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Bioeconomic modeling of farm household decisions for ex-ante impact assessment of integrated watershed development programs in semi-arid India

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Abstract The increasing population and urbanization have serious implications for sustainable development in less-favoured areas of developing countries. In an attempt to sustain the long-term productivity of natural resources and to meet the food and non-food demands of growing population in the semi-arid tropics, the Indian government invests and promotes integrated watershed development programs. A comprehensive tool to assess the impacts of watershed development programs on both social well-being and sustainability of natural resource is currently lacking. In this study, we develop a watershed level bio-economic model to assess the ex-ante impacts of key technological and policy interventions on the socioeconomic well-being of rural households and the natural resource base. These interventions are simulated using data from a watershed community in the semi-arid tropics of India. The model captures the interaction between economic decisions and biophysical processes and using a constrained optimization of household decision model. The interventions assessed are productivity-enhancing technologies of dryland crops and increased in irrigable area through water conservation technologies. The results show that productivity-enhancing technologies of dryland crops increase household incomes and also provided incentives for conserving soil moisture and fertility. The increase in irrigable area enables cultivation of high-value crops which increase the household income but also lead to an increase in soil erosion and nutrient mining. The results clearly indicate the necessity

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for prioritizing and sequencing technologies based on potential effects and trade-offs on household income and conservation of natural resources.

Keywords Impact assessment · Bioeconomic model · Watershed development program · Sustainability · Productivity-enhancing technologies

1 Introduction

In the era of 'Green Revolution', the intensive use of irrigation, fertilizers and pesticides along with the high-yielding varieties (HYVs) in favoured high potential zones was the major driving force for the impressive gains in food production, food security and rural poverty reduction in India. However, many regions in less-favoured rainfed areas of the semi-arid tropics (SAT)[1] have not benefited from this process of agricultural transformation (Pingali 2012). Low productivity of rainfed agriculture with widespread poverty, the changing globalized environment, scarcity of water and degradation of productive resources (land, water and biodiversity) are threatening to further marginalize smallholder agriculture and livelihoods in the Indian SAT (Rao et al. 2005). As opportunities for further expansion in more favoured regions are exhausted, food security and productivity growth in agriculture in India will be increasingly dependent on the rainfed regions. The emerging evidence of higher impacts on the poor households and higher marginal productivity gains from public investments in the less-favoured regions suggests the need to prioritize these hitherto overlooked areas in terms of technology development and policy (Shenggen and Peter 1999). It is important to recognize the potential of the less-favoured lands and design suitable strategies and policies for encouraging sustainable growth in this region.

The expected increase in the population in the coming decades and increasing urbanization in the developing countries such as India are not likely to be matched by the growth in crop and livestock production with the current management practices (Rosegrant et al. 2001). This has serious implication for sustainable development and achievement of the millennium development goals in terms of human nutrition, health and welfare in the less-favoured areas of the developing countries. In order to promote sustainable intensification of production and preserve the long-term productivity of natural resources and to meet the consumption needs of the increasing population in the SAT, new technologies, policies and improved access to market and better institutions are required. The new technologies include soil and water conservation measures, introduction of high-yielding and drought tolerant varieties, integrated pest management (IPM) and farming support policies enabling prudent long-term management of the natural resource base on which agriculture fundamentally depends. The technology and policy choices need to be made on the basis of not only their current impact but future economic and environmental outcomes as well.

1.1 Watershed development programs in India

Watershed development is one of the important development programs aimed at improving land use and sustainability of the natural resources as well as improving the livelihood

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[1] The Technical Advisory Committee (TAC) of the Consultative Group on International Agricultural Research (CGIAR) and FAO defines SAT as those areas which have (a) crop-growing period of 75–180 days; (b) mean monthly temperature higher than 18 °C for all the twelve months of the year; and (c) daily mean temperature during the growing period that is higher than 20 °C.

security of farm households in the rainfed areas. A watershed (or catchments) is a geographical area that drains to a common point, which makes it an attractive unit for technical efforts to conserve soil and maximize the utilization of surface and subsurface water for better crop production (Kerr et al. 2000; Kerr 2001).

Watershed management is a holistic approach dealing across resources (water, soil, biodiversity, etc.) with the aim of improving livelihood of the people through integrated (multiple) interventions, including utilization of improved crop genetic material and livestock production. In watershed management projects, physical or vegetative structures are installed across gullies and rills and along contour lines, and land is often earmarked for particular land use based on its suitability and capability classification. This approach aims to optimize moisture retention and reduce soil erosion, thus maximizing productivity and minimizing land degradation. In India, approximately 170 million hectares are classified as degraded land, roughly half of which falls in undulating semi-arid areas where rainfed farming is practiced (Farrington et al. 1999). To increase the natural resource productivity of the rainfed areas, a number of government projects, schemes and programs were formulated and which support the micro-watershed development. In India, micro-watersheds are generally defined as falling in the range of 500–1,000 ha (Syme et al. 2012).

Even though there are several case studies of successful watershed development in India (e.g., Wani et al. 2002; Kerr et al. 2000; Palanisami and Kumar 2009; Pathak et al. 2013), the impact of the watershed development programs on improving the welfare of the poor and the natural resource condition in the SAT areas is not fully known. This is partly because of data, measurement and attribution problems which make it hard to quantify the economic and environmental outcomes ex post. So it is important to apply a holistic and systems approach to simultaneously assess and evaluate the 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.

1.2 Challenges in impact assessment of watershed development programs

Watershed impact assessment needs to address important conceptual and methodological challenges that arise from several unique features of natural resource management (NRM). These challenges include thorough attribution, measurement, spatial and temporal scales, multidimensional outcomes (like economic, environmental and social) and valuation (Shiferaw et al. 2004; Wani et al. 2011). The cross-commodity and integrated nature of NRM interventions make it very challenging to attribute impact to any particular one among them. In crop genetic improvement where the research outputs are embodied in an improved seed, it is less difficult to attribute yield improvements to the investment in research (Freeman et al. 2005). For example, in the evaluation of watershed programs in India, it was difficult to attribute improvements in resource conditions and farm incomes to specific interventions, since increased participation and collaboration among the range of R&D partners were identified as significant determinants of success (Kerr 2001). Most agricultural NRM interventions are information-based but not embodied in easily measured indicators that complicate the attribution of observed impacts (Freeman et al. 2005).

Identifying appropriate spatial boundaries for assessing NRM impact is often fraught with difficulty (Cambell et al. 2001; Sayers and Cambell 2001). A watershed development program typically involves different spatial scales, from farmers' fields to entire watershed catchments, implying that many levels of interaction need to be considered in assessing the impacts of research interventions. Multiple scales of interaction create upstream and downstream effects that complicate impact assessment (Bouma et al. 2011). For example, assessing the impact of land-use interventions in a watershed may need to take into account multiple interactions on different scales because erosion and runoff in the upper watershed may not have the same impact on water quality downstream. It is also likely that interventions could have different effects, which in some cases can generate negative impacts on different spatial scales. For example, soil and water conservation intervention can have a positive impact on crop yields upstream but negative impacts by reducing water availability downstream where water is a limiting factor for production, or positive impacts by reducing sedimentation, runoff and flooding when water is not a limiting factor (Freeman et al. 2005).

The temporal dimension of NRM impact also presents methodological difficulties for impact assessment through slow-changing variables and substantial lags in the distribution of costs and the benefits. For example, soil loss, exhaustion of soil fertility and depletion of groundwater resources take place gradually and over a long period of time. In some cases, it is difficult to perceive the costs or the benefits of interventions to reverse these problems. In other cases, assessing the full range of the impacts of investments related to these slow-changing variables in a holistic manner may involve intensive monitoring of multiple biophysical indicators on different spatial scales over a long period of time. These factors make impact on monitoring and assessment of NRM interventions a relatively slow and expensive process. Differences in time scale for the flow of costs and benefits are translated into lags in the distribution of costs and benefits that complicate impact assessment. Typically, costs are incurred upfront while delayed benefits fall in incremental quantities over a long period of time (Pagiola 1996; Shiferaw and Holden 2001). Further, NRM interventions generate multidimensional biophysical outcomes across resource, environmental and ecosystem services. These might include changes in quality and movement of soil, quantity and quality of water, sustainability of natural resources and conservation of biodiversity. The multidimensionality of outcomes from NRM interventions means that impact assessment often faces measurement challenges, including very different measurement units, and potentially the integration of very different natural resource outputs into some kind of uniform aggregate yardstick (Byerlee and Murgai 2001).

1.3 Alternative methodological approaches for impact assessment

The limitations and complexities associated with measuring, monitoring and valuing social costs and benefits associated with NRM interventions require more innovative assessment methods. An important factor that needs to be considered in the selection of appropriate methods is the capacity for simultaneous integration of both economic and biophysical factors and the ability to account for non-monetary impacts that NRM interventions generate in terms of changes in the flow of resource and environmental services that affect economic welfare, sustainability and ecosystem health. Hence, a mix of qualitative and quantitative methods is the optimal approach for capturing on-site and off-site economic welfare and sustainability impacts (Freeman et al. 2005). The approaches that are developed recently for evaluating the impacts of agricultural and NRM interventions are economic surplus, econometric and bioeconomic modelling approach. The economic surplus approach estimates welfare gains using farm survey data to measure farmers' benefits from adoption of NRM technologies, unit cost reduction and higher income (Bantilan et al. 2005; Palanisami et al. 2009). The approach estimates the welfare benefits of research in terms of change in consumer surplus and producer surplus, resulting from a shift in the supply curve by adoption of productivity-enhancing technology. The presence of non-marketed externalities further complicates the approach, although in theory, the social marginal cost of production could be used to internalize the externalities (Swinton 2005). New methods (e.g., benefit transfer function) are developed to extend the economic surplus approach for assessment of non-marketed social gains from improved NRM technologies.

The econometric approach uses regression models (like probit, logit, tobit and two-stage least squares (2SLS) regressions) to explain variations in agro-ecosystem services through changes in NRM pattern. This approach uses the changes in biophysical, economic and environmental indicators as proximate indicators of impact of the NRM technologies. The indicators include changes in land productivity; total factor productivity; reduction in costs (e.g., reduced use of fertilizers, pesticides); reduced risk and vulnerability to drought and flooding; improved net farm income; and change in poverty levels (e.g., head count ratio). However, there are some limitations in this approach related to data availability and measurement errors, and problem in internalizing externalities and inter-temporal effects. For example, the time-varying nature of impacts of NRM practices requires time-series data, ideal panel data with repeated observations from the same households and plots over a period of many years, so that the dynamics of these impacts and their feedback effected on household endowments and subsequent NRM decisions are adequately assessed (Pender 2005). Unfortunately, household and plot-level panel data sets with information on both NRM practices and causal factors and outcomes are quite rare. In the absence of such data, inferences about NRM impacts will remain limited to those possible, based on available short-term experimental data and cross-sectional econometric studies. These can provide information on near-term impacts, for example, on current production, income and current rates of resource degradation or improvement, but do not reveal feedback effects such as how changes in income or resource conditions, may lead to changes in future adoption, adaptation, or non-adoption of NRM practices (Shenggen and Peter 1999; Pender 2005; Barrett et al. 2002; Kerr and Chung 2005).

Bioeconomic modelling approach integrates biophysical and economic information into a single integrated model. These models are capable of evaluating the potential effects of new productivity-enhancing crops and NRM technologies, policies and market incentives on human welfare as well as the quality of the resource base and the environment (Shiferaw et al. 2004; Woelcke 2006; Schreinemachers and Berger 2011). The bioeconomic models are useful to evaluate the potential effects of new productivity-enhancing crops and NRM technologies, policies and market incentives on human welfare as well as the quality of the resource base and the environment (Shiferaw et al. 2004). The analysis will provide the researchers and decision-makers in prioritization of technologies that may improve the farmers' economic efficiency and welfare as well as the condition of the natural resource base over time. Bioeconomic models have been applied at the household level (e.g., Holden and Shiferaw 2004; Holden et al. 2004; Woelcke 2006), at village and watershed levels (e.g., Barbier 1998; Barbier and Bergeron 2001; Sankhayan and Hofstad 2001; Okumu et al. 2002) and for agricultural sector (e.g., Schipper 1996).

The main advantages of using bioeconomic models for NRM technologies and policy impact assessment are (1) consistent treatment of complex biophysical and socioeconomic variables, providing a suitable tool for interdisciplinary analysis; (2) allow sequential and simultaneous interactions between biophysical and socioeconomic variables; (3) used to assess the potential impacts of new technologies and policies (ex-ante impact assessment); (4) capture both direct and indirect effects (i.e., the total effect of technology or policy change can be estimated); and (5) used to carry out sensitivity analyses in relation to various types of uncertainties.

2 Application of bioeconomic model for impact assessment

The individual impacts of various technologies are known, but there is little information on their combined impact or on the role of policy and institutional arrangements in conditioning their outcomes (Okumu et al. 2000). In addition, past watershed impact assessment studies seldom included the biophysical factors (like soil erosion, nutrient depletion, water conservation, etc.), which have a direct effect on the productivity of the agricultural and forestry enterprises. In the recent past, the methodologies that are capable of simultaneously addressing the various dimensions of agriculture and NRM technology changes and the resulting tradeoffs among economic, sustainability and environmental objectives have been developed (e.g., Barbier 1998; Barbier and Bergeron 2001; Holden and Shiferaw 2004; Woelcke 2006; Schreinemachers and Berger 2011). Given its merit and wide-spread application as an ex-ante tool, we adopt watershed level bioeconomic modelling approach to assess the multidimensional impacts of integrated crop and natural resource management interventions.

2.1 The study area

The Adarsha watershed in Kothapally village, located 40 km away from Hyderabad, capital city of Andhra Pradesh, India (Fig. 1), 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. Further, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) along with the Government of India and other partners implemented an integrated natural resource management program in this watershed (Wani et al. 2002; Shiferaw et al. 2003). This intervention provided a rich biophysical data. Hence, this site was selected because of the 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 data set was used in the study for construction and validation of the bioeconomic model.

2.2 Data

Weather and climatic variables were obtained from automatic weather station installed in Kothapally village. 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 categorized 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). Source of socioeconomic data was the panel data of 120 households and village census. The sample households were selected based on the census conducted by ICRISAT in 2001 on households in Kothapally village and five adjoining villages/non-watershed/control villages (namely Husainpura, Masaniguda, Oorella, Yenkepally 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 were collected annually for 3 years (2002–2004). Along with the other standard socioeconomic data, detailed plot and crop-wise input and output data

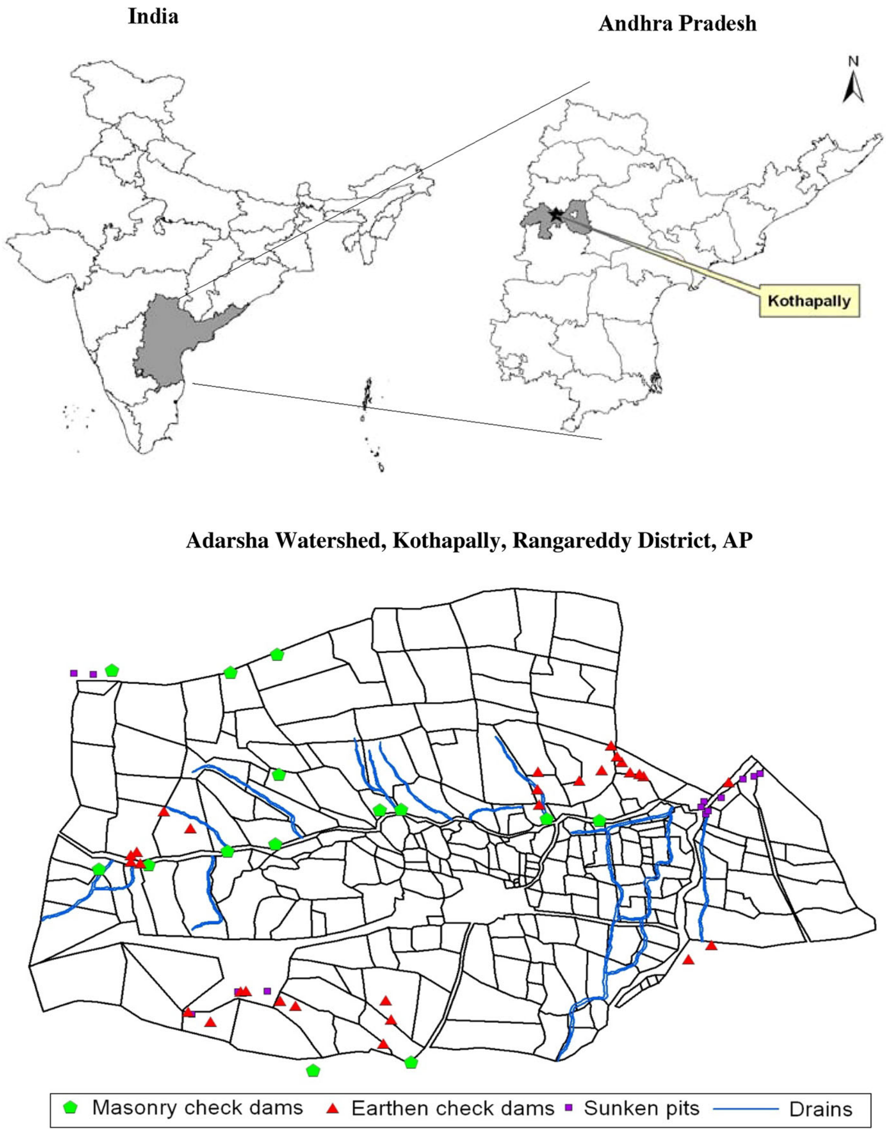

Fig. 1 Location of study area and layot of the Adarsha Watershed, Kothapally, Rangareddy District, AP

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 discussions in the sample villages.

2.3 Bioeconomic modelling

When dealing with rainfed agriculture and livelihood improvement in semi-arid fragile areas, two major components need to be considered seriously. The first component deals with socioeconomic aspects related to household behaviour, market structure, institutional arrangements, technology improvement and policy incentives. The second component deals with degradation of the natural resource base in terms of its biological processes related to water and nutrient cycling, plant and animal growth and erosion. Therefore, analysis of rainfed agriculture in the semi-arid tropics requires contributions from both biophysical and economic sciences.

The modelling approach consists of three components: (1) a mathematical programming model that reflects the farm household decision-making process under certain constraints; (2) estimation of crop yield response to soil depth; and (3) 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.

The mathematical programming model is a dynamic non-linear model that 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 and three soil depth classes). This gives 18 farm submodels within the watershed. The model was developed using General Algebraic Modeling System (GAMS). The model has been documented in the Appendix 1.

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 of the consumers in each household group. The following subsections describe the model in detail.

2.3.1 Crop production

The model includes nine crops namely sorghum, maize, paddy, cotton, chickpea, pigeon pea, vegetables, sunflower and onion, These crops were cultivated in two seasons, namely rainy (K*harif*) season and post-rainy (R*abi)* season. Cotton, vegetables and onions were cultivated in both rainfed and irrigated fields. Paddy was grown only under irrigated conditions. Sorghum and maize crops were intercropped with pigeon pea in the ratio of 80:20 during the *rainy* season. Crop choice in the watershed depends on the profitability (prices and yields), food, fodder, labour demand and distribution, suitability of different types 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. For the econometric estimation of yield variation due to changes in the topsoil depth, the household survey and plot and crop-wise input and output data in the survey villages were used. In order to capture the non-linear effects 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 parameters for production functions were obtained from the results of the econometric analysis of the plot-level input–output data (Eq. 1). The general form of the quadratic production function was:

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	

Authors' estimation

Note: *N* Nitrogen, *P* Phosphorus

$$Y_c = \beta_0 + \beta_i X_i + \beta_j Z_j + \beta_{ii} X_i^2 + \beta_k D_k + e_i \tag{1}$$

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;[2]) 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 1 cm 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 is presented in Table 1.

2.3.2 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

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[2] The variable soil depth (d) of each plot of the farm was not the exact topsoil depth in metres 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 ($0.5 < d < 1$ m); 3 = deep soil ($1 < d < 1.5$ m); and 4 = very deep soil ($d > 1.5$ m)). The difference between any two categories of soil depth was 50 cm.

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

scarcities in family labour. The hiring in and out of labour days within the watershed occurs at exogenously given wage rates.

2.3.3 Produce utlilization and consumption

In the model, produces of sorghum, paddy, chickpea and pigeon pea could either be stored and consumed by the households 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 (Indian Council of Medical Research (ICMR) recommendation for an adult for moderate activity in rural India is 2,400 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.

2.3.4 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 was 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 modelled as a function of crop type and crop grain yields. The decision to buy or sell animals was dependent on livestock productivity, mortality rates, buying and selling prices, fodder availability and cash constraint.

2.3.5 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 submodels land units was described in Eq. 2.

$$\mathrm{Sd}_t = \mathrm{Sd}_{t-1} - \tau \mathrm{Se}_t \tag{2}$$

where Sd = soil depth in cm; Se = soil erosion in tons per ha; τ = conversion factor (100 tons of soil erosion per ha reduces 1 cm of soil depth).

The amount of soil erosion under each crop in the watershed was estimated using USLE model (Appendix 2) 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 the production system was used to ascertain the sustainability of the systems (Pathak et al. 2005). Soils have a nutrient reserve controlled by their inherent

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

Table 2 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

fertility and management. A negative balance of such nutrients as N, P and K indicates 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 2.

2.4 Validation of the bioeconomic model

The challenge in the development of bioeconomic models is to ensure that the results are plausible and that the model can be re-used in similar settings. The validation of the complex models like bioeconomic models is much debated in the literatures (Parker et al. 2003; Janssen and van Ittersum 2007). For example, Janssen and van Ittersum 2007) reviewed 48 bioeconomic models and found that only 23 studies validated their results using observed qualitative and quantitative data.

Based on McCarl and Apland (1986), the bioeconomic model was validated by conducting regression analysis between observed and simulated land-use values. A regression line was fitted through the origin for the observed land use in 2003, and simulated land use of seven major crops was expressed in percentage to a total area of these crops. The comparison was done at watershed level. Figure 2 compares the observed with the simulated land use at the watershed level. The parameter coefficients are close to unity at watershed level with an explained variance of 97 % (Fig. 2) which indicates that the model results are almost identical with the current land-use trend in the Kothapally watershed.

The validation of the model was also done for biophysical variables like soil loss by comparing average soil loss per ha of crop land predicted by the model with the soil loss measurement done in the watershed using a sediment sampler. The measured soil loss in Kothapally watershed (treated and untreated watershed) is in the range of 1–3 tons per ha (Wani et al. 2002). The soil loss predicted by the baseline model is in the range of 3.5–4.5 tons per ha over 10 years. The two quantities differ slightly because the soil loss calculated by soil sediment sampler at the stream is not reflecting the exact soil loss at the plot/field level because the stream may deposit part of its sediments eroded from the field during its course before it takes off as a stream from the micro-watershed. The study conducted by Singh et al. (2003) for 6 years from 1995/1996 to 2000/2001 in the model watershed (BW7) at ICRISAT station measures the soil loss at field level and reported that the soil loss per ha is in the range of 2.5 and 4.5 tons in two land management types (BBF and flat, respectively) for an average annual rainfall of 800 mm in Vertic Inceptisol soils. This

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

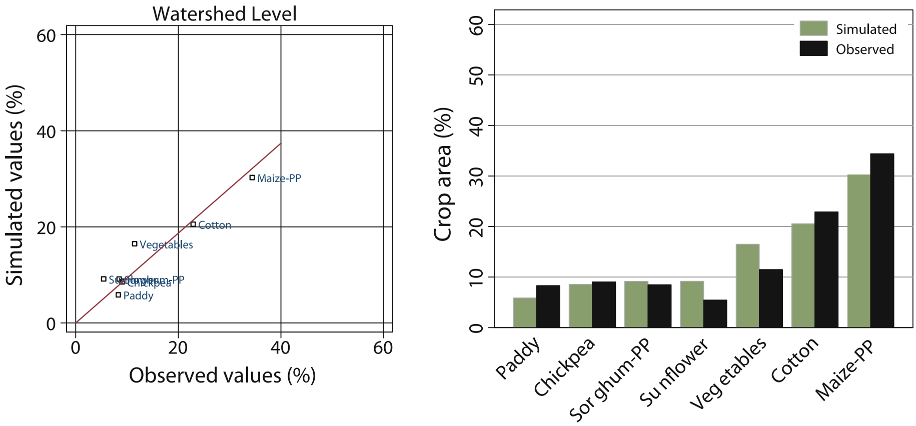


Fig. 2 Simulated versus observed land use as % of total crop area (watershed level). Regression line fit: Coeff = 0.93; SE = 0.51; $R^2 = 0.97$

value on soil loss per ha is consistent with the results predicted by the model for the study area. Hence, the predicted soil loss in the watershed (Adarsha watershed) by the bioeconomic model is valid because of the prevailing similar soil type and climatic conditions for both ICRISAT on-station watershed and the study area.

3 Scenario results and discussion

3.1 The impact of changes in the 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 was the important components of watershed development interventions to increase the income of the small holder farmers. In this study, an attempt was made using the bioeconomic model to test the hypothesis that introduction of technological innovations (like improved crop varieties and cropping systems) compensate for decreasing returns to labour from labor-intensive natural resource management interventions over the years. The study simulates two scenarios to test this hypothesis: (a) yield of dryland crops (sorghum, maize, pigeon pea and chickpea) increases by 10 % and (b) yield of dryland crops decreases by 10 %.

The simulation results showed that the per capita income of all three household groups were above the baseline level when the yields of the dryland crops were increased (Table 3). 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 in the initial years and starts declining from the fifth year of simulation (Fig. 3). The increase in the 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.

Table 3 Impact of change in the yield of dryland crops

Scenario	Per capita income (1000 Rs)			Soil loss (tons/ha)	Conservation labour (man-days)	Nutrient balance (tons)		
	Small	Medium	Large			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

Average of 10 years simulation

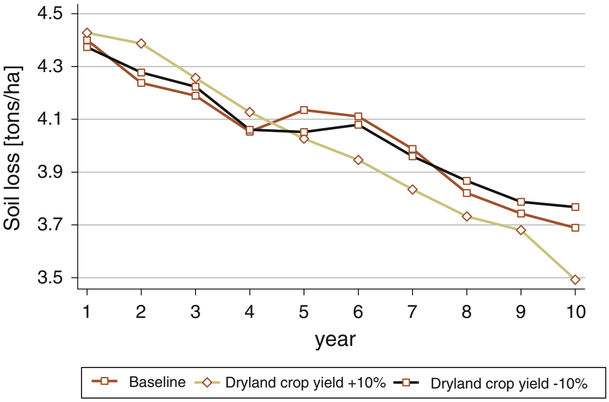


Fig. 3 Simulated average soil loss in the watershed (tons/ha) under alternative yield scenarios for dryland crops

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 (Figs. 3, 4). The result revealed that the decline in soil erosion was 6 % 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 the baseline scenario.

The increase in area under sorghum and maize and decline in the area of high nutrient mining crops like cotton and sunflower under the scenario of increased yields of dryland crops had reduced soil nutrient mining by 4, 1 and 3 % N, P and K, respectively, compared to baseline level (Table 3). If the yield of dryland crops had decreased by 10 %, then the results showed that nutrient balances in the watershed would be similar to baseline level.

3.2 Impact of change in irrigated area in the watershed

The important objective of watershed development program was to conserve rainwater by reducing outflows 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 would help to increase the area under irrigation in the watershed. In this context, simulation was carried out to assess the impact of changes in the irrigated area resulting from the adoption of soil and water conservation measures on household welfare,

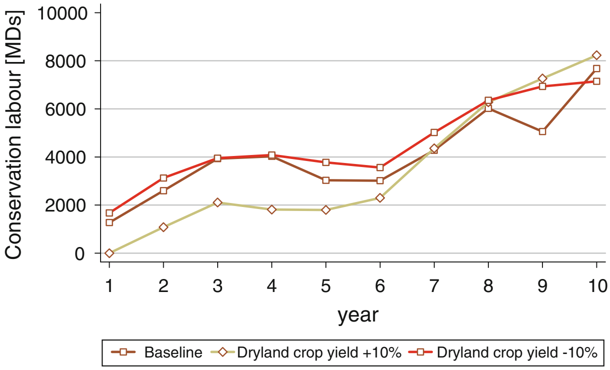


Fig. 4 Simulated labour uses for conservation measures (MDs) under alternative yield scenarios for dryland crops

soil loss and nutrient balance in the watershed. Hence, the baseline scenario of the watershed was compared with two alternative scenarios (a) increasing irrigated area by 25 % and (b) reducing the area under irrigation by 25 %. 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 the increase in irrigated area of the watershed increased the per capita income of all the three household groups above the baseline level (Table 4). The increase in income was attributed to higher productivity of crops like cotton, vegetables and sunflower under irrigation and expansion of the irrigated area under these crops which 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 % led to a reduction in the per capita income for small and medium farm households because the area under commercial crops like vegetables and cotton decreased. The per capita income of the large farmers had not changed because these farmers were not constrained by the irrigated land.

The soil erosion was higher when the irrigated area increased in the watershed compared to the baseline level (Fig. 5). 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 % compared to baseline level. On the contrary, reduction in irrigated land in the

Table 4 Impact of change in irrigated area in the watershed

Scenario	Per capita income (1000 Rs)			Soil loss (tons/ha)	Conservation labour (man days)	Nutrient balance (tons)		
	Small	Medium	Large			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

Average of 10 years simulation

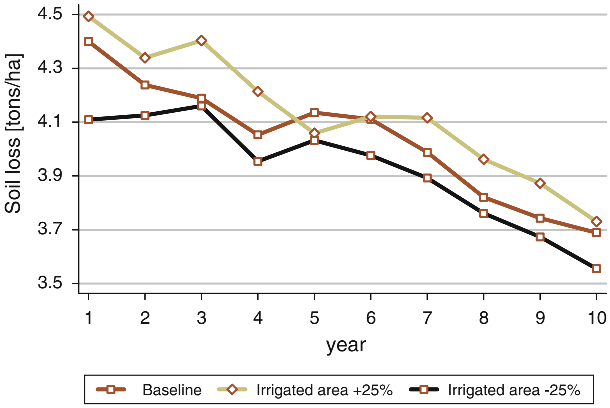


Fig. 5 Simulated soil loss in the watershed (tons/ha) under alternative irrigation scenarios

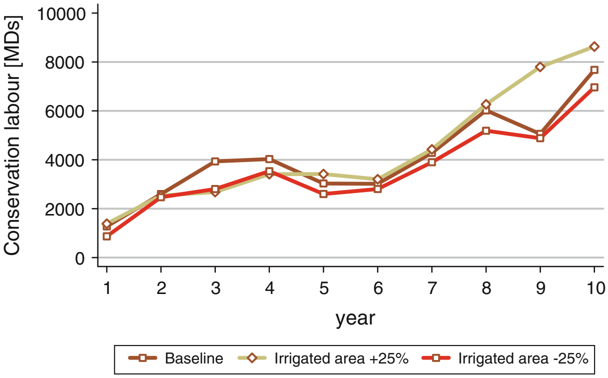
watershed increased the area under less erosive dryland crops like maize and sorghum which reduced the soil erosion by about 7 % (Fig. 5).

When irrigated area increases by 25 %, 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. 6). When the irrigated area decreased by 25 %, the total soil erosion was below the baseline level, even though the total labour used for conservation was lower than the baseline level. This could be mainly attributed to a change in the cropping pattern, whereas the area under less erosive dryland 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 the irrigated area increased *s* by 25 % (Table 4). This was due to an increase in the area of high nutrient extraction irrigated crops like vegetables, cotton and sunflower compared to the baseline level. The reduction in irrigated area increased the area under cereal–legume cropping systems like maize/pigeon pea and sorghum/pigeon pea which removed comparatively less nutrients from the soil and also improved the nutrient content by biological atmospheric fixation.

Though the increase in irrigated area in the watershed improved the welfare of the farmers, the change in the cropping pattern caused negative effect on the environment due to an increased level of soil erosion and nutrient mining.

Fig. 6 Simulated labour uses for conservation measures (MDs) under alternative irrigation scenarios



4 Conclusions

In an effort to reduce vulnerability and improve the livelihood of poor households, the Government of India started promoting an integrated watershed development approach with the help of multiple development agencies. These interventions are considered to be vital for arresting land degradation (nutrient mining and soil erosion) and revitalizing the mixed crop-livestock production systems in the rainfed drylands. Despite the presence of some case studies of successful watershed development in India, there is lack of empirical evidence on the impact of the approach on improving the welfare of the poor and the natural resource condition in semi-arid villages. Past impact studies of watershed development in India hardly integrated the biophysical factors with economic factors to assess the complementarities and the tradeoffs within the framework of farm household economic behaviour. This is mainly because of methodological challenges and lack appropriate analytical tools. In this paper, a holistic and integrated impact assessment tool was developed using a watershed level bioeconomic modelling approach, which is used to simultaneously assess and evaluate the multidimensional impacts of integrated watershed management on the welfare of rural households and the natural resource conditions. The model is also used to identify effective policy instruments and institutional needs for enhancing the effectiveness of the watershed approach.

The study concluded that introduction of high-yielding varieties and cereal–legume intercropping systems as component of integrated watershed programs can indeed help to improve the welfare of smallholder farmers by increasing their incomes and also enhancing the sustainability of the natural resources upon which their livelihoods depend. It also stimulates sustainable intensification of crop production in the semi-arid villages by controlling soil erosion and nutrient mining through the investments in soil and water conservation and adoption of better land-use patterns at the landscape level. This undescores the importance of developing high-yielding and drought tolerant 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 contributed to the significant growth in the income of the farmers. The level of soil erosion and nutrient mining in the watershed, however, increased because of the increase in the area under the erosive and nutrient mining crops. This suggests the need to promote inter-linked interventions when important trade-offs exist between economic and sustainability outcomes. Irrigation can also help to improve food security and household income through improvements in fodder production that create complementarities with livestock production that will increase manure availability for soil fertility management. The results clearly indicated that care should be taken while developing and promoting technologies for watershed development to avoid conflicting technologies and enhancing synergies between differnt intervensions.

Appendix 1: Detailed description of the micro-watershed level bioeconomic model

The model maximizes the present value of future income for the whole watershed. The watershed is managed by three groups of farmers. Each group has access to two types of land and three soil depth classes. This leads to 18 homogenous land units in the watershed.

The constraints are land, labour, capital, bullock labour, food, fodder for livestock and soil depth. The main activities are crops, livestock production and on-farm and off-farm activities.

Endogenous variables are capitalized, coefficients are in small letters and indices are subscripts.

Sets

a	Livestock production activities
$a1$	Milking animals (cows and she buffaloes)
$a2$	Bullocks
c	Crop production activities
ct	Conservation technology used to reduce soil erosion
cr	Type of credit (formal and informal)
f	Type of fertilizers (urea and DAP)
fl	Fertilizer level used ($fl = 1, 2, \ldots, 10$)
h	Three household groups (small, medium and large)
l	Two land types depending upon irrigation (irrigated and rainfed)
n	Dietary nutrients for human consumption (carbohydrates, protein and fat)
pn	Plant nutrients in fertilizers (N and P)
r	Discount rate
s	Three soil depth classes (shallow, medium and deep)
sa	Seasons (12 months of the year)
t	Time in years
z	Consumption of other purchased products (like meat, oil, egg, etc.)

Variables

ASOILER	Average soil erosion in each land unit in tons
BUYSED	Amount of crop seed stocks purchased in tons
BUYCON	Amount of crop product brought for household consumption in tons
BULHIRE	Number of bullock days hired
CROP	Crop production activities in ha
CROPYL	Crop yield after erosion in tons per ha
CRESID	Crop residual bought for animal feed in tons
CONS	On-farm consumption of crop product in tons
CONOWNA	On-farm consumption of young animals born or own animal slaughtering activities in heads
CONPURA	The amount of purchased animals consumed in heads
CONOP	The amount of other products consumed in tons (like meat, oil, egg, milk)
CREDIT	Credit borrowed from different sources in Rupees
CUMSOILER	Cumulative soil erosion in each land unit in each year in tons
CDEPTH	Soil depth reduction from initial depth in cm
DEPTH	Soil depth change due to erosion in cm
DMANURE	Total manure (in tons) production per year
FERTBUY	Fertilizers purchased in market in tons
FALLOW	Fallow land in ha
FAMLAB	Family labour in man-days
HINCOME	Household group income in Rupees
HIRLAB	Hired labour to work in the field in man-days
INCOME	Income of the household group in Rupees
LABHIN	Labour hired in from other households within the watershed in man-days
LABOFM	Labour used in off-farm activities in man-days
LABNFM	Labour work in non-farm activities in man-days
LIVPROD	Livestock production activities in number

LIVBUY	Livestock purchased in number during the year
LIVSAL	Livestock sold in number during the year
LIVREAR	New born rearing activities in heads
MANUSE	Amount of animal manure applied on the fields in tons
MPROD	Milk production in litres
MILCONS	Milk consumed in litres
MILSAL	Milk sold in litres
MIG	Permanent migration of population
NITRO	Nitrogen applied to crops in tons
POP	Population of the watershed village
PHOS	Phosphorus applied to crops in tons
RENTIN	Land rent in from other household group for cultivation in ha
RENTOUT	Land rent out by household group to other group in ha
SEED	Amount of own crop product used as seed stock in tons
SELCROP	Amount of crop production sold in tons
STORED	Crop product stored for next year in tons
STOREDC	Crop product stored for consumption in next year in tons
STOREDS	Crop product stored for sale in next year in tons
TINCW	Total income of the watershed in Rupees
TPROD	Total production of crops in tons
SOILER	Amount of soil eroded in each land unit in tons
TSOILER	Amount of soil eroded in whole watershed in tons
WFORCE	Work force in the watershed

Coefficients

area (h,l,s)	Available cultivable area of land (ha) for household group *h*, land type *l* , and soil type *s*
amilkp (a1)	Average milk production per milking animal *a*1 per year
bprice (c)	The buying price of crop output *c* in Rupees per ton
bwage	Wage rate for bullock hiring in Rupees
bullreq (l,s,fl,c,sa)	Bullock days required for a ha of crop production *c*, in land type *l*, soil type *s*, fertilizer level *fl* and in season *sa*
bavail (a2, sa)	The number of bullock labour days available in season *sa*
brate	Birth rate or calving rate of female animal
cprice (c)	The market price of crop output *c* in Rupees per ton
concost (a1)	Average amount spent for buying concentrates for milking animals *a*1 in a year
conslab (c,ct)	Labour used for conservation of field for crop *c* grown with conservation technology *ct*
cost (c)	The cost of pesticides used for each crop *c* in Rupees per ha
cnut (n,c)	The composition of nutrient *n* (carbohydrate, protein and fat) in crop products *c* consumed
culrate	The culling rate for livestock
drymreq (a)	Dry matter requirement for each livestock type *a* in tons per year
dm	Dry matter content of the crop residual
erosion (c,ct)	Soil loss in tons per ha of each crop *c* cultivated with conservation technology *ct*

erfact	Erosion soil depth conversion factor (100 tons soil erosion per ha reduces 1 cm of soil depth)
fprice (f)	The price of chemical fertilizers type f in Rupees per ton
fertlev (pn,fl)	Level fl of plant nutrients pn applied in tons per ha
fnut (pn,f)	The composition of plant nutrients pn per ton of fertilizers f (urea and DAP)
fmig	Fraction of population migrating
irate (cr)	Interest rate in per cent for different credit type cr in per cent
labsup (h,sa)	Labour supply per workforce in each household group h in season sa
labuse (h,l,s,fl,c,sa)	Labour required (man-days) for ha of crop c cultivation by household group h, in land type l, soil class s using fertilizer level fl in season sa
livlab (h,sa)	Labour required for livestock herd maintenance (man-days) for household group h in season sa
lprice (a)	The market price of livestock a in Rupees per head
livnut (n,a)	The composition of nutrients n (carbohydrate, protein and fat) in livestock a consumed
mprice	The price of milk in village market in Rupees per litre
mrate	The mortality rate for livestock
manpypa (a)	Collectable dry manure produced by livestock a (in tons) per year per animal
manut (pn)	The composition of plant nutrients pn (N and P) per ton of manure (FYM) applied
nfwage	The non-farm wage rate in Rupees
nres (c,pn)	Marginal effect of crop c yield for change in plant nutrients N in tons
nsqres (c)	Marginal effect of crop c yield for change in plant nutrients N square (N^2) in tons
nutreq (h,n)	The total annual nutritional requirement of the household group h for nutrient n
opnut (n,z)	The composition of nutrients n (carbohydrate, protein and fat) in other products z consumed
oprice (z)	The price of other products z consumed in Rupees per ton
popg	Growth rate of population
pres (c,pn)	Marginal effect of crop c yield for change in plant nutrients P in tons
psqres (c)	Marginal effect of crop c yield for change in plant nutrients P square (P^2) in tons
pliv	Proportion of productive milking animals
rprice	The price of crop residual in Rupees per ton
rent (l,s)	Price of rent in and out land by land type l and soil class s in Rupees per ha
sprice (c)	The price of crop c seed stock purchased in Rupees per ton
seedrate (c)	Seed rate of crop c per hectare in tons
sdepth (h,l,s)	Initial soil depth (cm) in each land units of household group h, land type l and soil class s
stoyld (c)	The stover yield for a ton of crop c grain yield in tons
vetcost (a)	Average veterinary cost for each livestock a in a year
wage	The village market wage rate in Rupees

yield (l,s,c)	Average yield of crop *c* in different land type *l* and soil class *s* in tons per ha
yred (s,c)	Marginal effect of crop *c* yield for 1 cm change in soil depth in tons in soil class *s*

Equations

Income functions

The model maximizes total income of the watershed defined as the present value of the sum of household groups' income over *T* periods.

$$\mathrm{TINCW} = \sum_{h=1}^{H}\sum_{t=1}^{T}(1/1+r)^{t}\cdot\left(\mathrm{INCOME}_{h,t}\right) \tag{3}$$

The household group *h* net income in time *t* is sum of crop, livestock, non-farm and wage income less than the costs incurred for farm production (like seed cost, fertilizers cost, labour cost), livestock rearing cost, feed cost and interest paid for the credit received from different sources. The income equation is as follows.

$$\begin{aligned}
\mathrm{INCOME}_{h,t} = {} & \sum_{c=1}^{C}\mathrm{TPROD}_{h,c,t}\cdot \mathrm{cprice}_{c} - \sum_{c=1}^{C}\mathrm{BUYSED}_{h,c,t}\cdot \mathrm{sprice}_{c} \\
& - \sum_{f=1}^{F}\mathrm{FERTBUY}_{h,f,t}\cdot \mathrm{fprice}_{f} - \sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{fl=1}^{FL}\sum_{c=1}^{C}\mathrm{CROP}_{h,l,s,fl,c,t}\cdot \mathrm{cost}_{c} \\
& + \sum_{a=1}^{A}\mathrm{LIVSAL}_{h,a,t}\cdot \mathrm{lprice}_{a} - \sum_{a=1}^{A}\mathrm{LIVBUY}_{h,a,t}\cdot \mathrm{lprice}_{a} \\
& + \sum_{sa=1}^{SA}\mathrm{LABOFM}_{h,sa,t}\cdot \mathrm{wage} + \sum_{sa=1}^{SA}\mathrm{LABNFM}_{h,sa,t}\cdot \mathrm{nfwage} \\
& - \sum_{sa=1}^{SA}\mathrm{HIRLAB}_{h,sa,t}\cdot \mathrm{wage} \\
& - \sum_{sa=1}^{SA}\mathrm{HIRBUL}_{h,sa,t}\cdot \mathrm{bwage} - \mathrm{CRESID}_{h,t}\cdot \mathrm{rprice} + \mathrm{MILKSAL}_{h,t}\cdot \mathrm{mprice} \\
& - \sum_{cr=1}^{CR}\mathrm{CREDIT}_{h,ct,t}\cdot \mathrm{irate}_{cr} - \sum_{a=1}^{A}\mathrm{LIVPROD}_{h,a,t}\cdot \mathrm{vetcost}_{a} \\
& - \sum_{a2=1}^{A2}\mathrm{LIVPROD}_{h,a2,t}\cdot \mathrm{concost}_{a2}
\end{aligned} \tag{4}$$

Crop production

Crop production is a function of yield of crop *c*, in land type *l*, soil class *s*, at fertilizer level *fl*, conservation technology *ct*, at time period *t* and cultivated area of crop *c*, by household group *h*, in land type *l* and soil class *s*. The basic yield of a crop *c* in household group *h*, land type *l*, soil class *s* at time period *t* can be increased by the application of inorganic fertilizers (N and P) and conversely yield would be decreased by change in soil depth of the cropland due to erosion. The quadratic yield function in the model is given as

$$\begin{aligned}\mathrm{CROPYL}_{h,l,s,fl,ct,c,t} = {} & \mathrm{yield}_{l,s,c} - \mathrm{yred}_{s,c} \cdot \mathrm{CDEPTH}_{h,l,s,t} + \mathrm{nres}_c \cdot \mathrm{NITRO}_{fl} \\ & + \mathrm{nsqres}_c \cdot \mathrm{NITRO}_{fl}^2 + \mathrm{pres}_c \cdot \mathrm{PHOS}_{fl} + \mathrm{psqres}_c \cdot \mathrm{PHOS}_{fl}^2\end{aligned} \tag{5}$$

Total crop production of crop *c* by household group *h* at time period *t* is a function of endogenous crop yield (CROPYL) of crop *c*, in land type *l*, soil class *s*, at fertilizer level *fl*, conservation technology *ct*, at time period *t* and area (CROP) of crop *c*, in land type *l*, soil class *s*, at fertilizer level *fl*, conservation technology *ct*, at time period *t*.

$$\mathrm{TPROD}_{h,c,t} = \sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{fl=1}^{FL}\sum_{ct=1}^{CT}\left(\mathrm{CROPYL}_{h,l,s,fl,ct,c,t} \cdot \mathrm{CROP}_{h,l,s,fl,ct,c,t}\right) \tag{6}$$

The total crop production of crop *c* by household group *h* in the year *t* is sold, stored and consumed by population and used as seeds. The household group *h* in year *t* is allowed to store the crop product for consumption and sell in the following year $t + 1$. The crop production balance equation for crop *c* by household group *h* in year *t* is as follows

$$\mathrm{TPROD}_{h,c,t} = \mathrm{CONS}_{h,c,t} + \mathrm{SELCROP}_{h,c,t} + \mathrm{SEED}_{h,c,t} + \mathrm{STORED}_{h,c,t} \tag{7}$$

$$\mathrm{STORED}_{h,c,t} = \mathrm{STOREDC}_{h,c,t+1} + \mathrm{STOREDS}_{h,c,t+1} \tag{8}$$

Land-use constraint

All the cultivable land in the watershed is divided into 18 homogenous land units. Each land unit is used for a different combination of crops, and the remaining land is left as fallow. The farmers in the watershed are allowed to rent in land for cultivation from other farmers. The land constrained equation in the model is

$$\sum_{c=1}^{C}\sum_{fl=1}^{FL}\sum_{ct=1}^{CT}\mathrm{CROP}_{h,l,s,fl,c,ct,t} + \mathrm{FALLOW}_{h,l,s,t} + \mathrm{RENTOUT}_{h,l,s,t} \le \mathrm{area}_{h,l,s} + \mathrm{RENTIN}_{h,l,s,t} \tag{9}$$

The rented in (demand) land by land type *l*, and soil class *s* in year *t* must be less than or equal to rented out (supply) land by land type *l*, and soil class *s* in year *t*.

$$\sum_{h=1}^{H}\mathrm{RENTIN}_{h,l,s,t} \le \sum_{h=1}^{H}\mathrm{RENTOUT}_{h,l,s,t} \tag{10}$$

Seed stock use

The seed rate per hectare of crop *c* is given exogenously. The total seed used by household group *h* in year *t* must be equal to sum of own seed stock (SEED) used by household group *h*, of crop *c* in year *t* and purchase seeds (BUYSED) by household group *h*, of crop *c* in year *t*.

$$\mathrm{seedrate}_c \cdot \sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{fl=1}^{FL}\sum_{ct=1}^{CT}\mathrm{CROP}_{h,l,s,fl,ct,c,t} = \mathrm{SEED}_{h,c,t} + \mathrm{BUYSED}_{h,c,t} \tag{11}$$

Fertilizer use

The macronutrients *pn* (N and P) required for crop *c* are applied through inorganic fertilizers (like urea and DAP) and farmyard manure (FYM). The nutrients applied to the fields by household group *h* in year *t* in the watershed must be equal to the sum of inorganic fertilizers bought and FYM applied to the field by the household group *h* in year *t*. The equation is given by

$$\begin{aligned}\sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{fl=1}^{FL}\sum_{c=1}^{C}\sum_{ct=1}^{CT}\mathrm{CROP}_{h,l,s,fl,ct,c,t}\cdot\mathrm{ferlev}_{pn,fl} &= \sum_{f=1}^{F}\left(\mathrm{fnut}_{pn,f}\cdot\mathrm{FERTBUY}_{h,f,t}\right)\\ &+\mathrm{MANUSE}_{h,t}\cdot 0.6\cdot\mathrm{manut}_{pn}+\mathrm{MANUSE}_{h,t-1}\cdot 0.4\cdot\mathrm{manut}_{pn}\end{aligned} \tag{12}$$

Capital or credit constraint

The capital is constrained in the model, the expenses incurred by household group *h* in year *t* for crop *c* and livestock *a* production is met through cash income earned by the household group *h* at time period *t* through the sale of crop *c*, livestock *a*, off income and non-farm income earned. The model is assumed to have access for formal and informal credit in the village. The capital and credit constraint equation of household group *h* in year *t* in the model is as follows.

$$\begin{aligned}&\sum_{c=1}^{C}\mathrm{BUYSED}_{h,c,t}\cdot\mathrm{sprice}_{c}+\sum_{c=1}^{C}\mathrm{BUYCON}_{h,c,t}\cdot\mathrm{bprice}_{c}+\sum_{a=1}^{A}\mathrm{CONPURA}_{h,a,t}\cdot\mathrm{lprice}_{a}\\ &\sum_{z=1}^{Z}\mathrm{CONOP}_{h,z,t}\cdot\mathrm{oprice}_{z}+\mathrm{CRESID}_{h,t}\cdot\mathrm{rprice}+\sum_{a=1}^{A}\mathrm{LIVBUY}_{h,a,t}\cdot\mathrm{lprice}_{a}\\ &+\sum_{cr=1}^{CR}\left(\mathrm{CREDIT}_{h,cr,t-1}\cdot(1+\mathrm{irate}_{ct})\right)+\sum_{sa=1}^{SA}\mathrm{HIRLAB}_{h,ss,t}\cdot\mathrm{wage}\\ &\quad+\sum_{sa=1}^{SA}\mathrm{HIRBUL}_{h,sa,t}\cdot\mathrm{bwage}\\ &+\sum_{f=1}^{F}\mathrm{FERTBUY}_{h,f,t}\cdot\mathrm{fprice}_{f}+\sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{fl=1}^{FL}\sum_{ct=1}^{CT}\sum_{c=1}^{C}\mathrm{CROP}_{h,l,s,fl,ct,c,t}\cdot\mathrm{cost}_{c}\\ &+\sum_{l=1}^{L}\sum_{s=1}^{S}\mathrm{RENTIN}_{h,l,s,t}\cdot\mathrm{rent}_{l,s}\\ &+\sum_{a=1}^{A}\mathrm{LIVPROD}_{h,a,t}\cdot\mathrm{vetcost}_{a}+\sum_{a2=1}^{A2}\mathrm{LIVPROD}_{h,a2,t}\cdot\mathrm{concost}_{a2}\\ &\le\sum_{cr=1}^{CR}\mathrm{CREDIT}_{h,cr,t}+\sum_{c=1}^{C}\mathrm{SELCROP}_{h,c,t}\cdot\mathrm{cprice}_{c}+\sum_{a=1}^{A}\mathrm{LIVSAL}_{h,a,t}\cdot\mathrm{lprice}_{a}+\\ &+\sum_{sa=1}^{SA}\mathrm{LABOFM}_{h,sa,t}\cdot\mathrm{wage}+\sum_{sa=1}^{SA}\mathrm{LABNFM}_{h,sa,t}\cdot\mathrm{nfwage}+\mathrm{MILKSAL}_{h,t}\cdot\mathrm{mprice}\\ &+\sum_{l=1}^{L}\sum_{s=1}^{S}\mathrm{RENTOUT}_{h,l,s,t}\cdot\mathrm{rent}_{l,s}\end{aligned} \tag{13}$$

Food consumption

The subsistence food consumption needs of the population are defined in terms of minimum nutrient requirement (carbohydrates, protein and fat). The daily calorie requirement for a consumer is converted into nutrients and multiplied with total consumers in the household group *h* in year *t* to arrive at the total minimum nutrients required in tons. It is important to note that in each year, the population growth will affect the number of consumers in each household group, and therefore, the minimum food requirement also grows proportionally with population growth. The minimum nutrient requirement of the population is met by on-farm consumption of crop *c* output, purchased consumption crop *c* products, consumption of own animals *a*, consumption of purchased animals *a* and consumption of purchased product *z* (like meat, egg, oil, etc.). The food consumption constraint equation for household group *h* in year *t* is given as

$$\begin{aligned}&\sum_{c=1}^{C}\mathrm{CONS}_{h,c,t}\cdot\mathrm{cnut}_{n,c}+\sum_{c=1}^{C}\mathrm{BUYCON}_{c}\cdot\mathrm{cnut}_{n,c}+\sum_{a=1}^{A}\mathrm{CONOWNA}_{h,a,t}\cdot\mathrm{livnut}_{n,a}\\&+\sum_{a=1}^{A}\mathrm{CONPURA}_{h,a,t}\cdot\mathrm{livnut}_{n,a}+\sum_{z=1}^{Z}\mathrm{CONOP}_{h,z,t}\cdot\mathrm{opnut}_{n,z}\geq\mathrm{nutreq}_{h,n,t}\end{aligned}\tag{14}$$

Population and labour

The population in household group *h* at the end of the year *t* is the beginning population ($\mathrm{POP}_{\text{t-1}}$) adjusted for population growth rate (popg) minus permanent migrants (MIG). The permanent migration is limited to a fraction of the population. The population in household group *h* at time period *t* is converted into workforce (WFORCE) based on age and adjusted for growth rate of population.

$$(1+\mathrm{popg})\cdot\mathrm{POP}_{h,t-1}-\mathrm{MIG}_{h,t}=\mathrm{POP}_{h,t}\tag{15}$$

$$\mathrm{MIG}_{h,t}\leq\mathrm{fmig}\cdot\mathrm{POP}_{h,t}\tag{16}$$

$$(1+\mathrm{popg})\cdot\mathrm{WFORCE}_{h,t-1}-\mathrm{WMIG}_{h,t}=\mathrm{WFORCE}_{h,t}\tag{17}$$

$$\mathrm{WMIG}_{h,t}\leq\mathrm{fmig}\cdot\mathrm{WFORCE}_{h,t}\tag{18}$$

The labour days used by household group *h* for different farm activities (crop and livestock) in season *sa* at time period *t*, labour days used for conservation of land by household group *h* at time period *t*, labour days work on other household group farms (LABOFM) by household group *h* at time period *t* and labour days work non-farm (LABNFM) by household group *h* at time period *t* have to be less than or equal to family labour (FAMLAB) in household group *h* in season *sa* at time period *t* plus the labour days hired in from other household group within the watershed (LABHIN) by household group *h* in season *sa* at time period *t*.

$$\sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{fl=1}^{FL}\sum_{ct=1}^{CT}\sum_{c=1}^{C}\left(\mathrm{CROP}_{h,l,s,fl,ct,c,t}\cdot \mathrm{labuse}_{l,s,fl,c,sa}\right) + \sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{fl=1}^{FL}\sum_{ct=1}^{CT}\sum_{c=1}^{C}\left(\mathrm{CROP}_{h,l,s,fl,ct,c,t}\cdot \mathrm{conslab}_{c,ct}\right) + \mathrm{livlab}_{h,sa,t} + \mathrm{LABOFM}_{h,sa,t} + \mathrm{LABNFM}_{h,sa,t} \le \mathrm{FAMLAB}_{h,sa,t} + \mathrm{LABHIN}_{h,sa,t} \tag{19}$$

The family labour plus off-farm and non-farm labour in household group *h* in season *sa* at time period *t* is less than the total work days available per household group *h* at time period *t*.

$$\mathrm{FAMLAB}_{h,sa,t} + \mathrm{LABOFM}_{h,sa,t} + \mathrm{LABNFM}_{h,sa,t} \le \mathrm{labsup}_{h,sa}\cdot \mathrm{WFORCE}_{h,t} \tag{20}$$

The following equation ensures the equilibrium of the supply of and demand for wage labour within the watershed in season *sa* at time period *t*.

$$\sum_{h=1}^{H}\mathrm{LABHIN}_{h,sa,t} = \sum_{h=1}^{H}\mathrm{LABOFM}_{h,sa,t} \tag{21}$$

Soil erosion and soil depth

The total annual soil loss in each land unit at time period *t* in the watershed is the result of cropping activities (CROP) for crop *c* by household group *h*, in land type *l*, soil class *s* at time period *t*. The following equation determines the soil loss in each land unit at time period *t*.

$$\sum_{fl=1}^{FL}\sum_{ct=1}^{CT}\sum_{c=1}^{C}\left(\mathrm{CROP}_{h,l,s,fl,ct,c,t}\cdot \mathrm{erosion}_{c,ct}\right) = \mathrm{SOILER}_{h,l,s,t} \tag{22}$$

The total soil erosion in the watershed in year *t* is given by

$$\sum_{h=1}^{H}\sum_{l=1}^{L}\sum_{s=1}^{S}\mathrm{SOILER}_{h,l,s,t} = \mathrm{TSOILER}_{t} \tag{23}$$

The average soil erosion in each land unit at time period *t* is given by

$$\mathrm{ASOILER}_{h,l,s,t} = \frac{\mathrm{SOILER}_{h,l,s,t}}{\mathrm{area}_{h,l,s}} \tag{24}$$

The cumulative soil erosion in each land unit in each year *t* is given by

$$\mathrm{CUMSOILER}_{h,l,s,t} = \mathrm{ASOILER}_{h,l,s,t-1} + \mathrm{ASOILER}_{h,l,s,t} \tag{25}$$

The soil depth decrease as a result of soil erosion in each land unit in year *t* is given by

$$\mathrm{DEPTH}_{h,l,s,t} = \mathrm{sdepth}_{h,l,s} - \mathrm{erfact}\cdot \mathrm{CUMSOILER}_{h,l,s,t} \tag{26}$$

The change in soil depth from the initial soil depth of the land in year *t* is given by

$$\mathrm{CDEPTH}_{h,l,s,t} = \mathrm{sdepth}_{h,l,s} - \mathrm{DEPTH}_{h,l,s,t} \tag{27}$$

Livestock modelling

The adult animal production by household group h in year $t + 1$ depends on initial animal in the start of the year t, animal bought, sold, young animal reared in the year, culling rate and mortality rate of the animal. The livestock type a production by household group h in a year t is estimated as follows.

$$\begin{aligned}\mathrm{LIVPROD}_{h,a,t+1} =& (1 - \mathrm{culrate} - \mathrm{mrate}) \cdot \mathrm{LIVPROD}_{h,a,t} + \mathrm{LIVBUY}_{h,a,t+1} \\ &+ \mathrm{LIVREAR}_{h,a,t} - \mathrm{LIVSAL}_{h,a,t+1}\end{aligned} \tag{28}$$

Production of young animal type a by household group h in year t is computed based on the birth rate or calving rate of animal, consumption of young animal on-farm and selling of young animal in year t. The equation for young animal balance is given as

$$\mathrm{brate} \cdot \mathrm{LIVPROD}_{h,a,t} = \mathrm{LIVREAR}_{h,a,t} + \mathrm{CONOWNA}_{h,a,t} + \mathrm{LIVSAL}_{h,a,t} \tag{29}$$

These equations are adjusted for different animal type a depending on the time required in different age classes and their reproduction characteristics.

Livestock feed requirement

The feed requirements for livestock type a in year t in the watershed have to be fulfilled by locally produced forage by crop c by household group h, in land type l, soil class s, at time period t or purchased crop residual by household group h, at time period t. The equation for livestock feed by household group h, at time period t, is as follows.

$$\begin{aligned}&\sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{fl=1}^{FL}\sum_{ct=1}^{CT}\sum_{c=1}^{C}\left(\mathrm{CROP}_{h,l,s,fl,c,t} \cdot \mathrm{CROPYL}_{h,l,s,fl,c,t}\right) \cdot \mathrm{stoyld}_{c} \\ &+ \mathrm{dm} \cdot \mathrm{CRESID}_{h,t} \geq \sum_{a=1}^{A} \mathrm{LIVPROD}_{h,a,t} \cdot \mathrm{drymreq}_{a}\end{aligned} \tag{30}$$

Milk production

The milk production in the watershed by household group h, at time period t, is estimated by multiplying the number of cows or she buffaloes in household group h, at time period t, milk production per cow or she buffalo per year and the proportion of productive cows or she buffaloes. The milk produced by household group h at time period t is either sold or consumed by the household groups.

$$\mathrm{amilkp}_{a1} \cdot \mathrm{pliv} \cdot \mathrm{LIVPROD}_{h,a1,t} = \mathrm{MPROD}_{h,a1,t} \tag{31}$$

$$\mathrm{MILCONS}_{h,t} + \mathrm{MILSAL}_{h,t} = \sum_{a1=1}^{A1} \mathrm{MPROD}_{h,a1,t} \tag{32}$$

Bullock labour constraint

In the watershed, farmers use bullock labour for land preparation, preparation of soil beds, transportation of produce from fields to houses and transportation of FYM to the fields. In the model, the demand for bullock labour days for household group h at time period t must be satisfied by the available bullock labour and through hiring of bullocks by household group h, at time period t in the watershed.

$$\sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{fl=1}^{FL}\sum_{ct=1}^{CT}\sum_{c=1}^{C}\left(\mathrm{CROP}_{h,l,s,fl,c,t}\cdot \mathrm{bullreq}_{l,s,fl,c,sa}\right) \le \mathrm{bavail}_{a2,sa}\cdot \mathrm{LIVPROD}_{h,a2,t} + \mathrm{BULHIRE}_{h,a2,sa,t} \tag{33}$$

Manure production

Organic manure (FYM) is used in the crop production to supply micronutrients along with inorganic fertilizers (urea and DAP). The manure production by household group h at time period t is limited by number of livestock produced and reared and collectable manure production by each animal type a of household group h, at time period t in the watershed. The manure production by each household group in year t in the watershed is given as

$$\mathrm{DMANURE}_{h,t} = \sum_{a=1}^{A}\left(\mathrm{LIVPROD}_{h,a,t}\cdot \mathrm{manpypa}_{a}\right) + \sum_{a=1}^{A}\left(\mathrm{LIVREAR}_{h,a,t}\cdot \mathrm{manpypa}_{a}\right) + \sum_{a=1}^{A}\left(\mathrm{LIVBUY}_{h,a,t}\cdot \mathrm{manpypa}_{a}\right) \tag{34}$$

The farmyard manure applied (MANUSE) in the fields by household group h at time period t must be less than the manure production (DMANURE) by household group h at time period t.

$$\mathrm{MANUSE}_{h,t} \le \mathrm{DMANURE}_{h,t} \tag{35}$$

Soil nutrient balance

Nutrient depletion in the soils is one of the main causes for soil degradation. A soil nutrient balance in the watershed at time period t is the net removal (inflow minus depletion) of nutrients from the rootable soil layer. Nutrient balances are computed using the following equation (Okumu et al. 2002).

$$\begin{aligned}\mathrm{NUTBAL}_{pn,t} = &\left[\sum_{c=1}^{C}\left(\mathrm{TCAREA}_{c,t}\cdot \mathrm{nutpha}_{c,pn,t}\right) + \sum_{c=1}^{C}\left(\mathrm{TCAREA}_{c,t}\cdot \mathrm{nitrofix}_{c,pn}\right) + \sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{h=1}^{H}\mathrm{area}_{l,s,h}\cdot \mathrm{nutdep}_{pn}\right] \\ &- \left[\begin{array}{l}\sum_{h=1}^{H}\sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{c=1}^{C}\sum_{fl=1}^{FL}\sum_{ct=1}^{CT}\left(\mathrm{CROPYL}_{h,l,s,fl,ct,c,t}\cdot \mathrm{npkconh}_{c,pn}\right) \\ + \sum_{h=1}^{H}\sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{c=1}^{C}\left(\mathrm{CROPRESY}_{h,l,s,c,t}\cdot \mathrm{npkconr}_{c,pn}\right) \\ + \mathrm{TSOILER}_{t}\cdot \mathrm{nleros}_{pn}\end{array}\right]\end{aligned} \tag{36}$$

Where,

Table 5 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

Authors' estimation

NUTBAL	Nutrient balance of N and P in time *t*
TCAREA	Total area of each crop *c* cultivated in the watershed in ha in time *t*
CROPYL	Grain yield of each crop *c* in land type *l*, soil type *s*, fertilizer level *fl* and household group *h* in time *t*
CROPRESY	Crop residual yield of each crop *c* in land type *l*, soil type *s*, and household group *h* in time *t*
TSOILER	Total soil erosion in watershed in time *t*
nutpha (c,pn,t)	Amount of nutrients *pn* applied on a unit (ha) of crop activity *c* through chemical fertilizers and FYM in time *t*
nitofix (c,pn)	Amount of nutrient *pn* added to the soil by crop activity *c*, e.g., nitrogen fixation
nutdep (pn)	Per ha addition of nutrient *pn* through atmospheric deposition
npkconh (c,pn)	Amount of nutrient *pn* contained in a unit grain of crop *c* harvested
npkconr (c,pn)	Amount of nutrient *pn* contained in a unit residual of crop *c*
nleros (pn)	Amount of nutrient *pn* in a unit of soil lost through erosion

Appendix 2: 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 was estimated using USLE, and the estimated values were presented in Table 5.

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