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Environmental sustainability in an agricultural development project: a system dynamics approach

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Regional agricultural projects based on water resource development have many potential impacts on social and natural environments. In this research, potential long-term environmental problems of the Southeastern Anatolian Project (GAP) related to water resources, land use, land degradation, agricultural pollution and demography are analysed from a systems perspective. The analysis focuses on the totality of environmental, social and economic issues. For this purpose, a system dynamics simulation model (GAPSIM) has been developed as an experimental platform for policy analysis. GAPSIM was validated, first 'structurally', using the tests suggested by the literature and then the model 'behaviour' was tested and calibrated with respect to available data. The reference behaviour of GAPSIM reveals that, as the irrigated lands are developed, GAP faces significant water scarcity because of the increased intensity of cotton, the crop with the highest demands for water. Simulation results also indicate that two key environmental factors, pesticide and fertilizer consumption may reach undesirable levels. Alternative irrigation water release strategies, development rates of irrigated fields and farm rotation practices appear as important policy tools in achieving long-term environmental sustainability. GAPSIM promises to be not only a useful laboratory for policy makers of GAP, but also a useful generic structure applicable to other similar regional development projects.

Keywords: Agricultural sustainability, irrigation-development projects, Southeastern Anatolian Project (GAP), land degradation, agricultural pollution, urbanization, simulation modelling, system dynamics.

Introduction

The Southeastern Anatolian Project (GAP) is an integrated development project in Turkey, consisting of 13 individual water development projects. It involves the construction of 22 dams and 19 hydropower plants on the Euphrates and Tigris rivers. Irrigation of 1·6 million ha and a hydropower production capacity of 7400 MW are projected. This constitutes 22% of Turkish national hydropower potential, and would yield a total energy production of 27 000 GWh/year if irrigation release is ignored (GAP-RDA, 1997). Also, through agro-industrial development stimulated by improved agricultural production and infrastructure, GAP aims to create an extra 1·25 million jobs within the urban areas (GAP-RDA, 1990). The total cost of the project is estimated as US$ 32 billion. 48% of this amount has been realized by the end of 1998 (GAP-RDA, 1998).

In the Master Plan, the territory of the provinces Adiyaman, Batman, Diyarbakir, Gaziantep, Kilis, Mardin, Siirt, Şanliurfa and Şirnak, located at the southeastern border of Turkey is called the 'GAP region' (Figure 1). This region constitutes about 10% of Turkish national territory (about 7·5 million ha) and according to the 1997 census, about 10% of the national population (ca. 6·1 million). The average number of children born to a married woman in her lifetime (fertility) is ca. 5. The

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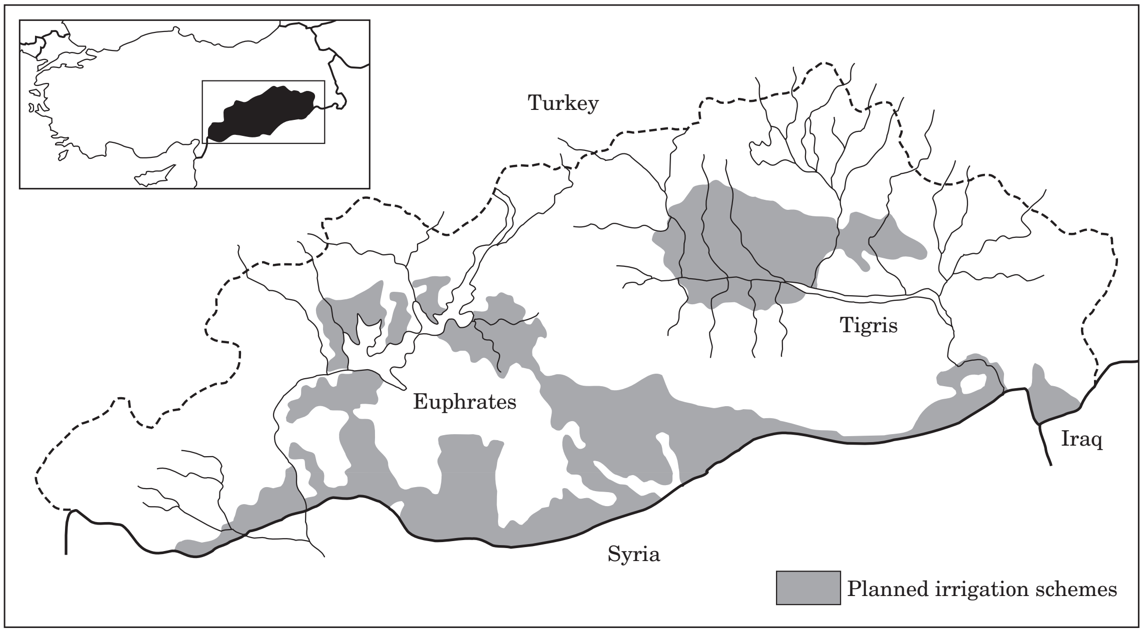


Figure 1. Southeastern Anatolian Project (GAP) Region.

emigration rate is around 3% but regional population still keeps increasing (SIS, 1997). Also, there is a strong migration from the rural to the urban parts of the region. Declining subsistence farming, rangelands degradation and armed political conflict of the 1990s have stimulated this tendency. On the other hand, the population absorption capacity of the urban areas is very low with an underemployment rate of around 50%.

The GAP region is semiarid, with average annual rainfall ranging between 350 and 835 mm/year from north to south with significant water deficit in the summer season. Low input, low and medium technology farming systems predominate, and ca. 90% of the farm units deal with crop production together with animal husbandry. Since subsistence is high, fodder production is low; livestock is fed on poor rangelands, on fallow areas or on crop residues. Traditionally, winter cereals and pulse production with fallow constitute the major agricultural practice and crop diversity is low.

With the huge potential for increased land fertility and highly underemployed population, the GAP region would appear to be a suitable candidate for irrigation development and agricultural modernization. A large number of academic researchers and state officials support GAP's officially declared objectives, which are that: (1) agricultural productivity will increase; (2) improved income levels will foster capital accumulation within the agricultural sector; (3) population absorption capacities of the urban areas will be enhanced; and (4) enhanced social stability and sustainable economic development will be achieved. It will permit the additional summer crops and increased yields from improved soil nutrition and irrigation. The most promising crops are fibre crops (basically cotton), oilseeds (sesame, soybean, sunflower), summer cereals (maize, sorghum), vegetables and fruits.

However, agricultural modernization and accompanying regional development can create many potential social and environmental problems with complex long-term dynamics. Some of the consequences of large-scale irrigation development projects are known to be irreversible. These include: the loss of fertile lands due to impoundment of water, loss of archaeological sites, resettlement problems of rural communities, sedimentation in artificial reservoirs, climate change and extinction of endemic species (Goldsmith and Hilyard, 1984). These problems often constitute the basis of the arguments against irrigation projects and construction of dams, since they cannot be reversed, once construction has been initiated and completed.

On the other hand, the transformation of traditional agricultural systems and incorporation of new crops and technologies in the territory can create some other environmental impacts which are different in their time horizon. Unlike the permanent irreversible effects, the interaction of people with natural environment creates long-term impacts, which can and should be managed so as to minimize unintended adverse consequences. These include increased soil erosion rates, salinization in semiarid environments and agricultural pollution due to increased chemical consumption (Arnon, 1987). Furthermore, agro-industrial development and urbanization often accompany agricultural transformation, significantly affecting population dynamics.

In order to achieve an integrated analysis of these long-term socio-environmental problems, they must first be summarized in terms of specific, strategic questions. These questions will be articulated in the next section, which will describe the scope and purpose of the system dynamics model.

Scope and purpose of system dynamics model

GAPSIM seeks answers to strategic questions related to the level of hydropower production, extend of irrigation, crop selection, environmental indicators, agricultural production and demography, in a long-term dynamic context. The time horizon of the model is 40 years, from 1990 to 2030. The model addresses strategic questions such as: how future crop patterns and their respective production levels will evolve, taking into consideration the availability of water resources, land degradation, market conditions and traditions; the various prospects for future water availability when alternative hydropower production levels and crop selections are considered; and how demography will be affected when agricultural production and urban growth are altered. Since the nature of the interactions between these components shapes the 'feedback' structure of the model, a brief discussion of some basic interrelationships should be helpful.

Different land regimes, crop intensities and rotations create changing requirements for irrigation water and agricultural chemicals. These varying levels of input consumption rates influence in turn, the levels of pollution and land degradation. Simultaneously, differences in the levels of input consumption and land degradation affect farm economies through increased unit production costs and changing yield levels. In the long term, these pressures on farm economies may shape agricultural land regimes, crop intensities and rotations.

At the same time, the water-consumptive nature of crops and the water release strategy for hydropower production determine the availability of water for irrigation purposes. Decreasing water availability on individual farms creates declining yields. Moreover, irrigation water scarcity inhibits the actual rate of transformation from rainfed fields to irrigated fields. Both the irrigation water availability on individual farmlands and the overall development rate of irrigated fields have direct effects on yields and production levels of crops.

In an agricultural system where subsistence farming predominates, development in favour of cash crops production such as fibre and oilseed crops, decreases of cereal and pulse production may create additional rural emigration to urban centres both within the region and out of it. The development of urban structures to accommodate these pressures, and the initiation of job opportunities will be needed to avoid creating a critical social problem.

The purpose of the system dynamics approach presented in this paper is to provide an experimental simulation platform for the analysis of these interconnected strategic problems in their interconnected context. The objective is to help provide policies/strategies that address the issues of water distribution management, land use, land degradation, agricultural pollution, agricultural production and population dynamics. The model was constructed to test alternative policies under different scenarios.

Methodology

The methodology used in the development of GAPSIM is '*system dynamics*' modelling and simulation, specifically designed for modelling and analysis of large-scale socio-economic systems. A detailed description of the methodology is given in Forrester (1961, 1968) and Sterman (2000). It has been used in many areas, including global environmental sustainability (Forrester, 1971; Meadows *et al*., 1992), regional sustainable development issues (Saeed, 1994; Bach and Saeed, 1992), environmental management (Mashayekhi, 1990), water resource planning (Ford, 1996) and ecological modelling (Wu *et al*., 1993).

The methodology focuses on understanding how the physical processes, information flows and managerial policies interact so as to create the dynamics of the variables of interest. The totality of the relationships between these components constitutes the system's 'structure'. Operating over time, the structure generates 'dynamic behaviour' (such as exponential growth or decline, S-shaped growth, collapse or oscillations). The typical purpose of a system dynamics study is to understand how and why the dynamics of concern are generated and to search for managerial policies to improve the situation. These policies refer to the long-term, macro-level decision rules used by upper management.

There are three types of variable in a system dynamics model: *stock*, *flow* and *converter (or auxiliary)*. Stock variables (symbolized by rectangles) are the state variables and they represent the major accumulations in the system. Flow variables (symbolized by valves) are the rate of change in stock variables and they represent the activities, which fill in or drain the stocks. Converters (represented by circles) are intermediate variables used for miscellaneous calculations. Finally, the connectors (represented by simple arrows) represent the cause and effects links within the model structure (HPS, 1996). The simplified *stock-flow diagram* and feedback loops (*causal loop diagram*) for GAPSIM rainfed fields sector (model segment) are illustrated in Figure 3.

Model description

The original computer model was developed as part of a thesis and consists of about 2000 variables and 14 sectors (model segments) representing different environmental and economic components. It was constructed using *STELLA Research* software (HPS, 1996) designed for dynamic feedback modelling of complex systems. Full details are available from the authors (see also Saysel, 1999).

In Figure 2, GAPSIM model sectors and their basic interactions are represented at a macro level. Possible *land flows* are represented with bold arrows. These flows are from rangelands and forestlands to rain-fed fields; from rain-fed fields to urban land; from rain-fed fields to irrigated fields and in-between fields and vineyards. Ordinary arrows represent a second type of interaction, information exchange (often as an input-output relationship) between sectors. *Rain-fed fields*, *irrigated fields* and vineyard sectors constitute the 'arable lands group'; for simplicity of presentation, they are treated as a single object in Figure 2.

In this section, descriptions of certain model components are given. However, model sectors representing rangelands and livestock production, forests, market and government are not discussed in this paper (see Saysel, 1999).

Arable land sectors

Arable lands in GAPSIM are central to the model, as they have interactions with all other sectors

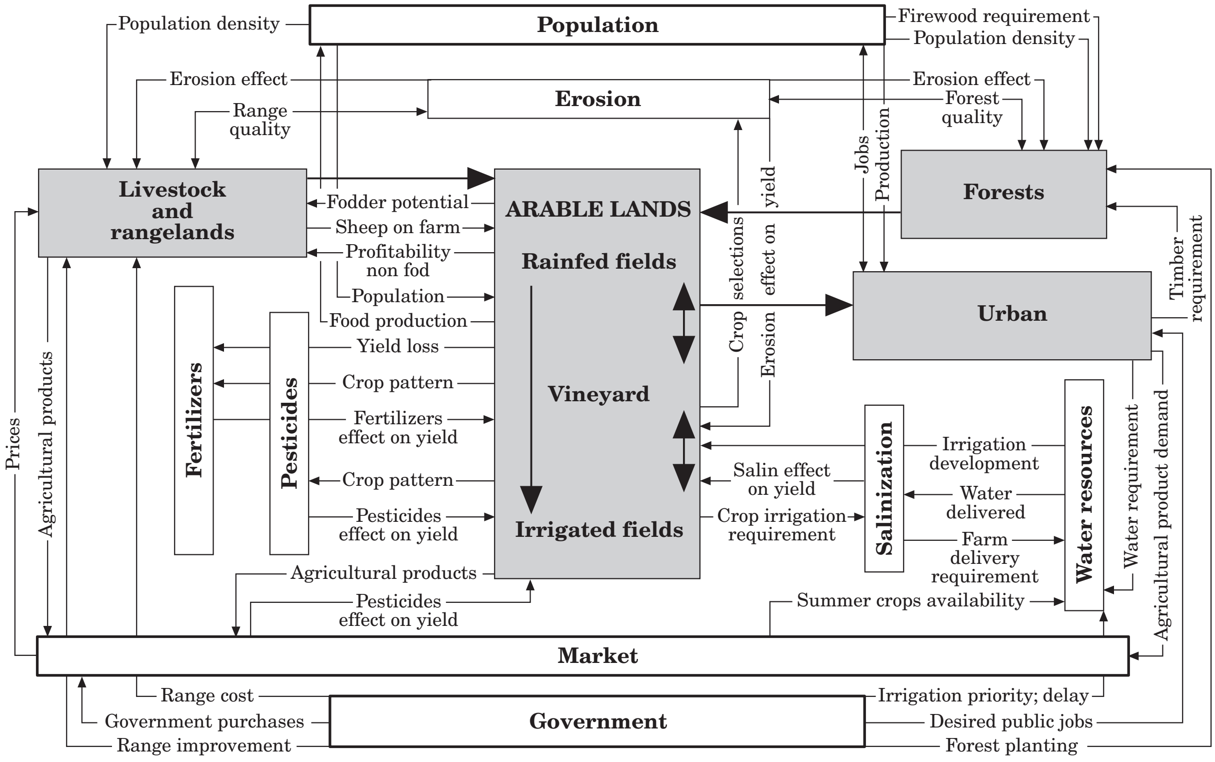
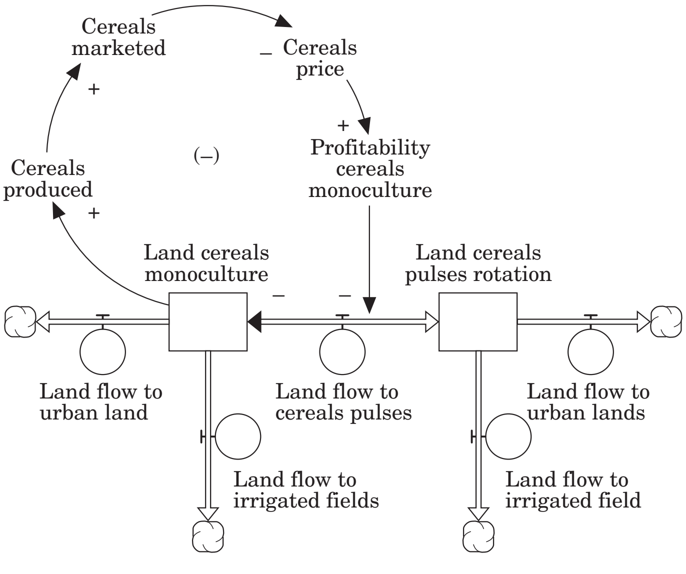


Figure 2. GAPSIM model overview.

except the *government sector* (Figure 2). Three sectors constituting arable lands (*rain-fed fields*, *irrigated fields* and vineyard) supply agricultural products to the *market* sector and receive from this sector the price information of these products. They provide information on current crop patterns and crop input requirements to the *fertilizers*, *pesticides*, *irrigation-salinization* and *erosion* sectors and receive from these sectors information on fertilizers and pesticide consumption rates and salinization and erosion effects on yields. Arable lands deliver the fodder potential of lands and profitability of non-fodder field crops to the *livestock and rangelands* sector and receive the population information of sheep fed on farmlands from this sector. They receive the rural population information from the *population* sector and supply food to this sector. Finally, arable lands in GAPSIM receive the irrigation development rate from the *water resources* sector (Figure 2).

In Figure 3, a simplified stock-flow structure of the rain-fed fields sector and the interaction of cereal production with the market are presented. The fields are identified according to the possible crop patterns in the GAP territory. For example, rain-fed fields are classified under two stock variables (rectangles in Figure 3), the first representing monoculture of cereals (with fallow) and the second representing the rotation of cereals and pulses (with fallow). The transition in between these two crop strategies, the transition from rain-fed fields to irrigated fields and the transition from rain-fed fields to urban lands are represented by flow variables (hollow arrows in Figure 3). The *negative feedback loop* demonstrates the interaction of cereal production with the market. As the land allocated for cereal monoculture increases, so does cereal production, resulting in decreased cereal prices and profitability of cereal monocultures. Cereal monoculture thereby loses its advantage with respect to cereal-pulse rotation; the land allocated to the latter increases, resulting in decreased land allocated to monocultures. Since an initial increase in land for monoculture eventually ends in a decreasing effect on this same variable, it constitutes a self-stabilizing, (balancing, counteracting, negative) feedback loop. (The term 'negative' comes from the algebraic product of all signs around the feedback loop. In a 'positive' or compounding loop on the other hand, the algebraic product of signs is positive, and the loop results in unstable growth). Associated numbers in the table represent the values for the stock and flow variables corresponding to the beginning and end of the simulation period in the model reference behaviour.



Year	Land cereals monoculture (ha)	Land cereals pulses rotation (ha)	Land flow to cereals pulses (ha/year)	Land flow to irrigated fields (ha/year)	Land flow to irrigated fields (ha/year)	Land flow to urban lands (ha/year)	Land flow to urban lands (ha/year)
1990	1 300 000	1 400 000	–2000	0	0	12	13
2030	1 079 000	688 000	–2500	3250	2080	550	350

Figure 3. Simplified stock-flow structure of rainfed fields sector and interaction of cereal production with the market.

On arable lands, seven major commodities are produced. Cereals, pulses, cotton, oilseed crops, summer cereals, vegetables and fruit, each aggregating a set of agricultural products proposed for the region. Each farm system generates its own yields, income, production factors and costs for calculation of profitability. These calculations are based on primary farm products and production factors such as fertilizers, pesticides, seeds, fuel, irrigation and labour. The land flows between different farm systems are calculated according to several criteria. These are: relative profitability of the competing crop systems, crop safety factor (a factor representing the marketing infrastructure, which means a bias towards those crops safe in marketing – basically cereals, pulses and cotton) and another factor representing the know-how requirements which means bias towards monoculture cropping (basically cotton and cereals) on irrigated fields.

Water resources sector

The water resources sector describes aggregate releases for hydropower production under different construction and operational constraints with respect to the changing water demand of the arable land sectors. Water resources sector informs *arable lands* sectors on the irrigation development rate. It supplies irrigation water to *irrigation and salinization* sector and receives water demand information form this sector. It also receives input about summer crops availability from *market* sector. Finally it receives information about probable delays in GAP construction from the *government* sector.

In Figure 4, the basic feedback loop acting on the irrigation development rate is represented. The demand for irrigation water increases either by increased irrigated lands or by the increased intensity of high water-demanding crops. According to the feedback loop in Figure 4, as the amount of irrigated land increases, so does demand for irrigation water. Then, the irrigation water use increase. As a result, the availability decreases. As less water is available, farmers slow down the rate of transforming their rain-fed farms to irrigated lands. This constitutes a negative feedback loop, which acts to stabilize the regional development of irrigation.

Irrigation and salinization sector

The irrigation and salinization sector represents quantity of irrigation water applied, the portion lost to evapotranspiration, which leaves salt in the soil root zone, and the portion infiltrated through the root zone, which flushes out the salt and recharges the groundwater (Johnson and Lewis, 1995). An average salinization profile and its effect on yields of different crops on the irrigated arable lands are calculated. The salinization model is discussed in detail in Saysel and Barlas (2001).

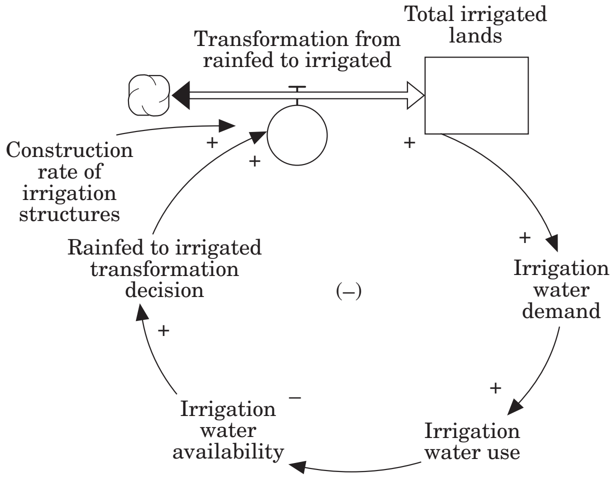


Figure 4. The major feedback loop acting on the development rate of irrigation.

Erosion sector

The erosion sector describes reduction of soil depth on arable lands, rangelands and forests according to the formulation suggested by the universal soil loss equation (Schwab *et al*., 1993) and parameters provided for the GAP region. It calculates the effects of soil erosion on farm yields and rangelands and forests regeneration. Together with the eroded soil, plant nutrients and organic matter are also lost which results in a decline in soil productivity (Hudson, 1971).

Fertilizers sector

Increasing use of artificial fertilizers is still the major and simplest practice of enhancing farm yields in transient-technology agricultural systems, masking adverse effects of soil erosion on fertility (Mannion, 1995). Decreasing soil fertility because of land degradation processes may be compensated for with increased application of chemical fertilizers (Pimentel *et al*., 1993). Bach and Saeed (1992), model the process of land degradation as a combination of the erosion, salinization, water-logging and intensive cultivation processes. In GAPSIM, land degradation is modelled as a combination of salinization and water-logging and erosion and it is assumed that, in the long term, farmers tend to increase fertilizer application rates as a reaction to decreasing yields in order to sustain output. The fertilizers sector represents changing fertilizer application rates in different fields and the amounts of mineral nitrogen leached from each field. Initial fertilizer application levels in the model are the minimum rates proposed in TOBB (1994) and GAP-RDA (1990).

Pesticides sector

Annual pesticide consumption rates for different farms are calculated according to distinct pest abundance levels and pest resistance development. Pest abundance is assumed to be a function of the average period a given crop pattern on a certain farmland remains unchanged. The level is thus assumed to be high for monocultures and low for multi-crop rotation systems. The structure of this model sector is based on knowledge of the increasing global trend in pesticide consumption. Accordingly, crop losses to pests increase despite intensified pesticide use. Reduction in crop rotations and diversity, the increase in monocultures and in pests that are resistant to pesticides play major roles in increasing crop losses (Pimentel, 1991). Resistance is exacerbated by insecticide overuse and acts as a stimulant for the pesticide industry (Mannion, 1995). Since resistance develops gradually, as the effect of pesticides decreases, farmers tend to increase application rates (Delen *et al.*, 1995). In the model, initial pesticide quantities are taken from GAP-RDA (1988).

Urban sector

The urban sector is an aggregation of all urban sites in GAP taken as a system of interacting industries, housing and urban populations (Alfeld and Graham, 1976). Each industry structure creates its own products for consumption of either other industry structures or population and creates demand for other industry products. Urban sector informs the market sector about demand for agricultural products and receives information on demand for agricultural production factors. It also delivers water and energy requirements to the water resources sector. This sector receives urban population from population sector and gives information on job availability to this sector. Finally it receives 'desired public jobs' information from the government sector (Figure 2).

Population sector

The population sector models the populations living in sub-settlements and villages and those living in towns and cities using net birth, emigration and immigration rates, as determined under urban employment and rural subsistence level (food availability) constraints.

Model validation

In *system dynamics* modelling, the ultimate objective of the validation process is to establish the *structural* validity of the model with respect to the modelling purpose. This is crucial, because the purpose of a system dynamics study is to evaluate alternative structures (strategies, policies) to improve the behaviour. Accuracy of the model *behaviour* is meaningful only if there is sufficient confidence in the structure of the model. Behaviour validation is typically performed, after structural validation. In behaviour validity tests, emphasis should be on pattern prediction rather than point prediction, mainly because of long-term orientation of the models (Barlas, 1996).

Although validation is applied to every stage of modelling, for detection of structural flaws formal procedures and some individual tests called 'structure-oriented behaviour tests' are used (Barlas, 1996; Forrester and Senge, 1980). A minimum crucial set involves the use of *extreme-condition*, *behaviour sensitivity* and *phase relationship* tests (Barlas, 1996).

Extreme-condition tests involve assigning extreme values to selected model parameters and comparing the model generated behaviour to the anticipated behaviour of the real system under the same extreme condition. *Behaviour sensitivity* tests consist of determining those parameters to which the model is highly sensitive and asking if the real system is also sensitive to those set of parameters.

Figure 5 is a simulation run of an extreme condition test. The cereal price is set to an extremely high value and the dynamic behaviour for lands allocated to cereal monoculture (variable 1) and cereal-pulse rotation (variable 2) is observed. Farmers

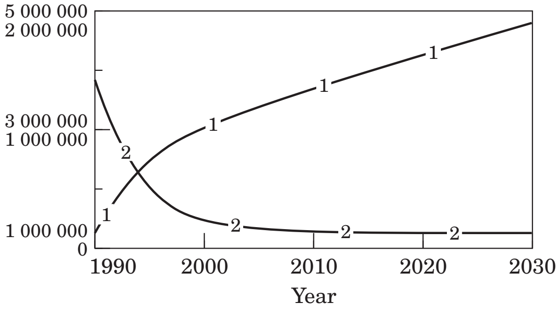


Figure 5. Rain-fed fields (both in hectares) under extreme cereal price. See text for explanation of variables in this and all subsequent figures.

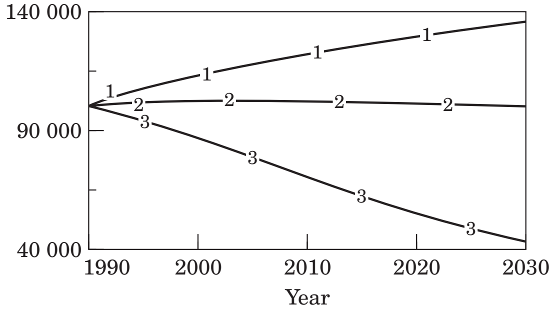


Figure 6. Behaviour sensitivity of lands for cotton monoculture (ha) to cotton price.

quit the latter in favour of the former confirming the anticipated behaviour.

In Figure 6, sensitivity of land given over to cotton monoculture to cotton price is illustrated. As cotton price decreases (runs 1 to 3) farmers tend to allocate less land for cotton monoculture, confirming the anticipated behaviour for the real system.

Figure 7 illustrates the behaviour validity (calibration) of the model for a set of variables for which data exist. In these runs, cereal production (kg/yr), pulse production (kg/yr) and population dynamics (capita) are compared, respectively, with historical data (productivity data, variable 1; historical data, variable 2). Model generated behaviour satisfactorily fits the available data.

The reference behaviour of the model

In this section, the reference behaviour of GAPSIM is summarized in terms of the dynamics of water resources, crop allocation of irrigated fields, pollution and land degradation, production and demography. The reference behaviour stands as a basis for evaluation of the scenario and policy analysis, which will be considered in the next section. In these runs, construction of hydropower structures begins in 1990 and irrigation structures in 1995.

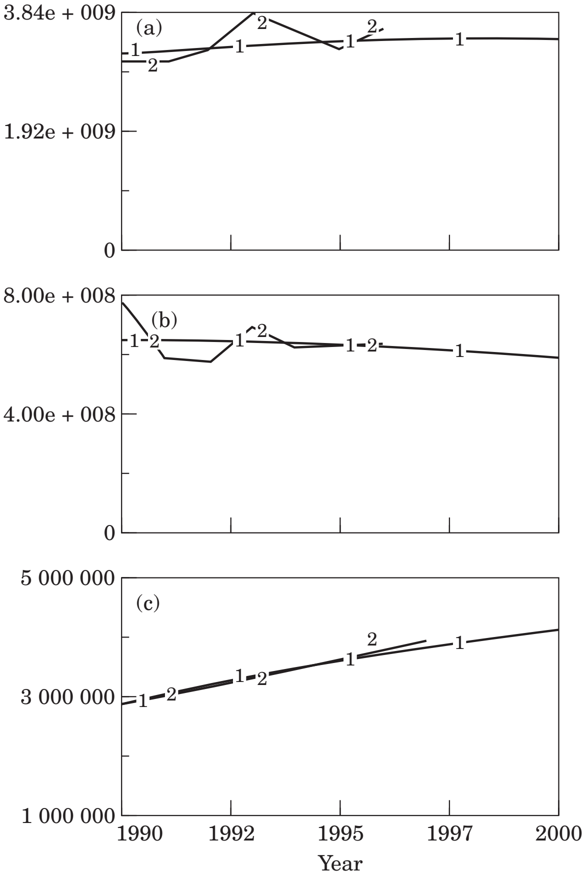


Figure 7. Historical comparison of model generated behaviour with real data. (a) Cereal production; (b) pulse production; (c) urban population.

Water resources development

Figure 8 illustrates the behaviours of variables representing water resource development. In this run, as the irrigated fields proliferate, GAP begins to face a significant water scarcity. With all hydropower plants constructed, the firms' energy production (variable 1) stagnates at 17 500 GWh/year, which is lower than the project target set as 24 000 GWh/year in the GAP Master Plan (GAP-RDA, 1997) with irrigation water releases considered. The irrigated lands (variable 2) become saturated at 1·1 million ha at the end of the simulation (year 2030). This is, again, far below the project target 1·6 million ha (GAP-RDA, 1990). The irrigation release ratio (variable 3) indicates that about 50% of the 35 billion m^3/year basin

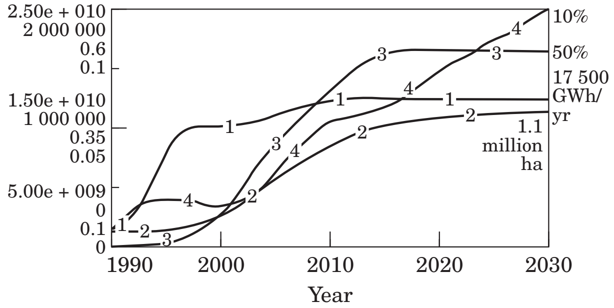


Figure 8. Water resource development in the reference behaviour.

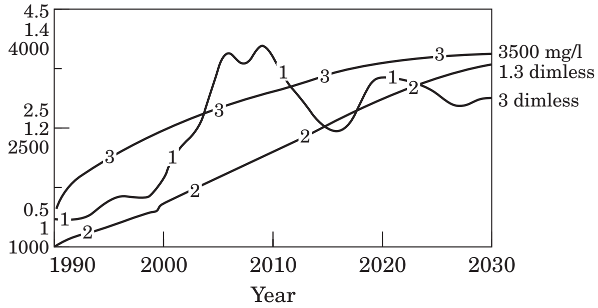


Figure 10. Pesticide, fertilizer and salinization dynamics in the reference behaviour. 'Dimless'=dimensionless.

yield of the GAP watershed is utilized for irrigation. On the other hand, the average yield loss for the high water demanding crops due to water scarcity on farmlands (variable 4) reaches ca. 10%.

Land use

The poor performance in water resource development is mainly a result of the predominance of the most water-demanding crop, cotton. Figure 9 illustrates the agricultural land use in the model reference behaviour. Land allocated to cotton monoculture on irrigated fields (variable 1) reaches almost half of the total irrigated lands by the end of the simulation (600 000 ha). Farms applying two-crop rotations (variable 2) constitute the other half (500 000 ha) and multi-crop farm systems (variable 3) gradually disappear.

Agricultural pollution

The increased intensity of cotton monoculture has adverse effects on agricultural pollution as well. Figure 10 illustrates the reference behaviour for agricultural pollution and salinization. The rate of increase in average pesticide consumption (variable 1) is four-fold in the period to 2010 and then settles at a level of about three-fold. This is due to increasing pest abundance and pest resistance especially on cotton monoculture fields. Average fertilizer consumption also increases, as farmers tend to mask the fertility losses by increasing fertilizer use. Hence, the rate of increase in average pesticide consumption (variable 2) approaches 1·3-fold. Finally, the root-zone salinity (variable 3) increases and saturates at a level of 3500 mg/l.

Agricultural production

Agricultural production is illustrated by some representative crops (cereals, pulses, cotton and oilseed) in Figure 11. As irrigated lands develop, farmers stop the production of traditional rain-fed crop cereals and pulses. In the reference behaviour, by the end of simulation at year 2030, annual cereal supply in the region (variable 1) declines to 1·8 billion kg/year and annual pulse supply (variable 2) amounts to 0·22 billion kg/yr. On the other hand, the annual cotton supply (variable 3) increases up to 2·5 billion kg/yr. Oilseed crops are taken to be representative for the summer crops group (oilseed crops, summer cereals, vegetables)

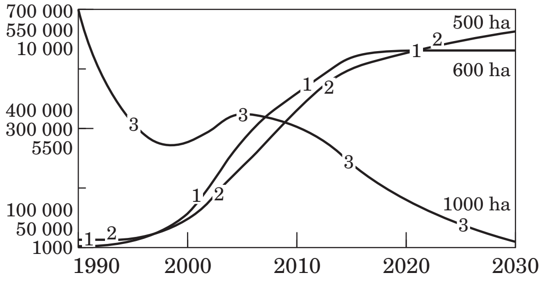


Figure 9. Land use in irrigated fields in the reference behaviour.

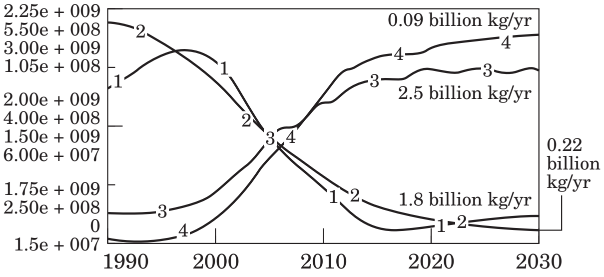


Figure 11. Agricultural production in the reference behaviour.

being produced on irrigated fields. The supply of oilseed crops (variable 4) also increases and reaches 0·09 billion kg/yr. This result suggests that food production will decrease in favour of cash crop.

Population and urbanization

The model reference behaviour illustrates that during the next thirty years rural population is projected to decline steadily and the urban population increase correspondingly in the GAP region. According to Figure 12, by the end of the simulation, rural population (variable 1) decreases to 1·5 million and the urban population (variable 2) increases to 7·25 million. This is a result of the increasing job opportunities in the urban regions and decreasing food production (cereals and pulses) in rural areas. As more industries are initiated in the cities and towns and as the subsistent rural economies are transformed, people will tend to migrate accordingly. However, when the behaviour of parameters representing the nutritional level of the rural community (food availability, variable 3) and the employment level of the urban community (job availability, variable 4) is considered, a significant improvement is not observed. Availability of food for local consumption in rural regions increases from 3·4 to 4·1 (dimensionless) after year 2000. Job availability increases from 0·55 to about 0·65 jobs/labour.

The integrated feedback structure of the model makes it possible to analyse synergistic effects of individual or combined policy alternatives on water resources, land use, pollution, production and population. In the next section, some policy alternatives are discussed and the behaviour of an integrated policy analysis is evaluated in comparison with the reference behaviour.

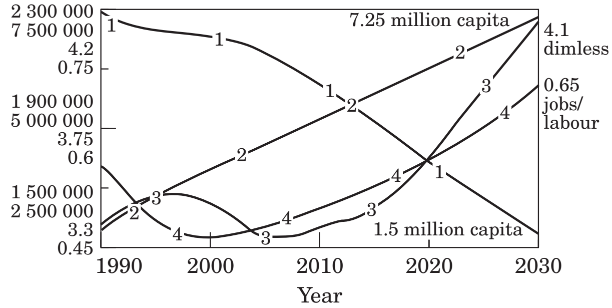


Figure 12. Population characteristic dynamics in the reference behaviour.

Policy analysis

The purpose of the model is to design policy alternatives that would be effective in achieving social and environmental sustainability in the long term. From this perspective, the irrigation water release strategy, rate of transformation from rain-fed fields to irrigated fields, alternative crop rotation strategies, government subsidies on certain agricultural commodities and salinization control and pest management turn out to be critical to system performance. Model analysis reveals that, policy experiments create significant modifications not only to the behaviour of the specifically intended components but also to the system as a whole (see Saysel, 1999).

Hence, for example, the management of root-zone salinity with improved soil drainage not only affects soil fertility and yields, but also creates a synergistic effect on agricultural land use, irrigation water requirements, levels of agricultural pollution and production. Accordingly, when the salinity is not as high as in the reference model behaviour, farmers tend to shift from salt-tolerant crops such as cotton to salt-vulnerable crops such as oilseeds, pulses and vegetables. This alters the irrigation requirements on GAP fields. As the cultivation of cotton is decreased in favour of other summer crops, total requirements for irrigation water decrease. As more water becomes available on individual farms, the yield loss due to water scarcity decreases and the regional supplies of crops such as oilseeds, summer cereals and vegetables significantly increase. Also, as farmers tend to shift from cotton to alternative crops, pest abundance on cotton monoculture areas decreases with concomitant reduction of pesticide application rates.

In this section, among the above mentioned policy considerations, changing irrigation water release strategy, alternative land transformation rates and effects of alternative crop rotation strategies are discussed. Finally, these three individual policies are integrated into a single systemic policy and simulation results are compared with the reference behaviour.

Increased hydropower production

The reference behaviour revealed that GAP would face a significant water scarcity as a result of intensive cotton monoculture demanding high quantity of irrigation water and open channel water conveyance systems, resulting in high evaporation and seepage losses. As 50% of the basin yield of the Euphrates and Tigris is utilized for irrigation purposes, hydropower production stagnates below the project targets. In order to increase the hydropower production, less water should be released for irrigation purposes and more allocated for downstream flow. However, doing so will further increase water scarcity in the fields and decrease the total amount of irrigated land. Therefore, in order to improve total performance in water resources, additional precautions must be taken.

Increased rate of land transformation

In GAPSIM, the construction rates of hydropower and irrigation structures are exogenous to the model. These construction rates are based on the information provided by the GAP Master Plan (GAP-RDA, 1990). But the actual rate of land transformation from rain-fed to irrigated fields is formulated as a function of the construction rate of irrigation structures and the decision of farmers to transform their lands (see Figure 4). In GAP, as the distribution of irrigation water among individual farms is not based on principles of equity (water utilization is not billed according to the actual consumption), upstream farms have the advantage of better access. Also, larger stakeholders have privileged access to irrigation water. Under such circumstances, irrigation water availability acts as a major factor in farmers' decision to transform their lands, thus, affecting the irrigation development rate as illustrated in Figure 4.

The irrigation transformation decision acts as an important behavioural variable. According to our experiments with GAPSIM, when farmers act rapidly in transforming their lands with available water, the total amount of irrigated land increase. However, as the total quantity of water released remains unchanged, its water availability on individual farms decreases. This creates a shift to less water demanding crops (namely, to oilseeds and summer cereals). As the cultivation of cotton decreases, the problems related to pest abundance on monoculture fields diminish. As less water is consumed, root-zone salinity does not reach the levels it does in the reference behaviour. Since the loss in soil fertility is decreased by comparison with the reference behaviour, the necessity for farmers to recover this loss with increased fertilizer consumption also decreases. Naturally, this modification of land use in irrigated fields and water availability on individual farms alters the production quantities of individual crops, making management options related to the transformation rate of individual farms an important policy instrument.

Farm rotation practices

Past experience in irrigation projects in Turkey reveals that profitability is not the only factor in crop selection. Farmers tend to cultivate those crops, which are easier to market (In southeastern Turkey, cereals and cotton), and there is a strong bias towards monoculture (TOBB, 1994). In GAPSIM, transformations between different crop selections/rotations are formulated by parameters representing profitability, market safety and know-how requirements. The model reference behaviour is based on the calibrated values of these variables with respect to available data (Figure 7). However, more efficient farming practices may alter the bias towards monoculture and traditional crops and crop rotation systems can be incorporated. Model analysis reveals that the farming systems turn out to be an important policy option for long-term environmental sustainability. Accordingly, as monoculture is replaced by rotation, crop diversity is achieved, irrigation water requirement (and thus scarcity) is decreased and pest abundance on cotton fields is avoided. Of course, this behavioural modification significantly alters regional production levels as well.

Simulation results based on the integration of the above three policy options are illustrated in the next section.

Simulation results: integrated policy analysis

When we integrate the three policy options (increased hydropower production, increased land transformation rate and improved farm rotation practices), we achieve better results in terms of water use and environmental sustainability. It should be noted, however, that simulation results related to the production and demography sectors do not point to any significant weaknesses or strengths in the reference behaviour.

Figure 13 illustrates water resource dynamics in the integrated policy scenario. Firm energy production stagnates at 19 500 GWh/yr (variable 1) and irrigated lands at 1·3 million ha (variable 2).

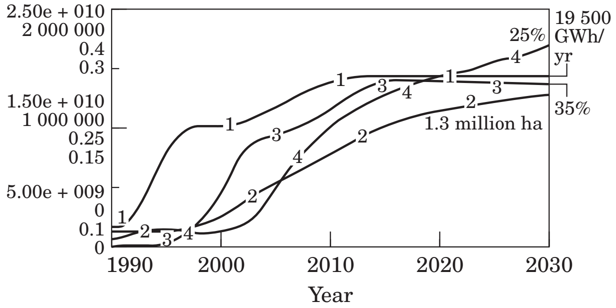


Figure 13. Water resources development in the improvement policy run.

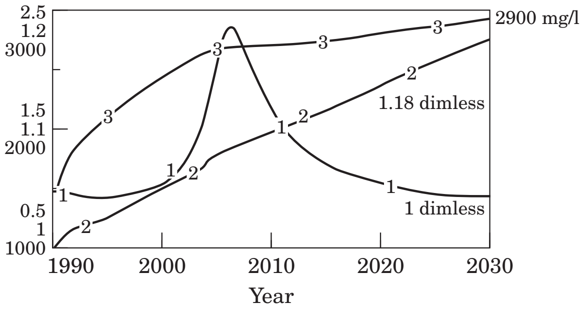


Figure 15. Pesticide, fertilizer and salinization dynamics in the improvement policy run.

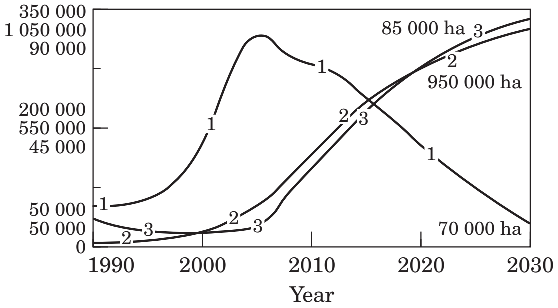


Figure 14. Land use on irrigated fields in the improvement policy run.

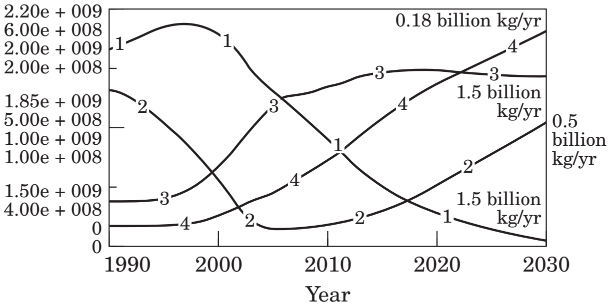


Figure 16. Agricultural production in the improvement policy run.

The ratio of the irrigation release volume to the total basin yield (variable 3) is 35% and the average yield loss due to irrigation water scarcity in crops with high water requirements (variable 4) is 25% at the end of the simulation.

Figure 14 illustrates land use on irrigated fields in integrated policy. Accordingly, cotton monoculture (variable 1) begins to decrease after year 2005 down to about 70 000 hectares at the end of the simulation. Two-crop farm systems (variable 2) exhibit significant take-off and reach 950 000 hectares. The multi-crop systems (variable 3) significantly increase also, reaching 85 000 hectares.

Figure 15 shows the reduction in agricultural pollution and land degradation. The modified rate of increase in pesticide consumption (variable 1) declines down to 1 after a sharp increase till year 2005. The average rate of increase in fertilizer application (variable 2) is about 1·18 at the end of simulation. Average root-zone salinity reaches 2900 mg/l by year 2030. (Compare to Figure 10 above).

In Figure 16 agricultural production parameters in the integrated policy analysis are observed. The supply of cereals (variable 1) decreases to 1·5 billion kg/yr. Pulses (variable 2) recovers after year 2010, as two-crop systems increase and reaches 0·5 billion kg/yr by year 2030. Cotton (variable 3) saturates at about 1·5 billion kg/yr after year 2015 and oilseeds (variable 4), which represents the supply dynamics of other typical summer crops, reaches 0·18 billion kg/yr. (Compare to Figure 11).

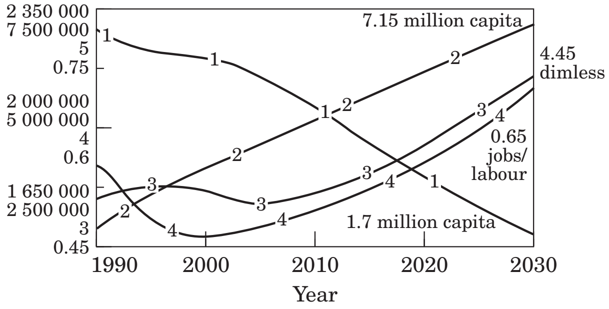


Figure 17. Population characteristic dynamics in the improvement policy run.

In Figure 17, the modified dynamics of population variables are demonstrated. In the integrated policy run, the basic behaviours of these variables do not change, but the scales are slightly modified. Accordingly, the rural population (variable 1) declines to 1·7 million and urban population (variable 2) increases to 7·15 million. At the end of the simulation, food availability (variable 3) is

Table 1. Comparison of reference behaviour and improvement policy results by year 2030

	Reference run	Integrated policy
Energy production (GWh/yr)	17 500	19 500
Irrigated lands (ha)	1 100 000	1 300 000
Cotton monoculture (ha)	600 000	70 000
Two farm systems (ha)	500 000	950 000
Multi-farm systems (ha)	1000	85 000
Rate of increase in pesticide consumption (dimensionless)	3	1
Rate of increase in fertilizer consumption (dimensionless)	1·3	1·18
Salt concentration root zone (mg/l)	3500	2900
Cereals supply (billion kg/yr)	1·8	1·5
Pulses supply (billion kg/yr)	0·22	0·5
Cotton supply (billion kg/yr)	2·5	1·5
Oil crops supply (billion kg/yr)	0·09	0·18
Rural population (million capita)	1·5	1·7
Urban population (million capita)	7·25	7·15
Food availability (dimensionless)	4·1	4·45
Job availability (jobs/labor)	0·65	0·65

4·45 (dimensionless) and job availability is 0·65 jobs/labor.

Table 1 contains a comparison of the base results of the model and the results under the integrated policy. Year 2030 values for the significant variables are demonstrated. The integrated policy points to an improvement in hydropower production and irrigation development, as compared to the reference behaviour. Yet, these values are still below the project targets (24 000 GWh/yr and 1 600 000 ha respectively). Further improvement in these variables would be a matter of water management at a micro, operational level. Specifically, water conveyance and distribution efficiency should be improved by appropriate technologies. Also, better irrigation scheduling should be achieved for water and land conservation on individual farms.

Comparison of the variables representing land use on irrigated lands reveals that, using an integrated policy, significant crop diversity is achieved: two-crop systems and multi-crop farming dominate the system and cotton monoculture almost disappears. This helps in achieving improved results in pesticide and fertilizer consumption rates and in root-zone salt concentration.

The relative decrease in cereal production in the integrated scenario is compensated for by increased pulse production, so that the regional food production is not diminished. Also, the decrease in cotton production is compensated for by increased summer crop production (oilseeds, summer cereals and vegetables).

The model analysis reveals that the problems related to population and job availability are extremely insensitive to changing agricultural policies. Thus, in the integrated policy, while relative improvement is observed in food availability for the rural population, urban job opportunities remain around the same as in the reference behaviour. This suggests that in order to accomplish the GAP project goals related to urban development, further measures should be taken in addition to the incentives on agricultural development.

Conclusion

In this paper, the long-term environmental sustainability of an agricultural development project (the Southeastern Anatolian Project–GAP) is analysed using a system dynamics approach. The simulation model GAPSIM serves as an experimental platform addressing the questions related to water resource development, land use, pollution, land degradation, production and population. The reference behaviour of GAPSIM indicates a significant potential water scarcity in the GAP region, which is exacerbated by intensive cotton monoculture on irrigated lands. Decreased crop diversity results in measures, which produce deleterious impacts (excessive pesticide and fertilizer consumption). Model analysis reveals that the dynamics of water resources, land use and environmental measures can be improved by an integrated policy. Water release for hydropower production must be increased, farmers must be encouraged to adapt irrigated farming and crop rotation systems must be improved. It is also observed that, urban employment problems are insensitive to the agricultural incentives and therefore, additional measures must be taken to tackle urban problems in the long-term. GAPSIM, developed in course of academic research can serve as a useful generic structure to be adapted to similar regional development projects as well. We plan to develop a much smaller, generic version of the model, representing the essence of the dynamic theory that emerged from the research. GAPSIM can also be used as an experimental laboratory for the policy makers of GAP in the future. For such a use, a team consisting of technical/modelling experts, as well as representative personnel from the GAP administration must first customize the model.

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