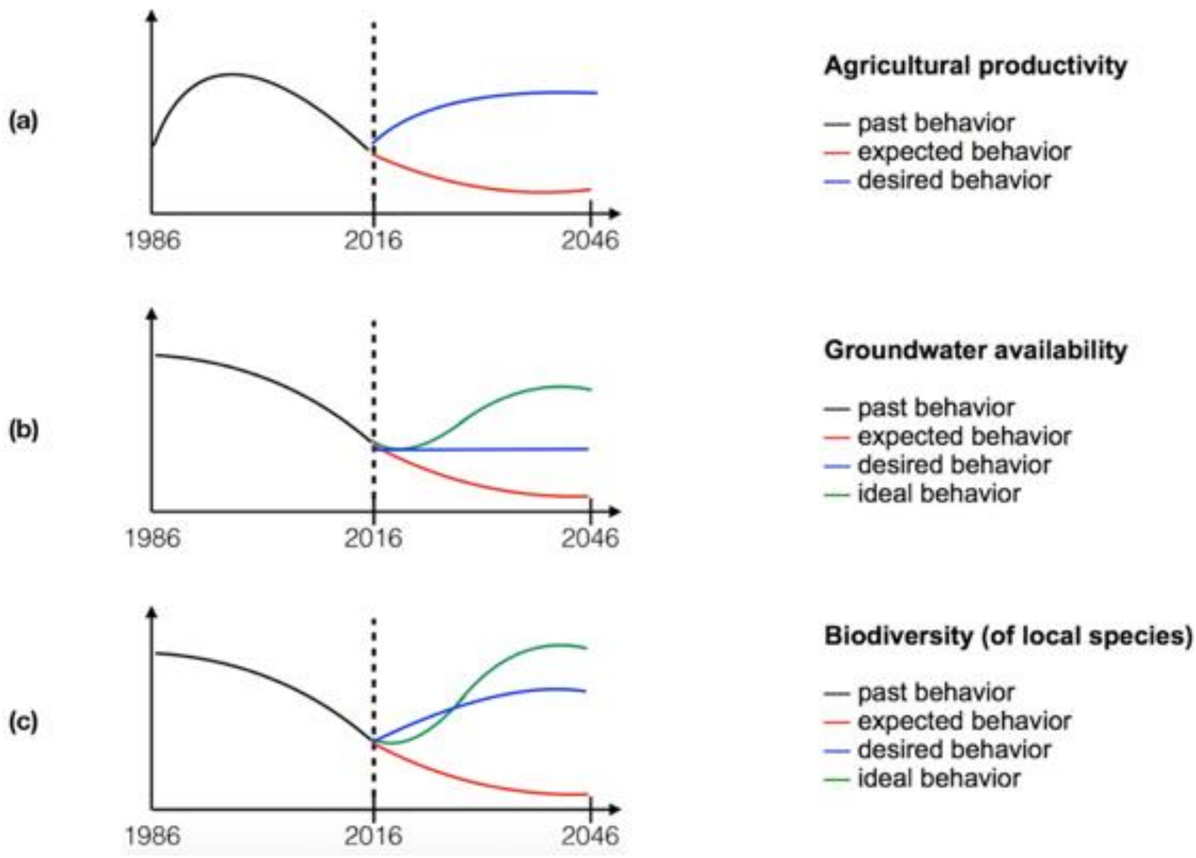

Figure 1. Priority areas, defined as key variables, elicited from participants in GMB workshops: (a) *Agricultural productivity*, (b) *Depth of water table in wells and groundwater*, (c) *Biodiversity of local species*. The three graphs are the reference modes that depict the behavior of key variables. Resilience objectives are defined as the behavior that GMB participants desire to see in the following 30 years (in blue). For the key variables "Levels of water table in wells and groundwater", and "Biodiversity" participants also expressed an ideal scenario, depicted in green (Ciobanu and Saysel, 2021).

For the central region of R. Moldova, the climate projections suggest a clear increase in temperatures by 2050 and beyond, and a less certain change in annual precipitation. The more favorable projection is that precipitations increase moderately. The least favorable one is the decrease in annual precipitation at least by 2050, as anticipated by the representative concentration pathway (RCP) 8.5. In this context:

- an adaptation policy is a policy that helps achieve the desired outcome in key variables under projected temperature and precipitation trends of RCP climate scenarios.
- a resilience-building policy is a policy that helps achieve the desired outcome in key variables under specific impact circumstances accompanying future climate scenarios, e.g., more frequent storms, higher evaporation rates or both.

3. Qualitative dynamic feedback model and first policy proposals

The participatory process has also helped identify several causes and results of change in key variables, and thus conceptually define the structure that might be capable of generating behaviors as those described in the reference modes. A qualitative dynamic feedback model was then built, describing four fundamental processes. The conceptual model was validated and analyzed by the GMB participants (Ciobanu and Saysel, 2021). Based on the insight gained thorough this learning process, the GMB participants put forward several policies that could potentially increase resilience of Ikel watershed to climate change impacts (Table 1). These policies were then integrated by the Ikel Watershed Committee in a five-year Local Watershed Climate Change Adaptation Plan (Ikel Watershed Committee, 2016).

Table 1. Policies proposed by GMB participants and their operationalization during simulation.

GMB policy number	Proposed policy or measure	How it is operationalized for analysis in Ikel CliRes	Explanation
#1	Increasing of forested area and involving citizens in reforestation.	Forestation fraction is increased	These four proposed policies refer to what is defined as the increased (re)forestation effort undertaken by various stakeholders in different locations within Ikel SES. To test the increased reforestation efforts, a most optimistic scenario is assumed: (re)forestation efforts are significantly increased.
	Increasing/rehabilitation of forest strips (for the protection of arable land) with walnut/fruit/melliferous tree species.		
	Increasing the length and surface of forested area in sanitary protection areas of rivers and lakes.		
	Rehabilitation of natural wetlands.		
#2	Increasing the access to water supply systems	Fraction of groundwater allowed for exploitation is increased and capacity construction rates for surface and groundwater exploitation are increased	This policy refers to increasing farmers' access to water for irrigation. In the base run, water for irrigation is only supplied from exploitable runoff, while the use of groundwater is not allowed. To test this policy, three parameters are changed simultaneously: up to 10 % of groundwater stock is allowed to be used for irrigation purposes, and the speed of investment is increased to twice of the current value for irrigation infrastructure from both groundwater and surface water resources.
#3	Reducing land abandonment of productive arable land and support its reintroduction into the production circuit	Abandonment rate is decreased and reclaiming rate of abandoned land is increased	This policy seeks to maintain a larger stock of arable land by preventing or reducing its conversion to abandoned land. To test this policy, abandonment is reduced compared to its current

			value, while at the same time increasing the reclaiming fraction (back from abandoned stock).
#4	Improving environmental law enforcement to reduce illegal logging and breaching of existing environmental legislation	Clearing fraction is decreased	To test this policy, the clearing fraction is reduced compared to the current value. This stands for law enforcement having been twice as effective as it is in the base run scenario.

From a resilience assessment perspective, eliciting policies for resilience building from participants, and integrating them into strategic plans completes the stage of resilience assessment (Resilience Alliance, 2010). From a SD perspective, a computer simulation model based analysis is fundamental for policy design. This constituted the motivation for building Ikel CliRes model.

4. Description of Ikel CliRes simulation model

Ikel CliRes, is built on the basis of the conceptual model with relative contribution of the GMB participants. More specifically, at this stage participants contributed with data gathering and knowledge sharing, as well as structural and behavioral validation of the computer model.

The model runs on annual basis for 30 years between 2020 and 2050. It consists of four model components representing different environmental, social and agricultural sectors and includes eight stock variables (standing for accumulations of *groundwater*, *arable lands* and *infrastructure* invested in for water provision).

4.1. Overview of sectors and their interactions

Water Resources, *Irrigation Infrastructure*, *Erosion*, and *Land Use* are the four interacting model components, also referred to as model sectors (Figure 2). The key variables identified during the GMB are concentrated in *Water Resources* and *Land Use* model sectors. All sectors exchange information and material, which are depicted with arrows. Description for these interactions are labelled on the arrows. Boxes depicting model components are illustrated with their major variables within.

Ikel CliRes runs under exogenous pressures created by *precipitation* and *temperature* (acting on the *Water Resources* and *Land Use* sector), *population dynamics* (on *Land Use* sector), *rainfall erosivity* (on the *Erosion* sector), and information for climate related forecasts (on the *Irrigation Infrastructure* sector). This is illustrated with climatic variables and population affecting model components.

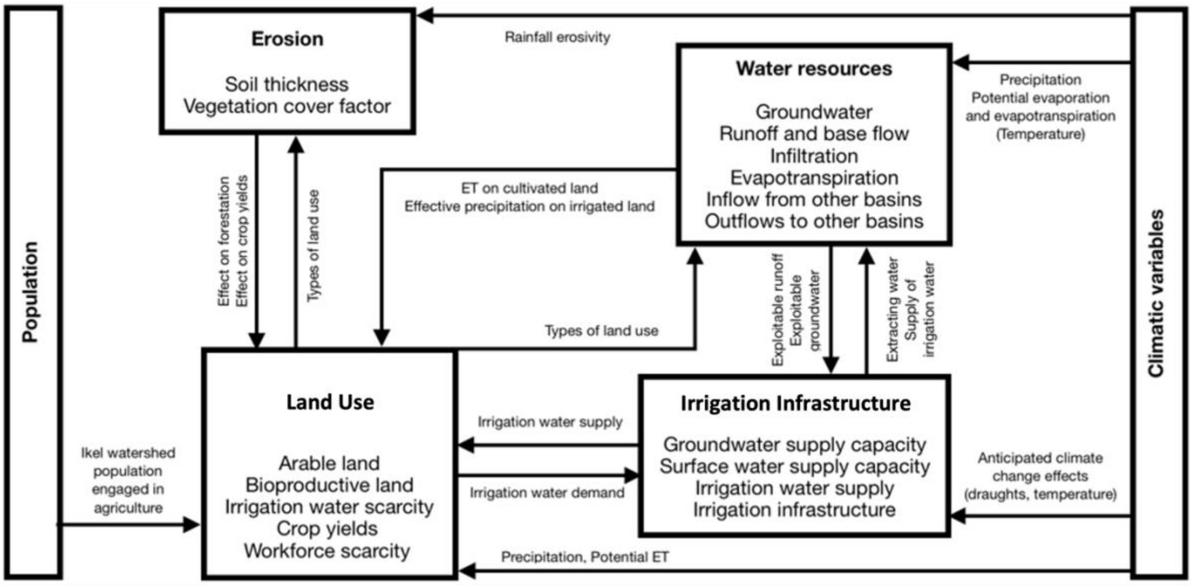

Figure 2. Overview of the model structure.

4.2. Water resources

This model sector builds the water budget of the watershed. It also provides *evapotranspiration* and *effective precipitation* to the *Land Use* sector. It receives information on *land use* from the *Land Use* sector, supplies the *Irrigation Infrastructure* sector with information on *exploitable runoff* and on *exploitable groundwater*, and receives *supply of water for irrigation* from this sector (Figure 3 in Appendix).

Within the scope of our research, water resources in Ikel watershed are conventionally divided into two: surface water resources (including Ikel river, lakes, subsurface flows and shallow groundwater) and deep groundwater. In this sector all surface water resources including unconfined aquifers located above the first aquitard (a thick layer of clays) are aggregated into a single variable that builds up the *runoff*.

Surface waters are replenished from precipitations and, to a certain extent, from deep groundwater that is extracted, used and then discharged from households, industrial settlements or irrigation return into surface water bodies. Water from the Dniester River itself is used in parts of the watershed for irrigation and other purposes.

The deep groundwater aquifer located in the Baden-Sarmatian bedrock layer at an average depth of 100-200 m below surface (Teleuta et al., 2004) is confined between the upper aquitard and lower aquitard. It is replenished by groundwater inflows from upstream. This aquifer consists of three groundwater bodies, which are aggregated in Ikel CliRes model as a single deep groundwater stock. *Groundwater stock* is replenished through *inflow* from upstream aquifers, *precipitation* and *irrigation water that percolates* through the upper aquitard. It is decreased directly with *outflows* to downstream aquifers and with *extraction* for household and industrial use, as well as for irrigation purposes.

4.3. Irrigation infrastructure

This model sector describes the building of capacity for irrigation water supply (Figure 4 in Appendix). It receives information on *irrigation water demand* from *Land Use* sector. It also informs the *Land Use* sector about the *level of water scarcity* or lack thereof. At the same time, it supplies *irrigation water* to the *Land Use* sector. It also receives information on *exploitable runoff* and *exploitable groundwater* from *Water Resources* sector, as well as *runoff* and *groundwater for irrigation*.

Irrigation supply capacity is an aggregated variable representing all infrastructure and workforce involved in the extraction, distribution, and application of irrigation. It is conceptualized as being supplied from *exploitable surface runoff* and from *exploitable groundwater*. Based on availability of water from these sources, and on the *demand for irrigation* from *Land Use* sector, investments are done for irrigation infrastructure.

4.4. Erosion

Erosion sector receives information on types of land use from *Land Use sector* and provides it information on the *effects of soil erosion on forestation* and *on crop yields* (Figure 5 in Appendix). This sector investigates the impact of a series of factors on the *soil erosion* and on *average soil thickness*. It determines the *effect of soil erosion on crop yield* and influences the *forestation*.

Erosion is the main process that affects the *average soil thickness* – a limited resource in this model. It can only decrease with *erosion* but does not regenerate. This is due to pedogenesis being an extremely slow process, which is equal to nearly zero within the timeframe of this model. The stock decreases with *erosion* – a much faster process in this context, which is modeled based on the universal soil loss equation (USLE), as defined by Wischmeier & Smith (Morgan, 2005).

In Ikel CliRes, *vegetation cover factor C* is defined as a weighted average of *C factors* for different land uses, which change over time: *cultivated land* including both *irrigated* and *rainfed arable land*, *abandoned land* and *bioproductive land*. Furthermore, the weighted C factor is multiplied with a factor corresponding to an *effect of vegetation density*, as proposed by Tozan (1998) and Saysel et al. (2002). The rationale is that the ability of soil to support a dense vegetative cover declines over time with declining soil depth caused by erosion.

4.5. Land use

This sector supplies the *Water Resources* and *Erosion* sectors with information on types of land use (Figure 6 in Appendix). It also supplies the *Irrigation Infrastructure* sector with information on *irrigation water demand*. It receives *water supply* from the *Irrigation Infrastructure* sector, *evapotranspiration* on cultivated land and *effective precipitation* from *Water Resources* sector, and information on the *effect of soil erosion on forestation* and *on crop yields* from the *Erosion* sector. Furthermore, it also receives information on *Ikel watershed workforce engaged in agriculture*.

The sector determines the change in the different types of land use, and some key mechanisms that influence this change. It describes the change in yields of irrigated and rainfed crops, analyses the role of demographical and climatic factors, as well as that of water availability on the land use change dynamics. The sector generates the *demand of water for irrigation*, which influences the dynamics of the *Irrigation Infrastructure* sector. It also informs the *Water Resource* and *Erosion* sectors about the area of various land uses.

In Ikel CliRes model, the non-constructed land within Ikel SES boundaries is divided into four main land stocks that exchange flows over time: *bioproductive*, *abandoned*, *rainfed arable* and *irrigated arable lands*. *Bioproductive land* is an aggregated variable representing forests, meadows and other forms of habitats that support local land biodiversity and help it thrive. *Abandoned land* is another aggregated variable that stands for both eroded areas and for productive arable land that has been either left fallow for a certain period or has been abandoned for other reasons than being eroded/unproductive. *Rainfed arable* land is the sum of all cultivated lands for which no artificial irrigation is used, whereas *irrigated arable* land is the totality of cultivated land plots where different forms of irrigation are used. The major drivers of change are defined in this sector as being *erosion*, *crop yield*, *workforce availability*, *irrigation water availability*. Agricultural land category includes arable land, multiannual plantations (orchards, vine and berry plantations).

Crop yields play an important role in *conversion rates* to/from irrigated and rainfed arable lands, as well as in the *abandonment* of cultivated lands altogether. *Rainfed crop yield* and *irrigated crop yield* in this sector are conceptualized as being primarily determined by 1) the *maximum attainable yield* in rainfed and irrigated conditions respectively, 2) the *effect of soil depth*, and 3) the *effect of evapotranspiration*. We use attainable yield values for the corn/maize as a reference crop due to it being one of the most commonly cultivated crop in the area.

Workforce scarcity is impacting the *conversion rate* to / from both rainfed and irrigated arable lands. We define the *workforce scarcity* as the ratio between the *demand* and the *supply of workforce* needed to grow crops on these lands. Both *workforce demand* and *supply* aggregates low-skilled agricultural workforce (people needed to cultivate the land) and qualified workforce (engineers, technicians, scientists, etc.). *Workforce demand* is given by the *arable area* and the *workforce needed* to cultivate a unit of it. Irrigated arable land is relatively more labor intensive compared to rainfed agriculture.

5. Model validation

The relevance of model-based analyses depends on the validity of the model. In system dynamics modeling, validation is meant to build confidence in its usefulness with reference to the purpose of the model (Barlas, 1996). Model validation is therefore a gradual process by which model validity is enhanced systematically, while stakeholder engagement in model validation is both welcome and recommended to enhance model relevance and usefulness.

This research was designed to include stakeholder participation in model validation, as well. Generally, validation methods are categorized into two large groups: structure validity and behavior validity (Barlas, 1996). Individual interviews and workshops were carried out for several structure and behavior validation tests. Among stakeholders were GMB participants and external experts who are knowledgeable of the different fields of inquiry.

The number and diversity of validation tests are high and constantly enriched by SD researchers, and it is very rare – if at all – that all existing tests are applied to a model. Instead, cessation of formal validity testing is a matter of modeler's heuristic for this decision (Groesser and Schwaninger, 2012).

Structure validation tests are aimed at assessing if the model's internal structure generating the behavior is attuned to the corresponding structure in the real world. Structural validation of Ikel CliRes included direct structural validation tests, carried out without simulations to assess the mismatches between the real-life system and the model structures, and indirect structure validity tests with computer simulation to assess the validity of the model structure through analyses of simulated behavior patterns.

Behavior validation tests compare simulated behavior patterns with those from the real system under study. The behavior of Ikel CliRes for the period 1990 – 2019 was used for its behavior validation by comparing it to real-life data wherever available. Behavior validation of Ikel CliRes included a number of behavior reproduction tests and pattern anticipation tests.

6. Results of model behavior analysis

All three key variables – crop yield, groundwater table depth and biodiversity – are dependent on climate conditions, among others. To understand future trends, projected climate data for both RCP 2.6 and RCP 8.5 scenarios has been downloaded from MarkSim® DSSAT website (ILRI, 2021). Downscaled daily weather data was aggregated to produce annual series from 2021 to 2050, and treated for bias correction using Delta change method (Beyer et al., 2020). Projected annual data showed a rather smooth behavior. Therefore, trends in the historical and projected annual data sets were calculated deriving the line of best fit (using the method of least squares) for average annual temperature and annual precipitation data.

Figure 3 illustrates the trends in average crop yield, in groundwater table and in bioproductive land expected under two RCP climate scenarios: the more favorable RCP 2.6 and the more detrimental RCP 8.5.

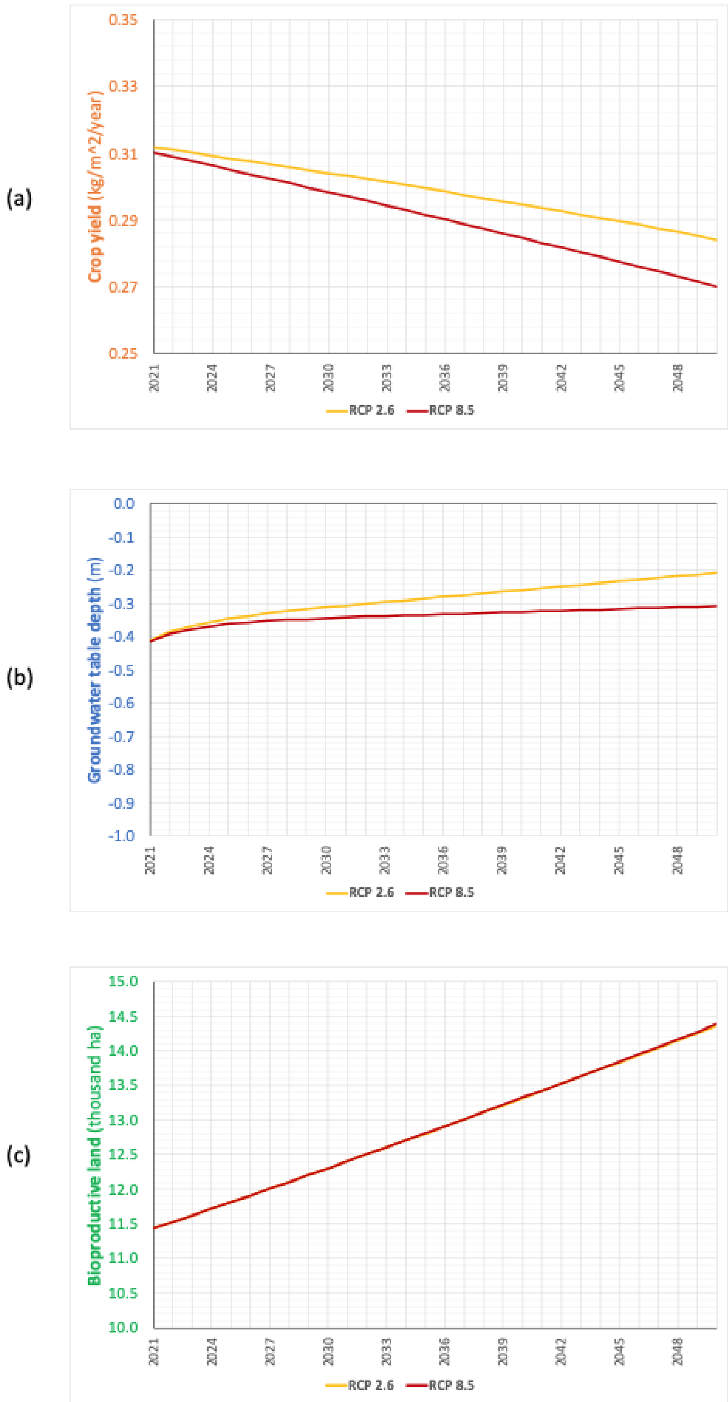

Figure 3. Trends in (a) average crop yield, (b) groundwater table depth and (c) bioproductive land expected under RCP 2.6 and RCP 8.5 climate scenarios. Of the two, RCP 8.5 scenario would have the most negative impact on the representative crop yield and on the level of groundwater table.

From a resilience assessment standpoint, the analysis of the model was done with respect to the more inimical RCP 8.5 climate scenario and to the following three sets of policies:

1. policies proposed by stakeholders in Ikel SES as means of achieving desired outcomes for priority areas in the face of climate change impacts (Table 1),
2. alternative policies identified during model validation and analysis, which could lead to the desired outcomes as expressed by members of the GMB process (Table 2), and
3. resilience policies designed by the modeler that could help achieve desired outcomes while facing specific climate change impacts (i.e. increased rainfall intensity, increased evaporation and evapotranspiration rates associated with higher temperatures).

Analysis of policy effectiveness focused on sensitivity of key variables to change in selected parameters, inputs, initial conditions and other structural changes representing alternative policies. This analysis is accompanied by demonstration of model-generated behavior and followed by a discussion on the effectiveness of policies proposed.

6.1. Policy analysis

There were four main policies proposed by GMB participants to support adaptation and resilience-building to climate change that arose from conceptual model analysis (Table 1). Comparative analysis of these four policies has revealed that the implementation of GMB policy #1 alone has a more positive impact on all three key variables than the implementation of any of the other three or of all policies combined (see Figure 7 in Appendix). Two of the GMB policies would have a deleterious effect: the one increasing farmers' access to irrigation water supply systems (GMB policy #2)– reducing the groundwater stock, and the one encouraging the reclaiming of abandoned land for agricultural purposes (GMB policy #3) – affecting all three key variables. Improving environmental law enforcement to reduce illegal logging and breaching of existing environmental legislation (GMB policy #4), on the other hand, would have no effect whatsoever because the rate of land clearing is already very small; additional efforts to reduce this rate will bring no visible improvement.

Six alternative policies were put together following the model validation and analysis that had revealed a number of potential leverage points. The performance of the six alternative policies (Table 2) is analyzed with respect to their impact on the desired outcomes for the three key variables (Figure 1). The analysis of outcomes pointed to several policies conducive to the increase in each of the key variables individually.

Table 2. Alternative policies and their operationalization for policy analysis using Ikel CliRes.

Alternative policy description	Operationalization for policy analysis in Ikel CliRes model
Alternative policy #1: Promote crop varieties that produce higher yields for the same water requirements. This policy encompasses investments in promotion and uptake of crop varieties that generate higher yields while consuming the same amount of water and benefiting from the same soil conditions as their less productive counterparts.	Behavior of key variables is compared between the base run scenarios and scenarios where *Attainable rainfed yield* and *Attainable irrigated yield* parameters are increased compared to the base run value.
Alternative policy #2: Promote crop varieties that are less water intensive. This policy foresees a switch to crop varieties that use less water, i.e., have a smaller PET, to generate the same quantity of produce.	To test this policy, the value of *PET* (potential evapotranspiration) for the selected representative crop is reduced compared to the base run value.
Alternative policy #3: Adopt and maintain better soil conservation practices. This policy refers to a widespread and consistent effort to conserve the soil health by adopting the best possible practices (e.g., no-till farming, contour farming, windbreaks and others), and thus reduce the soil conservation factor (P factor in USLE).	The effectiveness of this policy in producing desired outcomes for the three key variables is tested by reducing the soil conservation factor.
Alternative policy #4: Encourage and ensure that more people work in agriculture. This policy implies concerted measures to ensure that the more people are engaged in agricultural sector as unskilled, skilled and highly skilled workforce thus contributing to a larger percentage of the population being active in this sector.	By increasing the *Fraction of population in agriculture* parameter value, it is expected to see how the impact of this policy will be reflected on the average crop yield, groundwater table height and bioproductive land area in Ikel SES.
Alternative policy #5: Halt population decline in the region. In case of this policy, various measures are taken to ensure that the trend in population decline is reversed, and more people remain active actors in this social-ecological system.	To understand if by reversing the population decline the key variables will exhibit the desired behavior trends, *Ikel SES population* table function is manipulated as follows: compared to the current base run, in the modified version, population does not decline after 2020. Instead, it is maintained at 2021 level.
Alternative policy #6: Support the uptake of technologies in agriculture that require less workforce. This policy refers to supporting farmers in the adoption of various technologies that allow for competitive agriculture to be carried out with less workforce.	The performance of this policy is analyzed by increasing workforce efficiency, i.e., reducing the values of parameters *Workforce required on rainfed* and *Workforce required on irrigated*.

From the six alternative policies, all but one have a positive impact on average crop yield in Ikel SES, albeit for different reasons (see Figure 8 in Appendix). Alternative policies with the highest impact are the ones that require a change in cultivated crop varieties to less water demanding ones, i.e. policies #1 and #2. However, these policies are challenged by soil erosion, which limits the growth in agricultural productivity. This limitation is addressed by the alternative policy #3; it improves soil conservation practices and reduces soil erosion on both rainfed and irrigated lands. On the other hand, two alternative policies (#4 and #6) address the limitation imposed by workforce scarcity and help increase the average crop yield by ensuring that more of the Ikel SES crops are grown on irrigated lands. This drives up the average mathematical value of this key variable.

Two of the six alternative policies have a positive impact on the height of groundwater table: #4 that ensures a major increase in the percentage of Ikel SES population working in agriculture, and #6, which increases workforce efficiency in agriculture by adopting technologies that require significantly less workforce (see Figure 9 in Appendix). This is explained by the larger amount of water from irrigation percolating to the groundwater stock from irrigated arable lands that increase as a consequence of workforce availability and efficiency, and by the fact that this water is gauged from surface water resources only.

None of the six alternative policies facilitates a larger increase in the bioproductive land stock compared to the base run (see Figure 10 in Appendix). In fact, most of them have the opposite effect. Neither adopting crop varieties that are expected to produce more yield for the same PET value, nor slowing down population decline cause a visible change in this key variable compared to the base run.

Findings suggest that most of these policies positively impact the average crop yields, both individually and in various combinations. For groundwater, there are two alternative policies that help increase this stock. With regard to bioproductive land stock, the capacity to provide additional value is divided among the various alternative policies: while none of them is expected to reverse the projected increasing trends, some of them may reduce the speed of increase below the base run levels. However, these alternative policies still yield results that are above the base run levels if they are implemented in combination with the policy proposed by GMB participants that presupposes an enormous reforestation effort sustained throughout the 30-year period (see Figure 11 in Appendix).

6.2. Policy design for building resilience to climate change impacts

Rather than applying sectoral management of Ikel SES, seeking to achieve a narrow, isolated purpose such as improved agricultural production, enhancing resilience of the system as a whole would ask for policies and actions that simultaneously improve the situation in multiple key variables. Analysis conducted on GMB proposed policies and on alternative policies has pointed towards how that could be done. Yet, to enhance resilience of Ikel SES to climate change impacts, it is important to understand not only the trends in climate scenarios, but also the way in which Ikel SES would react to specific shocks that come with changing climate conditions.

Using Ikel SES simulation model, the behavior of key variables is compared under base run conditions and climate-stressed conditions. For average crop yield and groundwater table, where the projected behavior following the impact is opposite to the desired outcomes, a range of policies are tested based on the results of previous policy analysis. Alongside the more detrimental changes accompanying the RCP 8.5 climate scenario, some relevant impacts are investigated and discussed in the matter of resilience building. The list of climate change impacts subjected to policy design for resilience building is detailed in Table 3 below.

Table 3. Climate change impacts subjected to analysis for resilience building using Ikel CliRes model, and their operationalization.

Climate change impact scenarios	Operationalization for resilience analysis in Ikel CliRes model
Scenario #1: More intense precipitations. Climate change projections indicate that while towards mid-century, precipitations in central regions of R. Moldova might increase slightly, they are expected to change their patters: less frequent, but more intense rainfalls.	As rainfalls become more intense, the erosivity factor increases. This impact is simulated by increasing the rainfall erosivity factor and including more intense storms every five years.
Scenario #2: Higher evaporation rates due to higher temperatures. Annual average temperatures are expected to increase, with more episodes of extremely hot temperatures in summer alongside warmer winters. With higher temperatures, the evaporation happens faster.	As water evaporates faster, a smaller fraction of the precipitation water infiltrates to the deeper layers to build up the base flow and to percolate to the confined aquifer. To simulate this impact, *infiltration coefficients* on all types of land use are reduced.
Scenario #3: More intense precipitations and higher evaporation rates due to higher temperatures.	This scenario incorporates both impacts described before. Thus, rainfall erosivity factor and infiltration coefficients are adjusted as mentioned above for scenarios #1 and #2.

Of these, we focus particularly on the most likely impact scenario: cumulated impact of more intense precipitations and higher evaporation rates (impact scenario #3, illustrated in Figure 4).

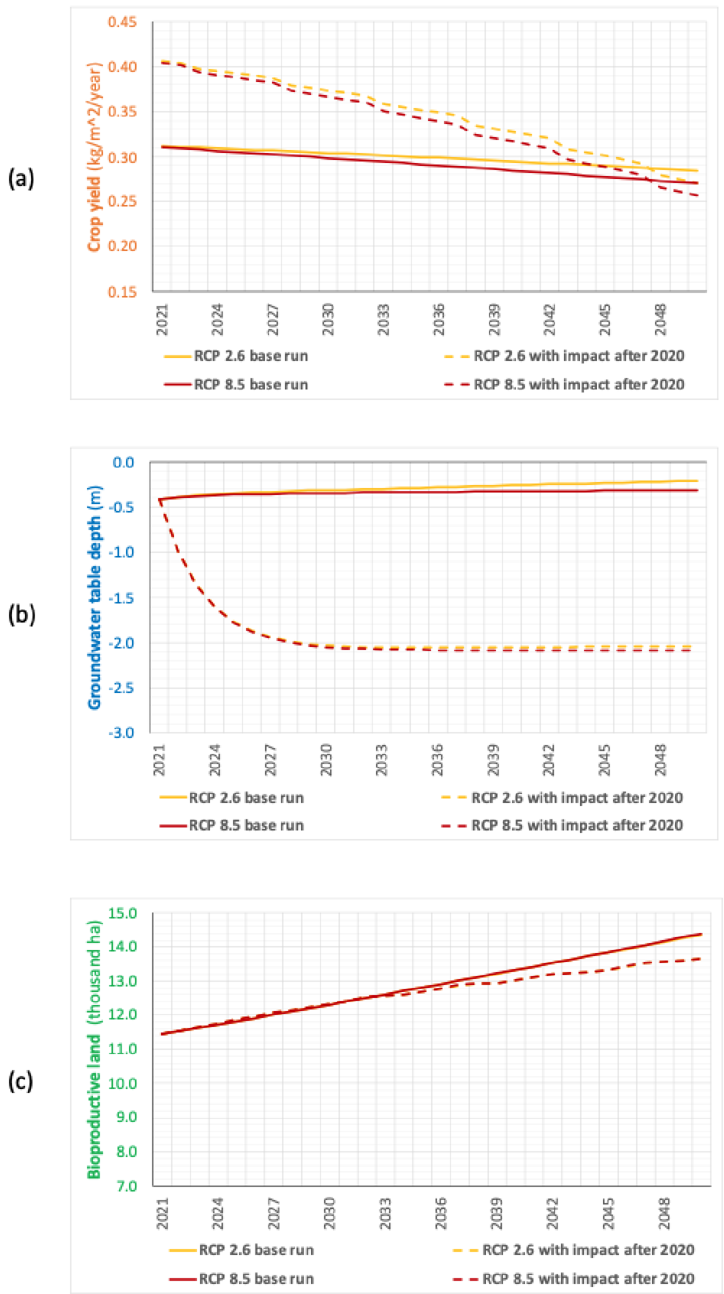

Figure 4. Cumulated impact of more intense precipitations and higher evaporation rates (impact scenario #3) on: (a) average crop yields in Ikel SES; (b) groundwater depth; (c) bioproductive land area under RCP 2.6 and RCP 8.5 climate scenarios.

Resilience assessment aided by Ikel CliRes simulator indicated that the most notable is the effect on crop yields and groundwater stock. In particular, impact scenario #3 demonstrated that the cumulated impact of more intense precipitations and higher evaporation rates leads to a dramatic decrease in average crop yield and in groundwater table compared to the base run, and a slowing down in the increase of bioproductive land stock. This calls for policy interventions that could prevent or at least alleviate their decline. Based on the previous analysis, the following set of resilience-building policies are expected to provide the best results for average crop yield and groundwater table behavior:

1. **Resilience policy #1:** Joint implementation of GMB policy #1 and alternative policies #2, #3 and #4, i.e., significantly increasing and sustaining (re)forestation efforts, adoption of crops with PET that is less than the base run value, ensuring constant implementation of better soil conservation practices that result in decrease in the soil conservation practices factor and ensuring that more people among Ikel SES population work in agriculture.

2. **Resilience policy #2:** Joint implementation of GMB policy #1 and alternative policies #4 and #6, i.e., significantly increased and sustained (re)forestation efforts, ensuring that more people among Ikel SES population work in agriculture, and ensuring the uptake of technologies that require less workforce to cultivate crops.

3. **Resilience policy #3:** Joint implementation of resilience policy #2 and increasing the percolation rate of precipitation to the confined aquifer.

There are two main findings from testing the three resilience policies against the behavior of average crop yield in Ikel SES. One is that Resilience policies #2 and #3 perform identically. The second finding is that the way policy #1 and policy #2 (and #3) build this key variable's resilience is rather different. From an engineering resilience perspective, all policies enhance the system's *hardness* and *robustness* – its ability to withstand this climatic disturbance without a negative change in the performance of the outcome and without significant loss of performance respectively. In all three situations, the yield would be higher than with impact and no resilience policies over the entire period. From this perspective, policy #1 is the best performing one. From an ecological resilience perspective, policy #1 enhances this system's *elasticity* and *index of resilience* – its ability to withstand the disturbance without changing to a different steady state and the probability of keeping the current regime respectively (Herrera, 2017). In more concrete terms, the regime shift does not happen, and the behavior pattern of this key variable remains a decreasing one. This, according to resilience objectives stated by the stakeholders, is not a desirable outcome. In contrast, policies #2 and #3 prompt a regime shift, meaning that the declining trajectory of average crop yields for this period is changed to an increasing one – an outcome aligned with the desired outcome.

Similar to crop yield, in relation to groundwater table the results of the three resilience policies are better than no resilience policy at all. Nevertheless, only policy #3 is successful in restoring the level of the groundwater to what would be its initial state. From an engineering resilience perspective, resilience policy #3 is the most helpful in increasing the system's *hardness*, followed by policy #2. In case of policy #1, it does not start recovering in the given period; it is therefore unclear if the system recovers at all with this policy alone in place. In terms of *robustness*, the hierarchy is the same. The situation is similar for *recover rapidity*, as well, i.e., the average rate at which the system returns to equilibrium after a disturbance. From the point of view of ecological resilience, policy #1 conserves the *elasticity* and *resilience index* of the system, whereby the behavior of the groundwater table would maintain a slightly declining trajectory. However, this outcome is not desirable. A desirable one would be to have a regime shift, and to see the level of groundwater increasing. To that end, resilience policy #3 is the most effective, followed by policy #2.

Based on the above, it follows that to achieve the best possible desirable outcomes, the most conducive of resilience policies is policy #3. It is both supportive of a trajectory that is more likely to preserve the equilibrium of average crop yield behavior and is the only one that is successful in restoring the level of the groundwater within the period in focus, while also providing maximum additional growth to the bioproductive land area (Figure 5).

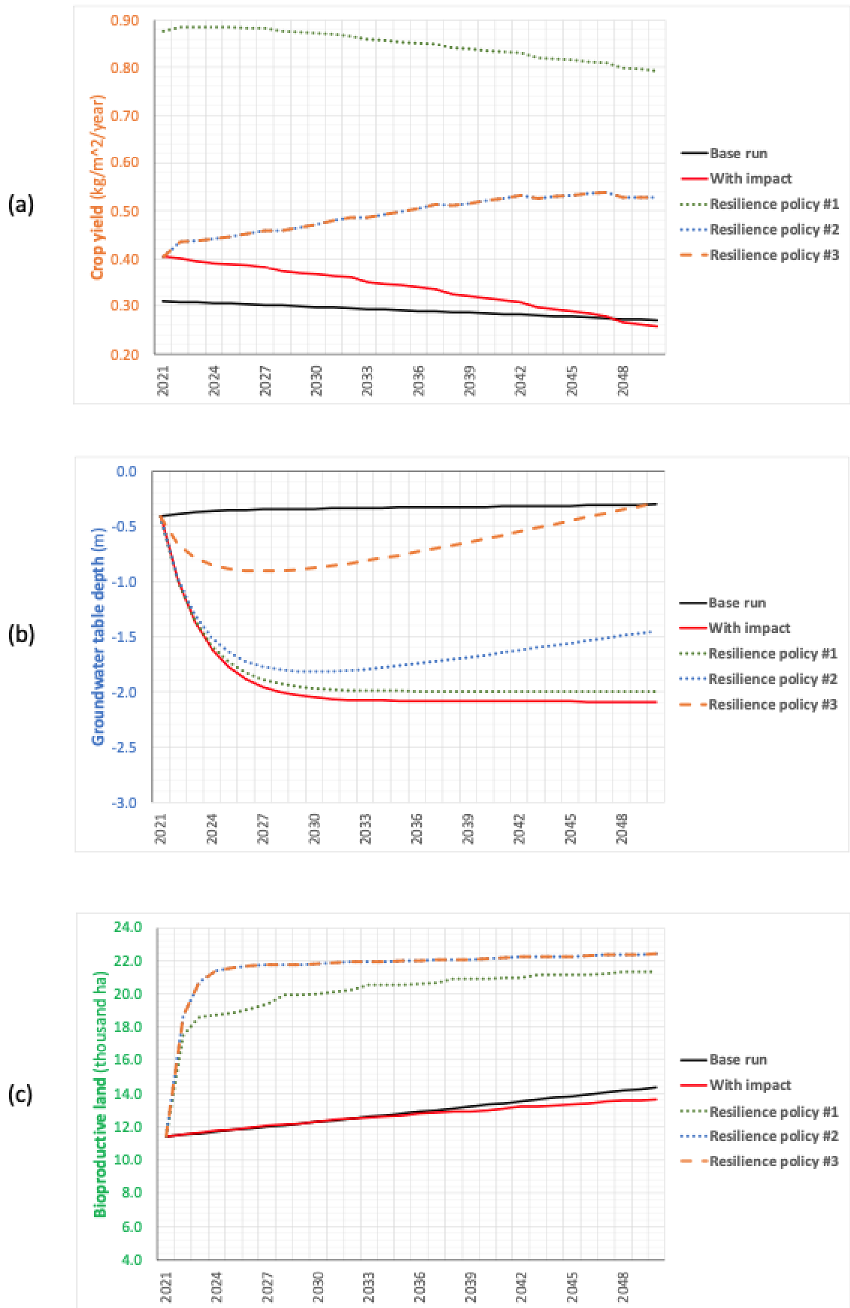

Figure 5. Performance of resilience policies under RCP 8.5 compared to the base run behavior and to the behavior in case of impact scenario #3 in relation to (a) average crop yield, (b) decline of groundwater table height; (c) bioproductive land area.

7. Conclusion

Stakeholder process has proposed average crop yield, depth of groundwater table, and the area of bioproductive land to be the key variables to define Ikel watershed as a social-ecological system for the scope of this research. GMB participants have expressed that the objective for Ikel SES in the face of looming climate change impacts is at least the conservation and at best the increase in all key variables between 2016 and 2050. For the central region of R. Moldova, where Ikel watershed is located, the climate projections suggest a clear increase in temperatures by 2050 and beyond, and a less certain change in annual amount of precipitation. The least favorable one is the decrease in annual precipitation anticipated by RCP 8.5.

The results of this resilience assessment point to the fact that Ikel SES is characterized by several resilience features that are undesirable and misaligned to the needs of the stakeholders involved in this resilience assessment exercise. It has also been shown that resilience policies are more complex than any of the individual policies discussed in the policy analysis chapter, and that their success is tightly connected to clarifying the desired performance of the outcome function (i.e., resilience objective). That is because, resilience policies put forward in this case study work best for some of the variables in some ways under certain climate change impact.

According to the reference modes elicited from GMB participants which are understood to be the resilience objectives, the resilience policy that performs best across the key variables for all three climate impact scenarios discussed in this chapter is the one referred to as *resilience policy #3.* It includes simultaneously an ambitious increase and sustaining of (re)forestation efforts, ensuring that significantly more people work in agriculture throughout the 30-year period, ensuring the uptake of technologies that require significantly less workforce to cultivate crops and increasing the percolation rate of precipitation to the groundwater table. Naturally, this should be regarded within the limitations of the model architecture and of the assumptions underlying both the model and the analysis.

Carried out in data-scarce conditions by design, the process developed in this research has proved to be helpful for understanding what builds or erodes resilience of a SES to climate-change impacts, as well as for engaging and informing policymakers, decisionmakers and other stakeholders. Indeed, stakeholder groups have contributed extensively to the initiation of a participatory process, defining higher-resolution vulnerabilities to climate change, building the conceptual model, identifying go-to adaptation policy interventions and less-known data sources. Notably, stakeholder role has been pivotal for structure and behavior validation of the formal simulation model, establishing sufficient confidence in Ikel CliRes model to progress toward policy evaluation and design. Trends based on the method of least squares rather than actual yearly data were used for policy analysis and design. On the one hand, this has rendered the endeavor of measuring all resilience attributes impractical. On the other hand, it has provided simulation results that could be assessed against these attributes, making it possible to design resilience policies that enhance the desirable attributes. In addition, using smoothed instead of fluctuating weather data prevents wrong assumptions by the layperson, who may risk interpreting fluctuations in simulated weather data as point predictions.

To sum up, the designed process that integrates a qualitative assessment with a dynamic simulation model facilitates policy design for resilience-building in Ikel watershed, a regional SES in a developing country. Whereas data scarcity has prevented a thorough measurement of Ikel watershed's resilience attributes, Ikel CliRes simulations have allowed for comparisons between how policy performances based on these attributes. This has facilitated the selection of policies that could be most conducive for achieving a stated resilience objective.

Funding: This work was supported by Boğaziçi University Research Fund [project number D11925]

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Supplementary Materials

APPENDIX

Figure 1. Location of the transboundary Dniester River basin (ENVSEC, 2015). Location of Ikel river is highlighted with red color.

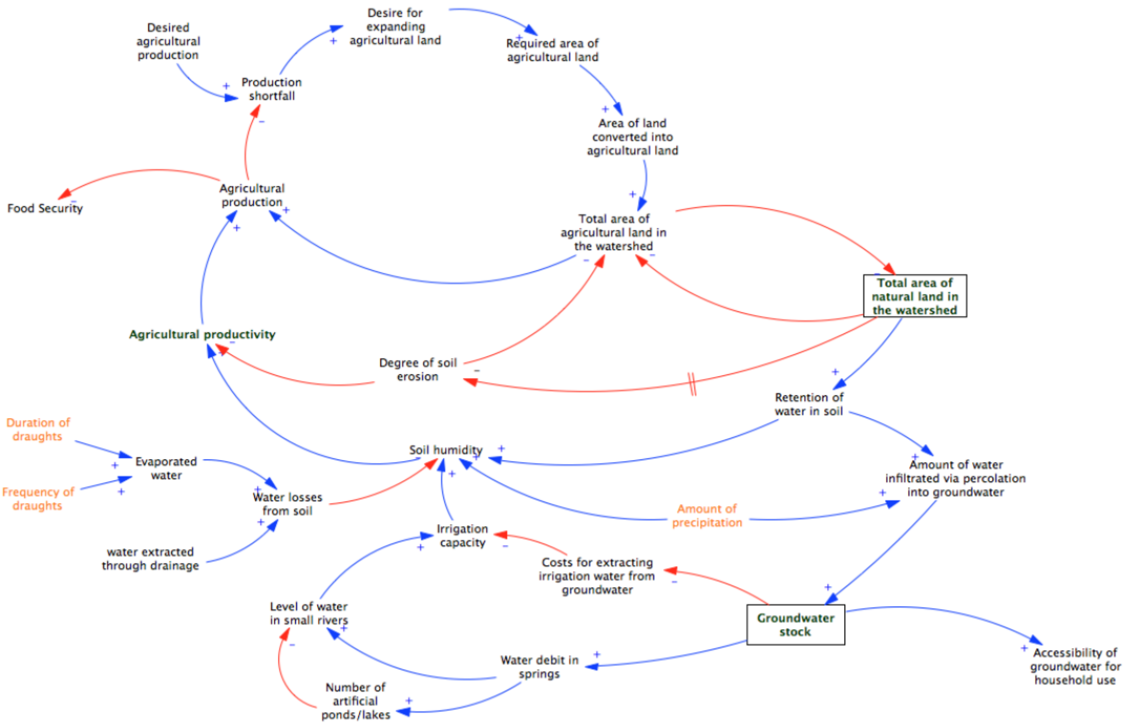

Figure 2. Conceptual model depicting the major loops that connect the key variables, as identified by the GMB participants (Ciobanu and Saysel, 2021).

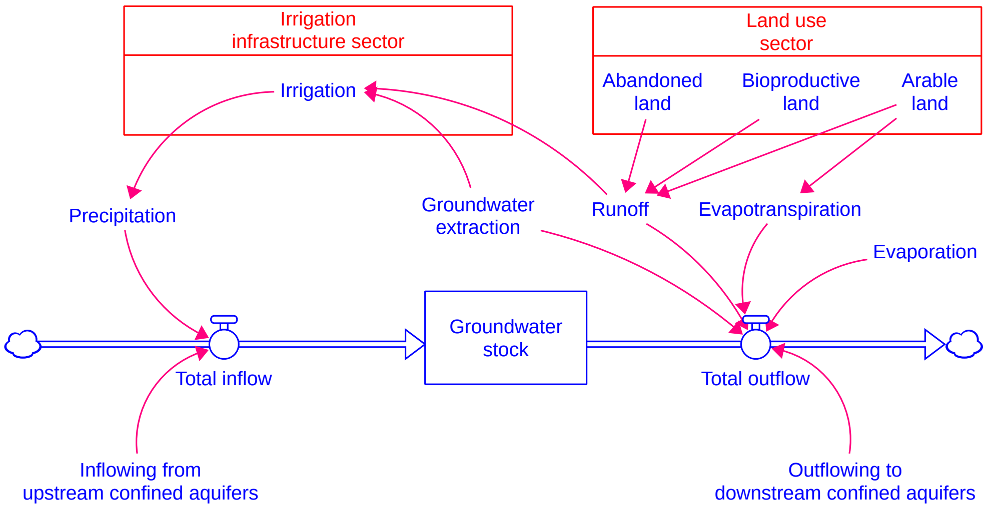

Figure 3. The water budget (mass balance) of the Ikel watershed. While the budget increases with precipitation and upstream flows, it decreases with runoff, evapotranspiration, evaporation and downstream flows. While part of the groundwater is also extracted from this budget, part of it returns through irrigation.

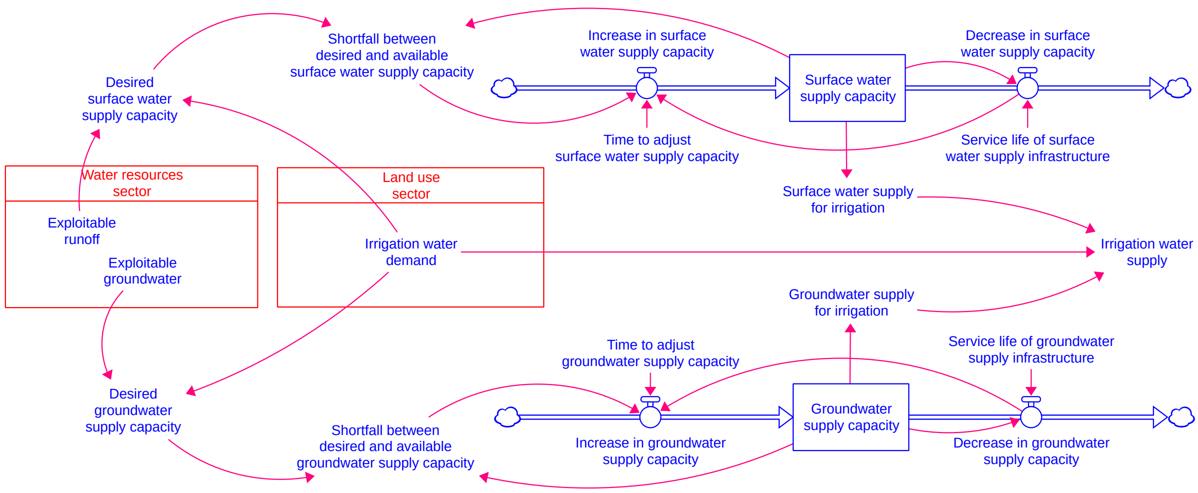

Figure 4. Overview of *Irrigation Infrastructure* model sector, which describes the formation of capacity for irrigation water supply. The stock-flow diagram illustrates the drivers of increase and decrease in the supply capacity stocks for surface water and groundwater irrigation. Capacity is increased when the desired capacity is larger than the available one. Desired capacity is given by either the exploitable water resources or the irrigation water demand – whichever is the smallest. The demand is distributed between surface and groundwater resources and capacities depending on the fractional availability (e.g., if exploitable surface water is ¾ and exploitable groundwater is ¼ of total, the demand and supply will be distributed accordingly).

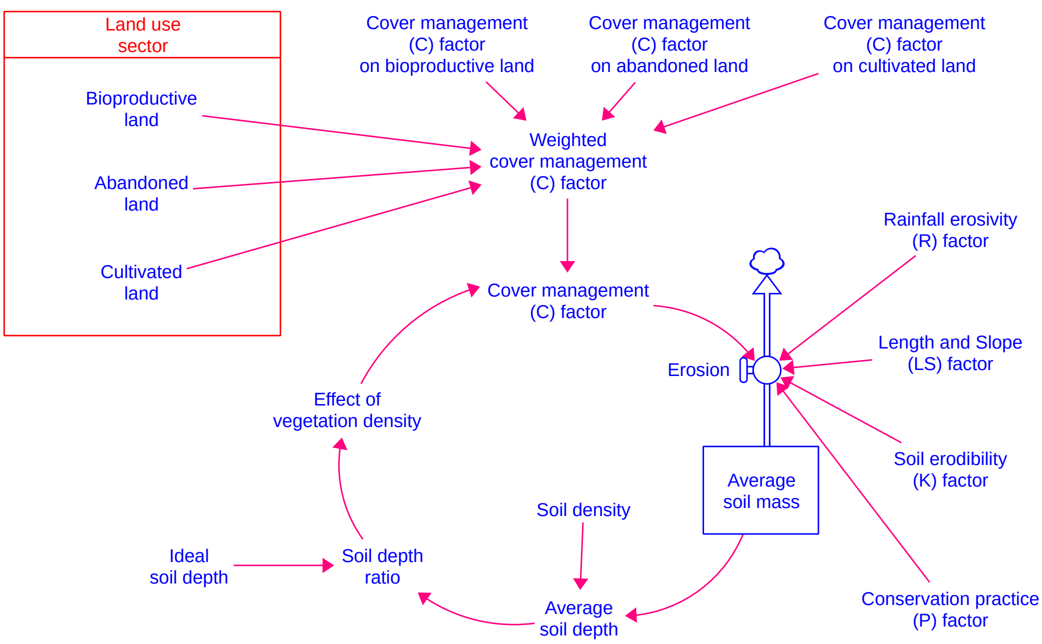

Figure 5. Overview of *Erosion* model sector. The stock-flow diagram illustrates the drivers of decrease in average soil mass stock.

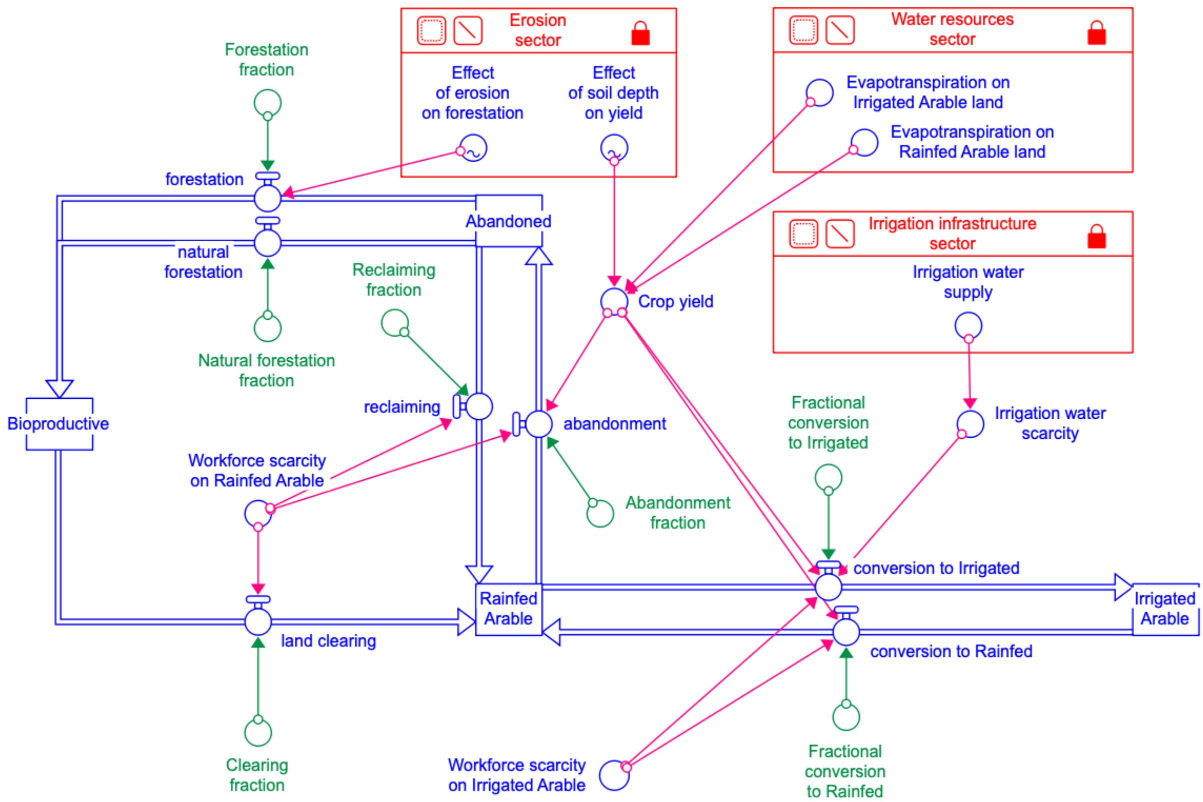

Figure 6. Overview of *Land Use* sector. The stock-flow diagram illustrates the four land stocks and the main drivers of flows in-between the land stocks. Exogenous variables are highlighted in green color.

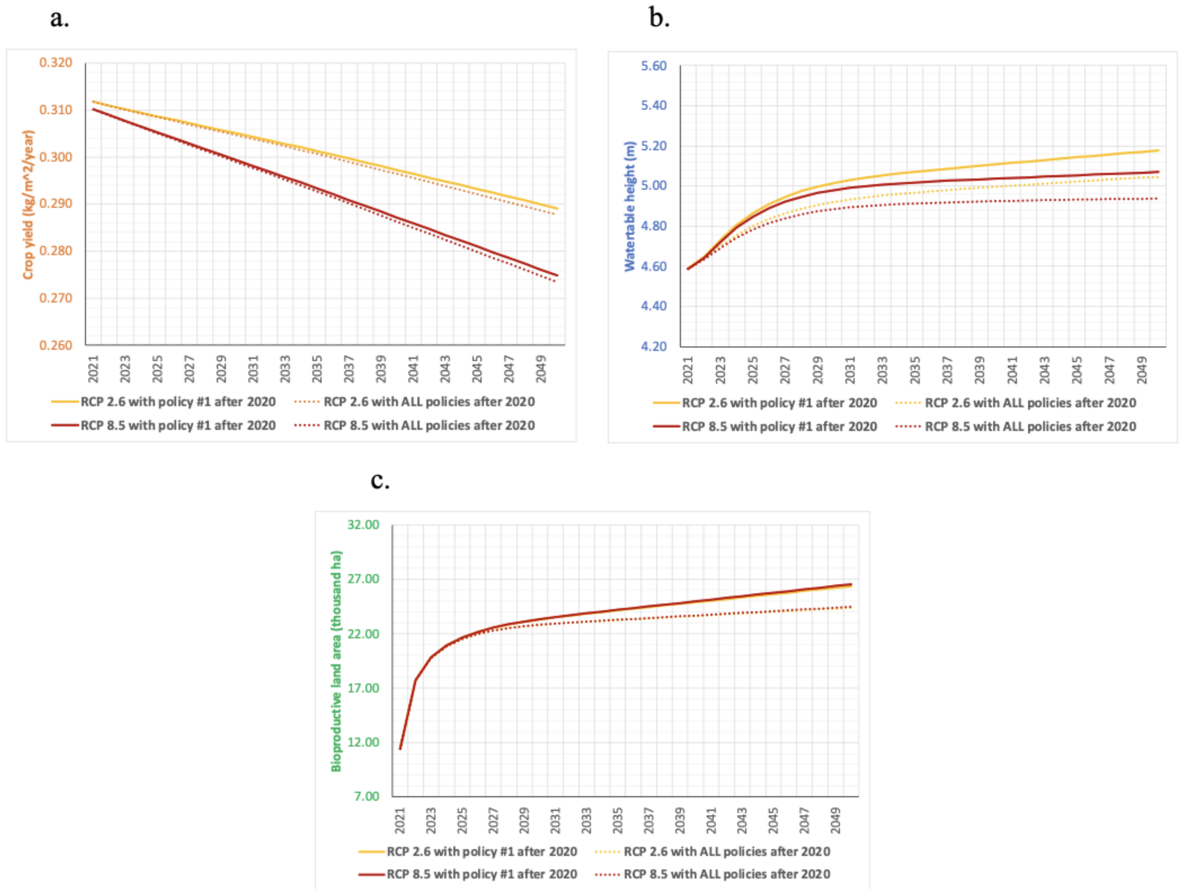

Figure 7. Impact on average crop yield (a), groundwater table (b) and bioproductive land (c) of the policy facilitating intensive and sustained (re)forestation efforts (solid lines) and of the simultaneous implementation of all policies proposed by GMB participants (dotted lines).

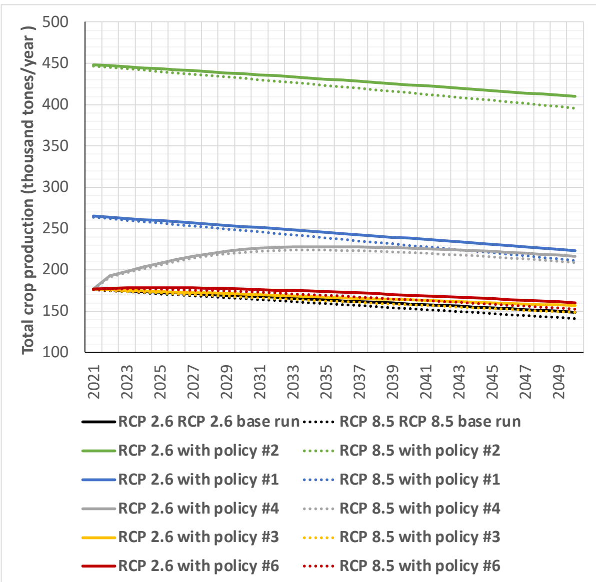

Figure 8. Performance of alternative policies on total crop production in Ikel SES under RCP 2.6 and RCP 8.5.

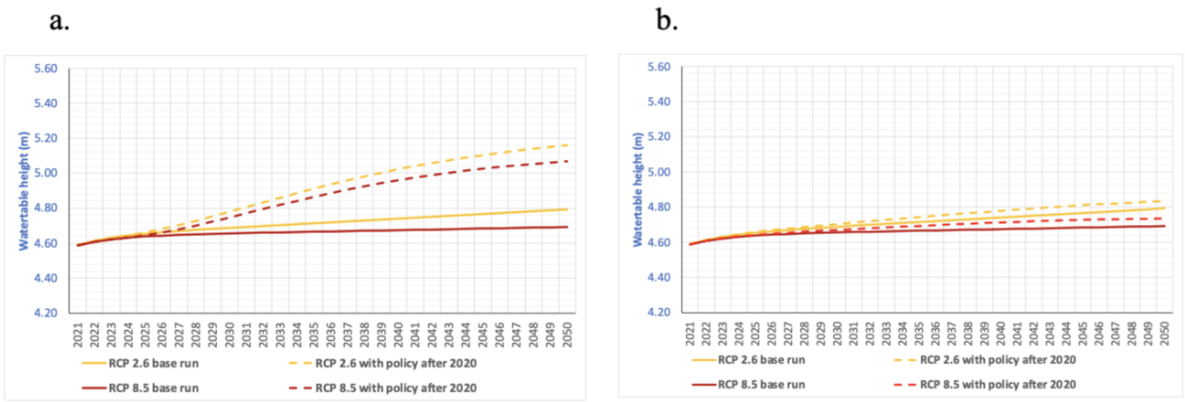

Figure 9. Performance of alternative policies with positive impact on the height of the groundwater compared to the base runs: a) Policy #4, aimed at ensuring that 10-times more of the Ikel SES population works in agriculture; b) Policy #6: support the uptake of technologies that increase workforce efficiency in agriculture and require five times less workforce to cultivate both rainfed and irrigated crops.

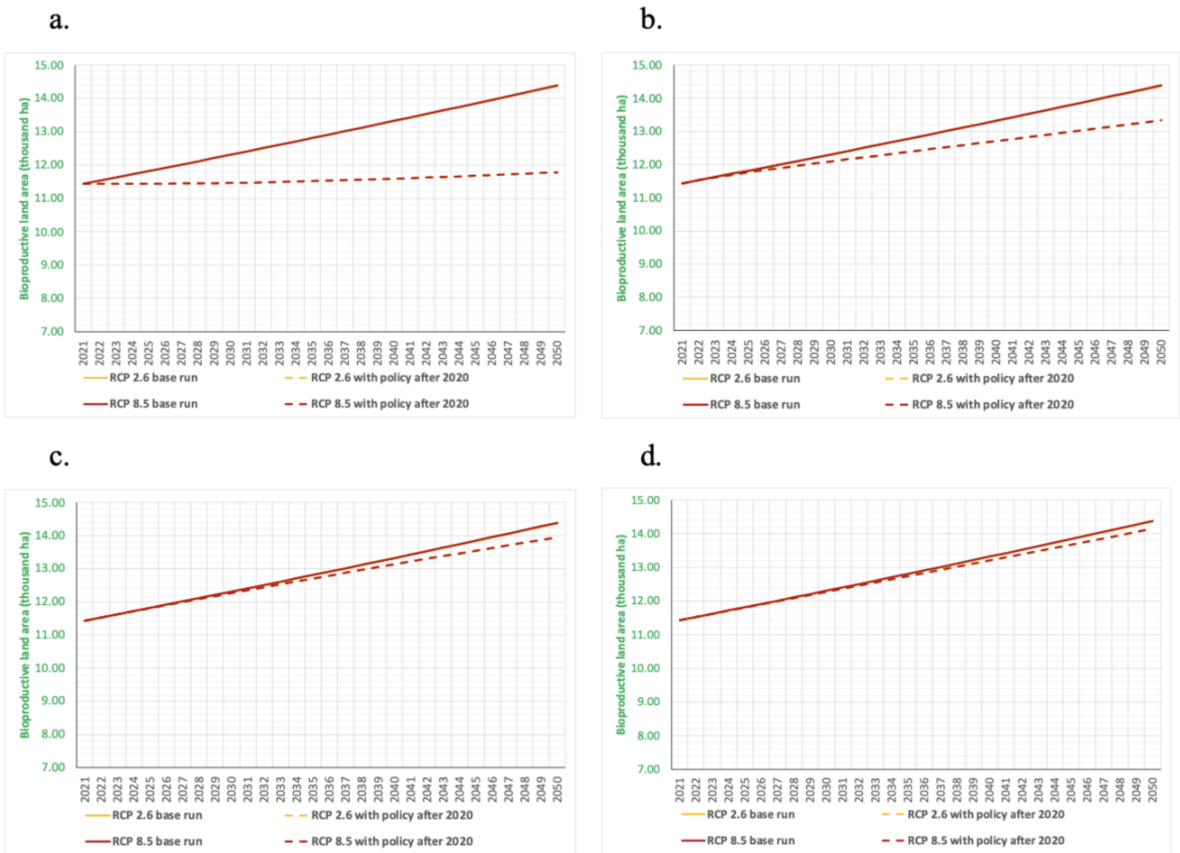

Figure 10. Performance of alternative policies #3 (a), #4 (b), #2 (c), and #6 (d), which have a negative impact on the rate of growth of bioproductive land area in Ikel SES. Their impact on the land stock is similar under RCP 2.6 and RCP 8.5. Hence, the red lines override the yellow lines.

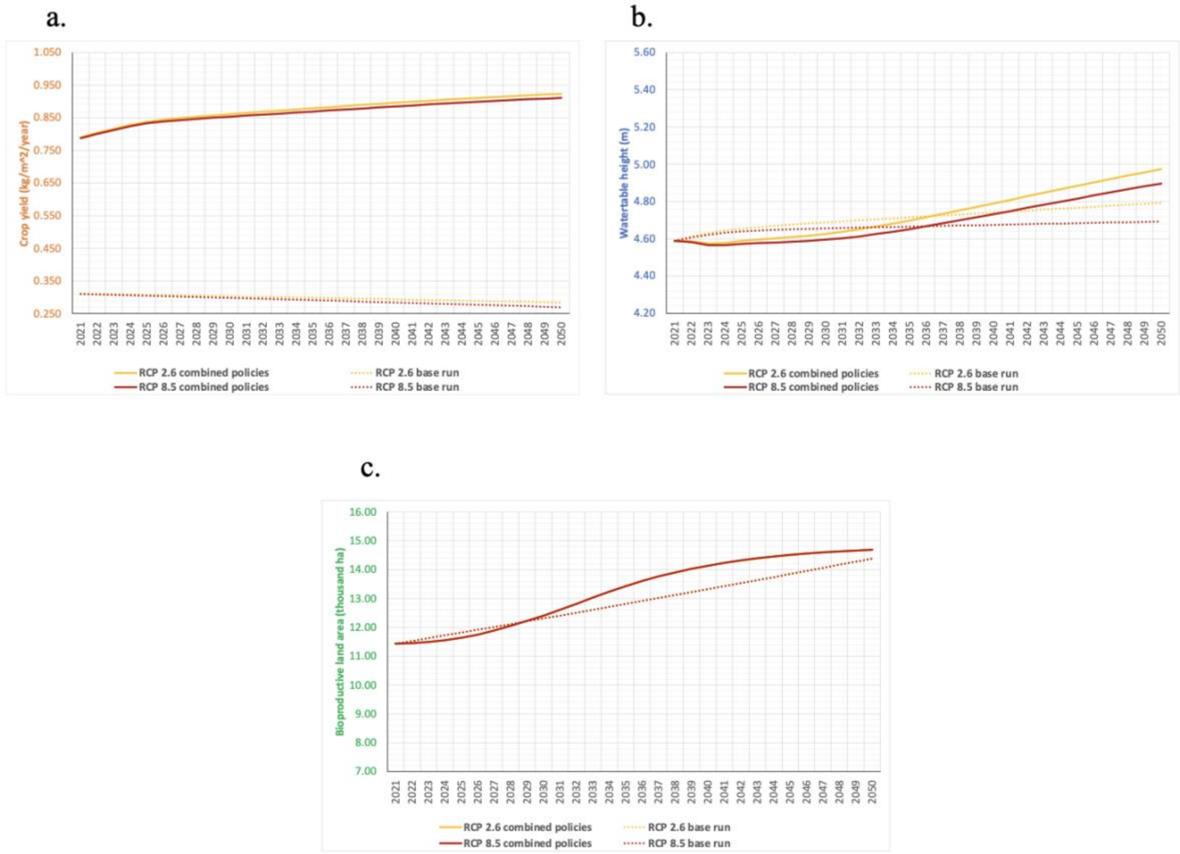

Figure 11. Performance of joint implementation of intensive reforestation policy proposed by GMB participants and alternative policies #2, #3, #4 and number #6 comparative to the base run, under all RCP climate scenarios for: (a) average crop yield in Ikel SES; (b) groundwater table height; (c) bioproductive land area.