Inter-Temporal Impacts of Technological Interventions of Watershed Development Programme on Household Welfare, Soil Erosion and Nutrient Flow in Semi-Arid India: An Integrated Bioeconomic Modeling Approach

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Abstract

A dynamic and non-linear bioeconomic model, incorporating both economic and biophysical aspects was developed for a micro-watershed to assess the impact of key watershed management technological interventions (like HYVs and soil and water conservation structures) on social well being of rural poor and condition of natural resource base. The simulation results revealed that productivity enhancing technologies of dryland crops has increased the income for all the farm household groups and also provided incentive to farmers for conserving land resulted in less soil erosion and the nutrient mining in the watershed. The increase in the irrigated area in the watershed has improved the income of the household by cultivating more area under high value irrigated crops and has negative impact on natural resource by increasing soil erosion and nutrient mining in the watershed. The results clearly indicated that care should be taken while developing technologies for watershed development to avoid promotion of conflicting technologies. Preferably, those technologies that have multiple impacts in terms of meeting both welfare of the farmers and sustaining natural resources objectives must be prioritized.

Key words: Bioeconomic model; watershed development; productivity enhancing technologies

Content

1. Introduction

In an effort to improve the livelihood of poor households in Semi-Arid Tropics (SAT), to arrest land degradation (nutrient mining and soil erosion) and revitalize the mixed crop-livestock production system, the Government of India started promoting watershed development approach. In realizing the potential of the micro watershed projects in enhancing the livelihood security of the poor in the rainfed areas, investment in India in the mid- 1990's by the Indian government and international organizations in collaboration with the NGOs and other development agencies, amounted to about USD 500 million per year (Kerr *et al*., 2000). Even though there were several exceptional case studies of successful watershed development in India (e.g., Wani *et al*., 2002; and Kerr *et al*., 2000), the impact of the approach on improving the welfare of the poor and the natural resource condition in the SAT areas was not fully known. This study was carried out to improve the understanding of the economic and ecological consequences of watershed development programme at a micro-watershed level.

It was important to apply a holistic and integrated approach like bioeconomic modeling to simultaneously assess and evaluate impact of watershed development on the welfare of the poor and the natural resource conditions at a micro level and also to identify effective policy instruments and institutional needs for enhancing the effectiveness of the watershed approach. However an impact study of watershed development programme which simultaneously integrates the biophysical and socioeconomic information in a dynamic decision making framework was lacking. The objective of the empirical study was to assess the inter-temporal impact of key integrated watershed management technologies (e.g., high yielding varieties and soil and water conservation structures) on household income, food security, soil erosion and nutrient mining in the selected micro-watershed. Based on the empirical findings, policy conclusions and their implication will be discussed.

2. The study area

Based on lessons learnt from the success of on-station soil, water and nutrient management (SWNM) research in watershed, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) developed a new Integrated Genetic Natural Resource Management (INRM)

model. In one of the on-farm watersheds in India (Adarsha watershed, Kothapally), a participatory community watershed management programme was initiated in collaboration with the Drought Prone Area Programme (DPAP) of Government of India. Along with ICRISAT, a consortium of NGOs and national research institutes were testing and developing technological, policy and institutional options for integrated watershed management in the village (Wani *et al*. 2002; Shiferaw *et al*. 2003). A package of integrated genetic and natural resource management practices were being evaluated on farmer's fields (including SWC, new high yielding varieties, IPM and INM) through participatory approaches.

The Adarsha watershed in Kothapally village, located 40 km away from Hyderabad, capital city of Andhra Pradesh, was selected as the study area for construction of the bioeconomic model to study the *ex ante* impacts of the technological and policy interventions on the welfare of the farming communities and the condition of the natural resources. The site was selected because of availability of adequate biophysical and socioeconomic data covering a period of 6-7 years and baseline information, which was collected prior to various integrated interventions. This unique dataset was used in the study for construction and validation of the bioeconomic model.

3. Data and modeling approach

3.1. Biophysical and socioeconomic data

ICRISAT has installed an automatic weather station in Kothapally village, which allows regular monitoring of diverse biophysical parameters (e.g., temperature, rainfall, runoff, soil and nutrient loss etc). The runoff, soil loss and nutrient loss from the treated and untreated segment of the watershed were measured using the automatic water level recorder and sediment samplers located at two different places in the watershed. Based on the plot level data (e.g., soil depth, soil type, plot size, etc) collected, the watershed area was divided into three soil depth classes based on top soil depth, namely shallow (less than 50 cm), medium (50-90 cm) and deep soil (above 90 cm).

In 2001, ICRISAT has conducted a census of all households in Kothapally village and five adjoining villages/non-watershed/control villages (namely Husainpura, Masaniguda, Oorella, Yankepally and Yarveguda) lying outside the watershed with comparable biophysical (rainfall, soil and climate) and socioeconomic conditions. Based on the information from the census

analysis a random sample of 60 households from watershed village (Kothapally) and another 60 households from non-watershed villages were selected for detailed survey. The data was collected annually for three years (2002-2004). Along with other standard socioeconomic data, detailed plot and crop-wise input and output data were collected immediately after harvest from the operational holdings of all the sample households. The associated biophysical data on major plots (like soil depth, soil type, level of erosion, slope of the plot, fertility status etc) were collected using locally accepted soil classification systems. The price data for the crops, livestock and market characteristics for crop produce, inputs and livestock were collected during the household survey, in the local markets and also through focus group discussion in the sample villages.

3.2. Bioeconomic modeling

Bioeconomic model combines both socio-economic factors influencing farmers' decision making with biophysical factors affecting crop production and natural resource conditions (Barbier, 1998; Krusemen et al., 1997; Woelcke, 2006). The model consists of three components: (i) a mathematical programming model that reflects the farm household decision-making process under certain constraints; (ii) estimation of crop yield response to soil depth; and (iii) nutrient balances as a sustainability indicator. The results of the marginal yield response for soil depth and estimation of soil erosion by different crops are then incorporated into programming model.

3.3. Estimation of crop yield change in relation to soil depth

For econometric estimation of yield variation due to changes in topsoil depth, the household survey and plot and crop-wise input and output data covering 12 villages in four districts of Andhra Pradesh were used. In order to capture the non-linear affects of soil depth, a quadratic production function was used for relating output with inputs and other factors reflecting farm characteristics such as soil depth and soil type. The general form of the quadratic production function was:

$$Y_c = \beta_0 + \beta_i X_i + \beta_j Z_j + \beta_{ii} X_i^2 + \beta_k D_k + e_i$$

Where,

Y_c = yield of crop c in kg/ha (c = crop grown in the watershed)

X_i = inputs (i = labour (man days), N, P, K, FYM, (kg/ha) and number of irrigation)

Z_j = biophysical variables (j = soil depth in ordinal values[1])

D_k = dummy variables [k = year dummy, variety dummy (improved or local), irrigation dummy (irrigated or rainfed)]

βs = coefficients

e_i = the error term $e \approx N(0, \delta^2)$

The marginal effect of 1cm of soil depth change on crop yield was estimated as follows.

$$\lambda = \frac{\beta \text{ of the soil depth}}{\text{Difference between the two soil depth categories (i.e. 50 cm)}}$$

Where,

λ = the marginal change in yield for 1 cm change in soil depth

β = the coefficient of soil depth in the quadratic production function

The marginal effect of changes in soil depth on crop yield in the watershed was presented in Table 1.

[1] The variable soil depth (d) of each plot of the farm was not the exact topsoil depth in meters but in ordinal categories. The plots were placed in any one of the four categories (1= shallow depth soil (d < 0.5 m); 2= medium depth soil (0.5< d <1m); 3= deep depth soil (1<d< 1.5 m); and 4= very deep depth soil (d >1.5 m)). The difference between any two categories of soil depth was 50 cm.

Table 1 Marginal response of crop yields to change in soil depth and plant nutrients (N and P)

Crops	Number of observations (n)	Marginal effect of soil depth (kg/cm/ha)	Marginal effect of fertilizer nutrients (kg crop/kg of nutrients)			
			N	N^2	P	P^2
Sorghum	342	2.43	7.78	-0.06	3.22	-0.02
Maize	308	3.34	13.45	-0.05	-7.69	0.08
Chickpea	147	3.78	12.22	-0.06	0.26	0.04
Pigeon pea	625	0.37	0.95	-0.03	-4.88	0.13
Sunflower	67	3.44	5.77	0.21	2.69	0.10
Onion	43	57.2	17.60	0.04	60.34	-0.05
Vegetables	160	10.16	2.02		-5.20	
Paddy	253	0	19.09	-0.21	-4.98	-0.01
Cotton	236	0.34	2.78		0.02	

Note: Authors' estimation

3.4. Estimation of soil loss on cropland

The average soil loss per hectare of cropped area in the watershed was calculated by using Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978), which was being widely used for soil loss prediction. Average annual soil loss due to sheet and rill erosion from a crop area was predicted by the following equation.

$$A = R * K * L * S * C * P$$

Where,

A = Average annual soil loss (t/ha/yr)

R = Rainfall erosivity factor

K = Soil erodability factor (t/ha per unit of R)

L = Slope length factor

S = Slope gradient or steepness factor

C = Land cover factor

P = Conservation practice factor

The average annual soil loss per ha for different crops grown in Adarsha watershed without any conservation practices were estimated using USLE and the estimated values was presented in Table 2.

Table 2 Estimated soil loss (tons/ha) using USLE method

S. No	Crops	Soil loss (tons/ha)
1	Sorghum	3.41
2	Maize	2.99
3	Pigeon pea	5.45
4	Chickpea	3.07
5	Cotton	5.45
6	Sunflower	3.56
7	Onion	4.89
8	Vegetables	4.56

Note: Authors' estimation

3.5. The mathematical programming model

A dynamic non-linear programming model was developed for the micro-watershed, includes three household groups (small, medium, and large framers), who were spatially disaggregated by six different segments in the watershed landscape (defined by two land types namely rainfed and irrigated land and three soil depth classes)[2]. This gives 18 farm sub models within the watershed.

The model maximizes the aggregate net present value of income of the watershed over a 10 year planning horizon. The income of the household groups were defined as the present value of future income earned from different livelihood sources (like crop, livestock, non-farm, wage, etc) subject to constraints on level, quality and distribution of key production factors (e.g., land, labour, capital, bullock power, soil depth), animal feed requirement and minimum subsistence food requirements for the consumers in each household group.

[2] The model was developed in the General Algebraic Modeling System (GAMS) (Brooke, Kendrick and Meeraux, 1992)

3.5.1. Crop production

The model includes nine crops like sorghum, maize, paddy, cotton, chickpea, pigeon pea, vegetables, sunflower and onion, which were cultivated in two seasons, namely rainy (*kharif*) season and post-rainy (*rabi)* season. Cotton, vegetables and onions were cultivated in both rainfed and irrigated fields. Paddy was grown only under irrigated condition. Sorghum and maize crops were intercropped with pigeon pea in the ratio of 80:20 during *rainy* season. Crop choice in the watershed depends on the profitability (prices and yields), food, fodder, labour demand and distribution, suitability of different type of soil and land types and access to inputs (like seeds and fertilizers).

A simplified crop production function was used in the model to represent farmers' average expected response to different factors of production. The parameters for production functions were obtained from the results of the econometric analysis of the primary data.

3.5.2. Population and labour

The available farm family labour was constrained by the active population residing in the watershed each year. Based on the exogenously given initial population in each household groups and annual growth rate of population in the region, the total workforce in each household group was projected[3]. The available family labour was allocated seasonally into on-farm and off-farm activities in the village and non-farm activities outside the village. Farmers could hire or sell seasonal labour days within the watershed to meet seasonal scarcities in family labour. The hiring in and out of labour days within the watershed occurs at exogenously given wage rates.

3.5.3. Produce allocation and consumption

In the model, produces of sorghum, paddy, chickpea, and pigeon pea could either be stored and consumed by the population or sold in the nearby markets. The population in the watershed was assumed to consume a fixed amount of grains and vegetables depending upon the nutritional requirement for each year. The minimum nutrient requirement for each consumer in the watershed for a year was constrained in the model to a quantity ensuring a minimum daily calorie intake and protein requirement per adult equivalent (ICMR recommendation for an adult

[3]The total family labour days available was calculated by deducting the regional festival holidays and important village functions in available labour days for each work force in a household group.

for moderate activity in rural India is 2400 calories and 60 g of proteins per day). The model was also flexible for complementing consumption by buying grains in the village or nearby markets. All the prices were exogenously given in the model based on the market prices for selling and buying of grains in the village and nearby markets.

3.5.4. Livestock production

Cows, buffaloes, bullocks, sheep, goat, and backyard poultry (chicken) were the common livestock types in the watershed[4]. The productivity of livestock, birth rates, mortality rates, feed requirement, labour required for maintenance, milk production and culling rates were included in the model. Bullocks were used for land preparation and transportation and cows and buffaloes for producing milk, which was sold or consumed in the farm. Livestock was fed with crop residues produced in the watershed or purchased feed in case of scarcity. Stover yields were modeled as a function of crop type and crop grain yields. The decision to buy or sell animals was depend on livestock productivity, mortality rates, buying and selling prices, fodder availability, and cash constraint.

3.5.5. Land degradation

The main form of land degradation in the model was soil erosion and nutrient depletion. The soil depth in each land units depends on the initial soil depth and the cumulative level of soil erosion in the land units. Soil erosion affects soil depth in the model through a transition equation (Holden *et al*. 2005). The equation for estimating change in soil depth due to soil erosion in the 18 land units was;

$$Sd_t = Sd_{t-1} - \tau Se_t$$

Where,

Sd = soil depth in cm

Se = soil erosion in tons per ha

τ = conversion factor (100 tons of soil erosion per ha reduces 1cm of soil depth)

[4] To simplify the model solution the number of animals in each category was treated as a continuous number, not an integer

Soil erosion under cropped area in the watershed was estimated using USLE model and exogenously included in the model. The total soil erosion in a land unit in the watershed was a function of the area grown under each crop in the unit land and soil loss under respective crop.

Nutrient balance in production-system was used to ascertain the sustainability of the systems (Pathak *et al*., 2005). Soils have a nutrient reserve controlled by their inherent fertility and management. A negative balance of such nutrients as N, P and K indicate nutrient mining and non-sustainability of the production system. The balance or depletion of nutrients per unit of land in the watershed depends on crop choice, yield of grains and residues, application of fertilizers and manures, soil or land type and erosion level[5] in the watershed. The nutrient balances in the soil were measured using the input and output factors governing the nutrient flow in the soil in kg/ha/yr (Stroorvogel and Smaling, 1990; Okumu *et al*., 2002). The input and output factors considered in this study were listed in Table 3.

Table 3 Input and output factors in nutrient balance equation

Input	output
1. Mineral fertilizers	1. Harvested grains
2. Manures applied	2. Crop residues
3. Deposition of nutrients	3. Erosion
4. Biological N fixation	4. Leaching

3.5.6. Model validation

The model validation and calibration was conducted by comparing the baseline data collected in the watershed with the simulation results. The important variables used to validate the models were area under various crops, income of the household groups and soil loss. The validated bioeconomic model developed was used for analyzing different scenarios.

[5] Nutrients were also lost through eroded soil, and these soils were richer in nutrients than the soil remaining behind.

4. Scenario results and discussion

4.1. The impact of changes in yield of dryland crops

The main objective of integrated watershed management was to enhance the productivity of agriculture. The introduction of high yielding and drought tolerant crop varieties and improved cropping systems were the important component of watershed development intervention to increase the income of the farmers. In this study, an attempt was made using bioeconomic model to test the hypothesis that introduction of technological innovations (like improved crop varieties and cropping systems) compensate for decreasing return to labour and improve the natural resource base over the years. The study simulates two scenarios to test this hypothesis, a) dryland crops (sorghum, maize, pigeonpea and chickpea) yield increased by 10 per cent and b) dryland crops yield decreased by 10 per cent.

The simulation results showed that the per capita income of all three household groups were above baseline level when the yields of the dryland crops were increased (Table 4). The increase in area of the dryland crops (sorghum and maize) in the watershed increases fodder production, which in turn enhances the carrying capacity of livestock in the watershed. This increased livestock production increases the income from livestock gradually for all the household groups.

The soil erosion under the scenario of increased yield of dryland crops was higher than the baseline level at the initial years and starts declining from the fifth year of simulation (Fig. 1). The increase in area of the dryland crops cultivation increases the demand for on farm labour in the initial year which reduces the incentive to use the labour for conservation measures and they cause higher soil erosion in the initial year of simulation. However, the population growth in the watershed over the years drive the farmers to use more labour for conservation measures in the field, which declined the soil erosion towards the end of the simulation period (Fig. 2). The result revealed that the decline in soil erosion was 6 per cent compared to the baseline in the final year of simulation. Under the decreased dryland crop yield scenario, the soil erosion had not changed much compared to baseline scenario.

The increase in area under sorghum and maize and decline in the area of high nutrient mining crop like cotton and sunflower under the scenario of increased yields of dryland crops had reduced soil nutrient mining by 4, 1, and 3 per cent N, P, and K respectively compared to

baseline level (Table 4). If the yield of dryland crops had decreased by 10 per cent, the results showed that nutrient balances in the watershed were similar to baseline level.

Table 4 Impact of change in the yield of dryland crops

Scenario	Per capital Income (.000 Rs)			Soil loss	Conservation labour	Nutrient Balance (tons)		
	Small	Medium	Large	(tons/ha)	(man days)	N	P	K
Baseline	5.08	9.11	16.16	4.04	4092.2	-11.74	12.25	-94.79
Dry land crops yield (+10%)	5.31	9.68	17.7	3.99	3523.79	-11.03	13.41	-93.05
Dry land crops yield (-10%)	4.75	8.98	17.7	4.04	4562.9	-11.68	11.94	-94.79

Note: Average of 10 years simulation

Fig.1 Simulated average soil loss in the watershed (tons/ha): Alternative scenario for change in yield of dryland crops

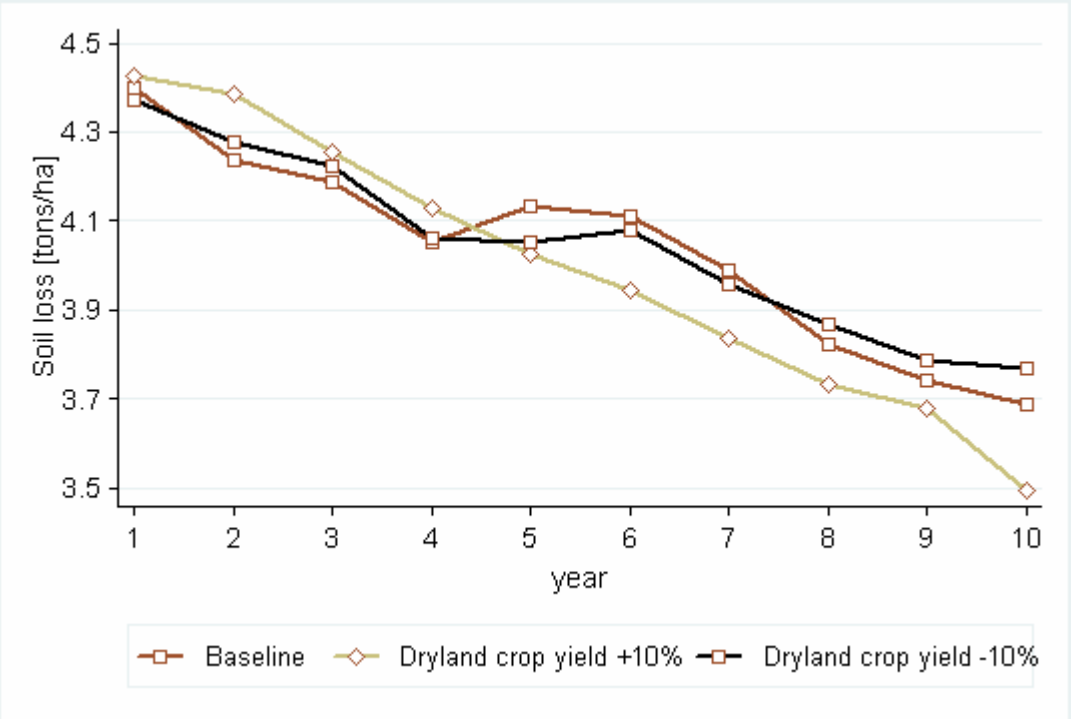
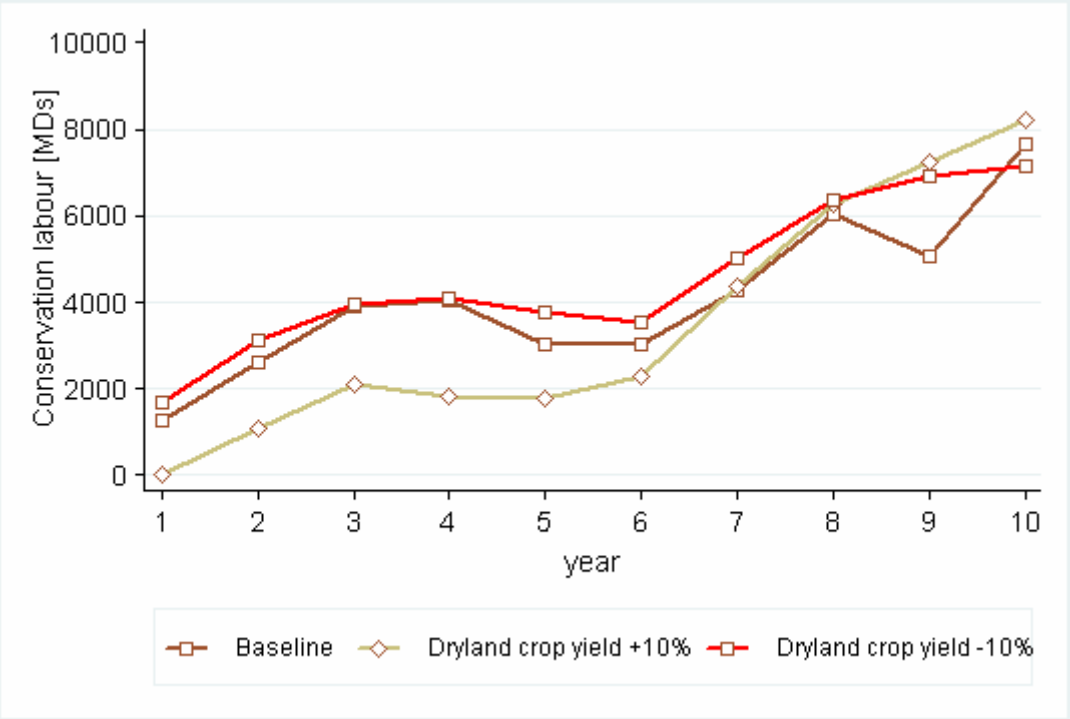


Fig. 2 Simulated labour uses for conservation measures (MDs): Alternative scenario for change in yield of dryland crops



4.2. Impact of change in irrigated area in the watershed

The important objective of watershed development programme was to conserve rainwater by reducing out flows from the watershed by constructing check dams and other *in situ* soil and water conservation systems. The stored water would certainly improve the groundwater table, which in turn helps to increase the area under irrigation in the watershed. In this context, simulation was carried out to assess the impact of changes in irrigated area resulting from adoption of soil and water conservation measures on household welfare, soil loss and nutrient balance in the watershed. Hence, the baseline scenario in the watershed was compared with two alternative scenarios a) increasing irrigated area by 25 per cent and b) reducing the area under irrigation by 25 per cent. These changes were simulated through comparative adjustments in dryland area so that the total cultivable area in the watershed remained unchanged.

The results revealed that if irrigated area increases, the per capita income of all the three household groups were more than the baseline level (Table 5). This was due to higher

productivity of crops like cotton, vegetables and sunflower under irrigation and increasing the area of these crops under irrigation resulted in increased production in the watershed. The increased marketable surplus of these crops increased the income of the household groups. The scenario of decreasing the irrigated area by 25 per cent led to reduction in the per capita income for small and medium farm household because the area under commercial crops like vegetable and cotton decreased. The per capita income of the large farmers had not changed much because these farmers were not constraint by irrigated land.

The soil erosion was higher when irrigated area increased in the watershed compared to the baseline level (Fig. 3). The area under the irrigated cotton, sunflower and vegetables increased because of expanding irrigated land. The increase in the area of erosive crops (wide spaced crops) like cotton and vegetables resulted in higher erosion by 2 per cent compared to baseline level. On contrary, reduction in irrigated land in the watershed increased the area under less erosive dryland crops like maize and sorghum reduce the soil erosion by about 7 per cent (Fig. 3).

When irrigated area increases by 25 per cent, the labour used for conservation measures was less than the baseline level in the initial years and increased above the baseline level towards the end of simulation (Fig. 4). When the irrigated area decreased by 25 per cent total soil erosion was below the baseline level, even though the total labour used for conservation was lower than the baseline level. This was mainly due to change in cropping pattern, where area under less erosive dry land crops like maize and sorghum increased in the watershed.

The soil nutrient balance indicated that nutrient mining was higher compared to the baseline level when irrigated area increases by 25 per cent (Table 5). This was due to increase in the area of high nutrient extraction irrigated crops like vegetables, cotton and sunflower compared to baseline level. The reduction in irrigated area increased the area under cereal-legume cropping systems like maize/pigeonpea and sorghum/pigeonpea which removed comparatively less nutrients from the soil and also improved the nutrient content by biological atmospheric fixation.

The increase in irrigated area in the watershed even it improved the welfare of the farmers, the change in the cropping pattern caused negative effect on the environment by increasing the erosion level and soil nutrient mining.

Table 5 Impact of change in irrigated area in the watershed

Scenario	Per capital Income (.000 Rs)			Soil loss	Conservation labour	Nutrient Balance (tons)		
	Small	Medium	Large	(tons/ha)	(man days)	N	P	K
Baseline	5.08	9.11	16.16	4.04	4092.2	-11.74	12.25	-94.79
Irrigated area (+25%)	5.16	9.5	17.81	4.13	4374.18	-14.38	11.37	-98.94
Irrigated area (-25%)	4.73	8.7	16.72	3.92	3600.95	-9.2	14.46	-88.98

Note: Authors' estimation

Fig. 3 Simulated soil loss in the watershed (tons/ha): Alternative scenario for change in irrigated area

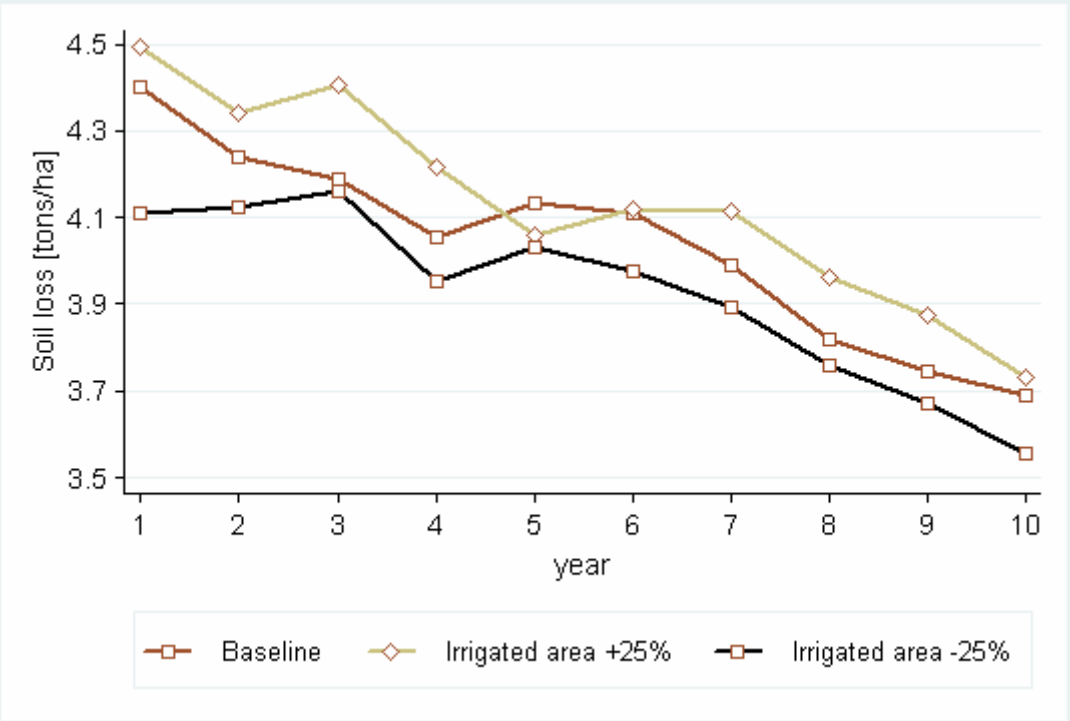
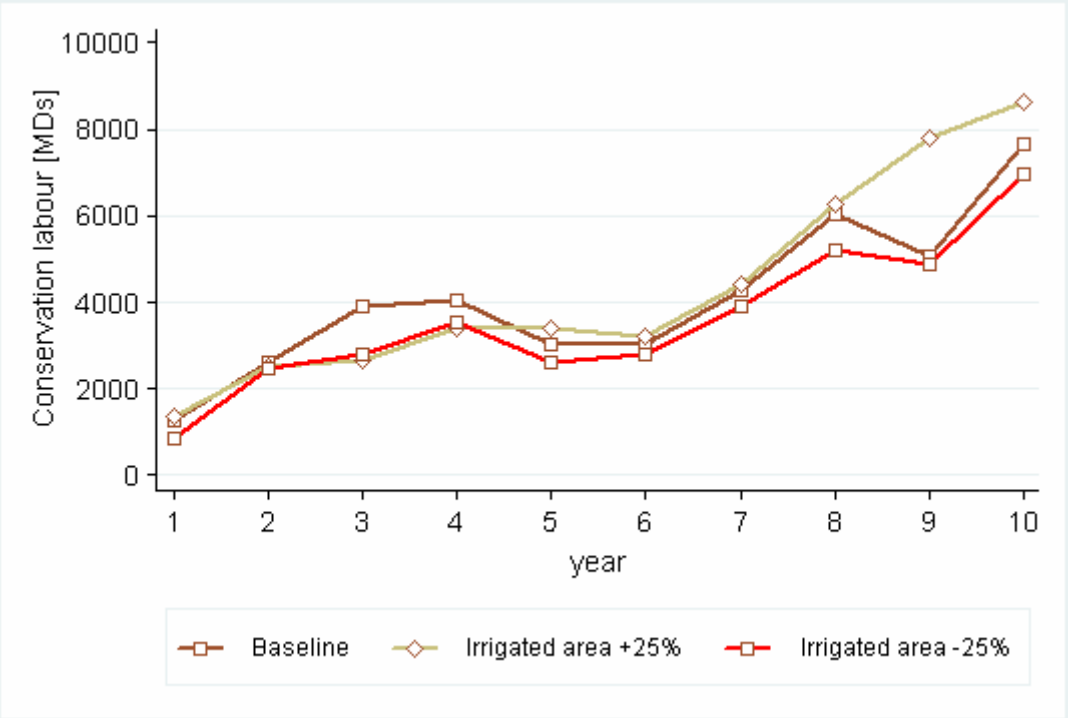


Fig. 4 Simulated labour uses for conservation measures (MDs): Alternative scenario for change in irrigated area



5. Conclusions and policy implications

The study concluded that introduction of high yielding varieties and cereal-legume intercropping systems helped to improve the welfare of smallholder farmers by increasing the income while also enhancing the sustainability of the natural resource base. It also stimulate sustainable intensification of production by controlling soil erosion and nutrient mining through investment in conservation and adoption of better land use patterns in the watershed. So it is important to concentrate more on crop-specific research to develop drought tolerant HYVs of dryland crops, which are also resistant to pests and diseases. The increase in irrigated area under cotton, vegetables and sunflower due to the availability of water from community and *in situ* soil and water conservation in the watershed improved the income of the farmers. The erosion level and nutrient mining in the watershed however increased because of increase in the area under soil erosive and nutrient mining crops. It is important to promote irrigated cereal crops in the watershed, so that erosion level will be minimized and improves the fodder production to create complementarities with livestock production that would in turn increase manure availability and

application in the field to sustain soil nutrients. The results clearly indicated that care should be taken while developing technologies for watershed development to avoid promotion of conflicting technologies.

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