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ANALYSIS

Conserving energy in smallholder agriculture: A multi-objective programming case-study of northwest India

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Abstract

In semi-arid conditions in Northwest India, smallholder agriculture has made increasing use of subsidised mechanisation and energy inputs to reduce short-term risks. However, detrimental environmental consequences have occurred, not least a rapidly falling water table, and energy-intensive production is threatened by the prospect of increasing scarcity and expense of energy supplies, especially as urban demands are forecast to grow rapidly. This paper describes the energy flows through four subsystems of smallholder agricultural villages: the crop system; non-crop land uses; livestock systems; and households. It employs a multi-objective programming model to demonstrate choices available for maximands either of net solar energy capture or financial surpluses. Applied to three villages selected to represent major settlement types in the Saurashtra region of Gujarat, the results demonstrate that both energy conservation and financial performance can be improved. Although these results need qualifying because of the reductionist, linear character of the model used, they do provide important insights into the cultural role of mechanisation and the influence of traditional agricultural practices. They also underline the need for local energy conservation strategies as part of an overall approach to improved self-determination in progress towards rural sustainability.

Keywords: Energy conservation; Smallholder agriculture; Optimising model; India

1. Introduction

Energy is a fundamental ingredient in the process of economic development, as it provides essential services that maintain economic activity and the quality of human life. Thus, shortages of energy are a serious constraint on the development of low-income countries (WEC, 2000; IEA, 2001). Shortages are caused or aggravated by widespread technical inefficiencies, capital constraints and a pattern of subsidies that undercut incentives for conservation. Also, the world is likely in the medium to long term to

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become increasingly energy-scarce, particularly in oil. As easily recoverable supplies dwindle, unconventional sources such as oil shale and conversion from coal will become important, prices will rise and the probability of supply disruptions and price shocks will increase (IEA, 1998).

India was the world's sixth largest consumer of commercial energy in 1998—its use of 270.6 million tonnes of oil equivalent corresponded to about 13% of total commercial US consumption (BP Amoco, 1999). In absolute terms it is clearly highly dependent on global energy resources, although obviously per capita consumption is much lower (WEC, 2000). Indian commercial energy supplies come primarily from local coal stocks, which contributed 57%; oil, of which over two-thirds is imported, contributed 32%; and the remaining 11% was derived from natural gas, hydroelectricity and nuclear sources (TERI, 2000).

However, although India, in common with other low-income countries, has much lower per capita energy consumption than high-income countries, it correspondingly experiences energy shortages in meeting its growing industrial and household demands. Urban centres face worsening environmental problems from rapid and continued growth in the use of fossil fuels due to rising incomes and greater access to consumer products among middle and upper income groups. Over recent decades, shortages of coal and electricity have progressively increased, and various barriers impede progress towards energy efficiency including, conspicuously, subsidies that keep energy prices artificially low.

According to a report from IIASA (1998), energy shortages are compounded by disparities in economic activity and living standards, and a priority for decision-makers concerned with sustainable energy development in all countries is to extend access to commercial energy services to people who do not have it, and to coming generations who are likely to be similarly deprived. This problem is most acute in rural areas, where traditional fuels meet a quarter of India's total energy needs. Shortage of these has led to their substitution with lower quality fuels such as crop residues and dung cake, and greater efforts to extract fuel wood, with consequential degradation of vegetation cover (Qureshi and Kumar, 1996). Rapid population growth requires either intensified agricultural production or a substantial increase in cropped area, both of which imply an increase in energy input. Rural–urban migration trends suggest that, soon, insufficient additional human labour will be available in rural areas; and there is also little possibility of an increase in the availability of animal power, due to a slow reduction in pasturage area, competition for survival between humans and animals, and the increasingly uneconomic energetics of bullock farming (Rao, 1984). Hence, the energy shortfall may largely have to be made up by external sources of power for electric pumps, tractors and power tillers.

However, since growth in output is increasingly dependent on limited fossil fuel reserves, it seems that "...current agricultural techniques are unsustainable in the long run ... since present consumption of fossil energy has the effect of reducing consumption availability to future generations" (Conforti and Giampietro, 1997: 232). Thus, future energy scarcity is likely to radically alter price ratios, making it important to identify priorities to improve the efficiency and sustainability of smallholder agro-ecosystems in the subcontinent by minimising energy use whilst at the same time maintaining and (if possible) enhancing incomes. Continuation of the present technical path of agricultural development risks, at some stage, serious impairment of the incomes of poor rural people and their food security.

Our aim in this paper is to explore the possibility of maximising both net revenue and energy returns in the agricultural sector at village level to fulfil food, fuel and feed requirements. By using a multi-objective programming approach, trade-offs between optimal solar energy capture and financial surpluses are investigated; and changes in agricultural activities required to optimise energy use are explored to determine whether economic conditions and local energy utilisation of the village can be improved, and energy imports reduced. This technique is applied in the context of villages practicing smallholder agriculture in a semi-arid region of northwest India. The section following this introduction reviews energy studies in agriculture, particularly in the context of low-income countries. The next sketches the energy budgets of three representative villages chosen as case studies for further analysis.

The subsequent section sets out the framework of the modelling exercise undertaken to improve understanding of structural and dynamic aspects of semi-arid rural agro-ecosystems, as they currently exist, and to highlight both the long-term unsustainability of agriculture as practised in the region, and the implications of unsustainable energy use. The penultimate section reviews the results of the multi-criteria programming model, and the final section of the paper concludes by reflecting on the implications for policymakers and farmers concerned with the long-run sustainability of agriculture in the region.

2. Energy studies in agriculture

The importance of energy in agriculture was underlined by the dramatic increase in oil prices in 1973, when it began to be appreciated that most agro-ecosystems powered by fossil fuel in most high-income countries were outstandingly energy inefficient. For example Stanhill (1984) estimated that intensive agricultural systems in high-income countries required inputs of more than 10–12 units of fossil fuel energy to produce 1 unit of food energy output. Therefore, many subsequent studies have tried to formulate appropriate strategies for agricultural development in an energy-expensive future.

This concern drew attention to earlier pioneering studies providing a comparative examination of the energetics of the world food production system, carried out by Transeau, (1926), Odum, (1967), Pimentel, (1980). Traditional smallholder village ecosystems are sometimes thought to have low productivity due to a lack of external inputs and the inefficiency of human and animal power, for which the popular solution is increased mechanisation. However, Singh and Chancellor (1974, 1975) have shown that mechanisation does not necessarily increase productivity This is supported by Lee (1979), who reported that rice yields obtained from intensively mechanised farming in Japan were less than those of almost completely animal powered rice production in Korea. Similarly, Bhatia (1977) demonstrated that, for India, there is no cost or environmental advantage in using mechanical power, such as tractors, rather than bullock labour input. Close study of animal powered village agro-ecosystems in Asia and Africa suggests that village ecosystems consistently achieve higher yields than equivalent large mechanised farms, when nutrient inputs and other biotic factors are similar (Moerman, 1968; Chandler, 1979; Wortman, 1980).

With regard to energy efficiency, in Meghalaya, in north-eastern India, Mishra and Ramakrishnan (1982) carried out village ecosystem analysis for a typical khasi village ecosystem under slash and burn agriculture (jhum agriculture) at higher elevations, and concluded that although high energy input–output ratios were achieved, this depended critically on already overexploited renewable forest resources, and that horticulture, plantation and fuelwood production systems might be preferable. Kumar and Ramakrishnan (1989) also studied the village ecosystem function of some tribal societies of north-eastern India, in which jhum cultivation and its effect on environmental degradation, energy efficiency and crop production were considered. Their study revealed that a major input in shifting agriculture was human labour and that the energy efficiency (i.e. the net energy yield) of animal husbandry was low. Despite this, most food requirements of domestic subsystems were met from shifting agriculture, except for rice, which was imported to the village ecosystem. Pandey and Singh (1984) conducted a detailed study of three villages in the central Himalayas to investigate the energy efficiency of agricultural ecosystems with respect to agricultural activity. Although the study revealed that agriculture in these villages was energy efficient in terms of net energy yield, agronomic production coupled with the milk yield from the animal system was not enough to meet minimum energy requirements of villagers and, as a result, food-grains were imported from the market.

Traditionally, farmers have relied on experience, intuition and comparisons to make their decisions. It is only that, comparatively recently, widely available personal computers have developed to allow mathematical programming support for farm planning in more complex situations. These may be of some use in assisting farmers to adapt efficiently to a changing economic and technological environment. Coupled with the various studies of rural energy use in India, several models have been developed, by Joshi et al. (1992), Sinha and Kandpal, (1992), Srinivasan and Balachandra, (1993), Painuly et al. (1995), Malik et al. (1994), Raja et al. (1997) and Parikh and Ramanathan (1999a,b). In all these studies the traditional linear programming approach was used, seeking to maximise a single objective function and focusing on household energy at regional or macro level models.

However, hardly any such studies have been carried out in the villages of semi-arid agro-climatic zone of India, where water scarcity and high temperature are limiting factors for agricultural operations. Equally, it is clear that, whilst energy efficiency is of fundamental importance when considering long-term sustainability, recommendations that would lead to farmer impoverishment stand little chance of being adopted. Therefore, policymakers and advisors may almost certainly encounter multiple objectives with a need for simultaneous optimisation. As it is difficult (normally impossible) to optimise all objectives together, a preferred trade-off between several objectives is the best that can be achieved. One way of exploring trade-offs is the multiple objective programming technique, which seeks, subject to a given set of constraints, to find a subset of efficient solutions from amongst an entire set of feasible solutions. Some energy studies of this type have been conducted in India, prominent among which are those of Chetty and Subramanian (1988), Ghosh et al. (1995) for rural India as a whole and Singh et al. (1996) for a Punjab village. Given the lack of attention in the literature to the semi-arid agro-climatic regions of India, this paper focuses on the water-scarce region in the western peninsular region of Gujarat, which experiences frequent droughts and practices energy-intensive agriculture. In such circumstances, a study focusing on energy–agriculture linkages assumes considerable significance.

3. The energy situation of the case-study villages

An essential pre-requisite for modelling improvements in energy and financial efficiency is the identification of resource flows at village level for a semi-arid agro-ecosystem. The context of the analysis is the agriculture practised the Saurashtra sub-region, which contributes over 25% of total Indian groundnut production. Although smallholdings are predominant, mechanisation is becoming increasingly common, supported by state subsidies for tractors and other agricultural equipment. The region lies between 20°42′ and 2°33′ N latitude and 69°4′ and 72°18′ E longitude. The climate is hot, with rainfall of between 550–1000 mm annually. The sub-region is surrounded by sea on three sides, and the central part is hilly (although only a small portion has an elevation of 300 m above mean sea level) and has undulating terrain extending into plains towards the seashore. Two districts (Bhavnagar and Rajkot) were chosen as typical of the agriculture of the region as a whole (see Fig. 1). The major source of data for this study originates from farm surveys conducted in 18 villages within these two districts, chosen by a multi-stage random sampling procedure.

Drawing on the concept of the farm model for energy dynamics suggested by Odum (1983) and Han et al. (1985), four subsystems of the village ecosystem have been identified and explored: the crop subsystem, the non-crop subsystem (involving low intensity grazing land), the animal subsystem and the human subsystem. Variables allowing the identification of major energy and financial flows for each subsystem were collected by questionnaire for the production season of 1997/1998 (Table 1 provides summary information for crop inputs: further details can be found in Thankappan, 2003). Because of the sheer volume of data, three representative villages have been chosen from this survey by hierarchical agglomerative cluster analysis involving variables describing land area and village size, standard deviation of holding area and energy intensity. The villages closest to the cluster means at the three-cluster level of aggregation were selected in an attempt to represent different types of energy use.

Baghi is the smallest village of the three, encompassing 637 ha and, with a population of 1307, it had the highest population density. However, the distribution of land holdings was the least unequal of all the villages. 40% of the vegetables produced from the crop subsystem, 92% of the oilseeds and the entire cotton produced were sold outside the village. From the animal subsystem, households consumed 42% of

Fig. 1. Bhavnagar and Rajkot districts of Saurashtra region: location map.

the total milk produced, and 50% of the total dung production was used as fuel[1]. There was a deficiency of food-grains. In the survey year, total energy (including household commodities) imported into the village ecosystem amounted to 7199 GJ annually while the net total energy exported amounted to 18,135 GJ, In all the three villages, the energy imports included seeds for the next season, food-grains to make up for the shortage if any, cattle feed and fossil fuel-based imports included fertilisers, diesel for irrigation pumps and tractors. The energy exports in the villages included mainly crop products like oilseeds, cotton, vegetables and animal products included milk and wool.

Jamanvav is the largest village, with the least equal distribution of land holdings, and covers 1576 ha with a population of 1934. Groundnut is the important cash crop of the village, accounting for about 35% of the total cultivated area. Other kharif[2] crops cultivated in the village were cotton, pearl millet and sesame. Sorghum was cultivated for fodder, together with alfalfa, which is grown throughout the year with repeated harvests. Rabi[3] crops grown in the village included mustard, gram and wheat. Vegetables were also cultivated in a marginal piece of land. The overall performance of the village ecosystem shows 47% of the vegetables produced from the crop subsystem, 95% of the oilseeds and the entire cotton crop were sold outside the village. From the animal subsystem,

[1] Half the dung collected from animals was recycled back into the agro-ecosystem, while other half was dried and used as household fuel. The women and children generally responsible for livestock ensure the collection of dung while animals graze.

[2] Summer season (March to September).

[3] Winter season (October to February).

Table 1
Annual energy inputs (MJ/ha)

	Pearl millet	Wheat	Gram	Groundnut	Sesame	Mustard	Cotton	Sorghum
Baghi								
Seeds	132.83	2432.28	1048.78	3248.70	72.74	138.62	55.91	473.56
Human labour	5.60	0.61	9.14	2.85	8.620	8.38	5.78	4.30
Animal labour	11.56	2.66	32.32	2.30	21.537	17.89	30.96	10.51
Machine labour	37.75	10.82	30.25	73.73	26.125	30.74	54.26	79.02
FYM	–	–	140.08	101.96	–	–	–	–
Chemical fertilisers	7.20	1.76	22.85	10.93	10.495	11.51	113.65	6.29
Pesticide	–	–	10.99	–	–	4.58	23.47	–
Irrigation	8.38	3.51	18.74	12.12	–	23.10	60.82	15.20
Jamanvav								
Seeds	115.44	3774.09	1032.89	1727.81	60.21	123.60	51.63	4310.83
Human labour	8.89	34.31	23.85	19.90	17.55	16.40	26.63	11.25
Animal labour	14.95	74.77	80.56	20.05	24.17	49.35	19.76	10.73
Machine labour	266.11	872.12	453.00	358.33	388.94	334.11	1125.79	271.49
FYM	–	–	712.66	271.66	–	–	–	–
Chemical fertilisers	18.23	56.53	27.32	20.93	36.68	23.86	40.84	15.40
Pesticide	–	–	20.42	–	–	18.71	11.13	–
Irrigation	39.31	335.66	97.56	26.83	–	33.19	54.78	36.36
Kundaich								
Seeds	124.16	2370.71	1048.75	3080.66	64.37	138.67	55.97	454.67
Human labour	110,318.99	183,531.28	2802.07	318,098.29	13,902.45	13,867.36	16,311.93	109,259.94
Animal labour	1,000,707.65	1,514,864.00	5051.90	405,034.30	197,793.25	19,153.32	18,159.82	1,096,497.35
Machine labour	3,792,173.96	7,332,468.89	1654.77	6,739,658.42	12,208.22	15,040.60	16,358.79	4,978,438.34
FYM	–	–	6142.30	6366.20	–	–	–	–
Chemical fertilisers	772.09	979.30	57.87	1396.49	121.40	78.31	145.93	766.55
Pesticide			939.39			1698.46	2737.75	
Irrigation	–	7,534,354.68	–	872,074.34		1,470,926.19	1,361,101.33	–

76% of the total milk produced was consumed by the human subsystem, with the remainder, together with total wool production, exported to the market. In the survey year, 19,485 GJ of energy in total were imported in to the village ecosystem, while the exports amounted to 41,386 GJ.

Kundaich is also a large village, with a land area of 1434 ha and a population of 1529, but it has a less skewed distribution of landholdings and far more uncultivable land than either Baghi or Jamanvav. Groundnut was the major kharif crop grown, in about 74% of the cultivated area, while the other kharif crops were cotton, sesame, sorghum and pearl millet. During the rabi season, wheat, mustard and gram were cultivated, while vegetables were grown throughout the year with about 3 harvests per year. The entire food-grain output of the village was consumed in the village. Of the total vegetables produced, 47% were consumed within the village, while the rest were marketed. 8% of the total oilseeds produced were retained as seed, and the rest exported to the market, and households consumed 65% of milk production. In the survey year, imports of energy to the village ecosystem amounted to 10,785 GJ while total exports amounted to 71,785 GJ.

Detailed analysis of financial flows in the three villages reveals positive returns over direct cash expenses for crop subsystems in two villages, Baghi and Kundaich, while in Jamanvav the crop subsystem shows a substantial financial loss. Reasons for the high expenses in this village could be attributed to the increased spending on fossil fuel-based inputs and expenses on labour. Revenue from the crop subsystem was higher in Kundaich than in the other two villages, as a large percentage of fodder produced was sold externally, boosting total sales.

Division of the expenses incurred in the crop subsystem reveals that fossil fuel-based inputs formed a major component in the villages Baghi and Kundaich (96% and 64% respectively). Human labour[4] contributed less than 2% of cash expenses in Baghi, although rather more, 36%, in Kundaich. In the case of the village Jamanvav, the share of fossil fuel-based inputs was less (27%) and labour expenses were relatively high (73%). It might be argued that the financial returns from each village reflect a positive correlation between the fossil-based inputs and financial returns, significant from the perspective of the long-term sustainability of the region's agriculture.

4. Framework of the modelling exercise

The major consideration when formulating the a problem within a mathematical programming framework is to identify the forces that shape the productivity of energy use in village ecosystems and thereby estimate the changes in agricultural activities that are required to optimise energy use. We have chosen to model activities at village level as a means of simplifying the framework: this avoids the problem of accounting for inter-household transfers within the village, but also reflects the fact that custom and the influence of the village headman are important determinants of this type of smallholder agriculture. We also examine the interplay between two objectives: to date, researchers have mostly modelled decision-making either on the basis of economic criteria or energy efficiency. Finally, to focus the exercise, households have not been incorporated directly into the model; rather, only the points of interchange between them and the livestock, crop and non-crop systems have been accounted for, so that the quantitatively larger interactions taking place within the agricultural systems can be focused on. Fundamentally, the programming problem involved in modelling the rural energy system of a village and emerging consumption patterns involves finding a suitable way of cultivating *m* crops and rearing *n* livestock by using *r* external inputs corresponding to energy needs whilst meeting, at the same time, the objectives of maximising net energy outputs from the village agro-ecosystem and maximising financial net revenue from the village agro-ecosystem.

Formally, the maximands are:

$$Z_1 = \sum_{j=1}^{11} C_i e_i + \sum_{j=1}^{3} A_j e_j - \sum_{k=1}^{4} M_k e_k \tag{1}$$

$$Z_2 = \sum_{i=1}^{11} C_i y_i p_i + \sum_{j=1}^{3} A_j y_j p_j - \sum_{k=1}^{4} M_k p_k \tag{2}$$

Z_1 is diverted solar energy flow, C_i represents the ith land use, in hectares; A_j the jth livestock type, in head of animals; and M_k the kth external input in tonnes of fertiliser, pesticides and feed and litres of diesel fuel. The coefficients e_i, e_j and e_k convert crop and livestock outputs and external inputs into energy values expressed in megajoules. Z_2 is total income. The set of coefficients p_i, p_j, p_k denote prices per ton, in rupees, of each commodity while the coefficients y_i, and y_j denote the output of each commodity per hectare or per head.

The constrained optimisation of these maximands is based on the resource limits of the villages, in particular the land area, in which availability of land and crop rotation have been used to capture the effect of cropping intensity, and also the local needs of the village population and its livestock. All seed requirements are met from purchased inputs, except groundnut, where customarily seeds are saved from the previous season's crop. We have dealt with this by estimating the net yield of crops after seed inputs have been accounted for.

Nutrient requirements are supplied through the recycling of animal waste and from nitrogen fixed by leguminous crops, offsetting the need for chemical fertiliser purchases by the village. Human and animal labour availability determine crop labour intensity. Due to the abundance of labour in the region's villages, it has been assumed that the opportunity cost of labour is minimal such that labour is immobile in the short run, and there are no purchases of labour input from within or outside the village. In the village agro-ecosystem, animals play a dual role,

[4] In these villages, most farm labour is contributed by households and very little is hired; consequently, energy and financial inputs diverge significantly.

cows and buffaloes providing milk, while bullocks supply animal power. Both groups consume fodder and produce manure and therefore need to be related through the constraints to crop production and external energy input. The constraints applied to the maximands in Eqs. (1) and (2) are as follows.

Land use is limited to the total land available in the village, and uncultivable land is constrained to be a minimum of the existing area of the wasteland, effectively constraining the total potential cultivable area to a maximum. This constraint has been set since, generally and by definition, it is not possible to bring the wasteland under cultivation.

$$\sum_{i=1}^{10} C_i \leq \mathrm{TCL} \tag{3}$$

where TCL is the total cultivable land area available in the village.

Legume crops are an important component of the crop rotation cycle, and are grown approximately one year in three; therefore, the crop constraint has been set such that non-leguminous crops may not exceed 70% of the land area.

$$\sum_{i=1}^{7} \mathrm{NLC}_i \leq 0.7 \times \mathrm{TCL} \tag{4}$$

where NLC_i is the land area of the ith non-leguminous crop. Oilseed crops are also fundamental in the medium term, because of the region's economic dependence on them; hence these are constrained to be a minimum of 50% of the crop area.

$$\sum_{i=1}^{3} \mathrm{OL}_i \leq 0.5 \times \mathrm{TCL} \tag{5}$$

where OL_i is the land area of the ith oilseed crops. Although sesame and mustard are important oilseed crops, their acceptance is limited due to agronomic problems; therefore, a balance is required such that the area of groundnuts (considering the fact that groundnut is an important crop of this region) is restricted to that of the total area under the other two oilseed crops.

$$\mathrm{OL_g} - \mathrm{OL_s} - \mathrm{OL_m} \geq 0 \tag{6}$$

where, respectively, $\mathrm{OL_g}$ is the area under groundnut, $\mathrm{OL_s}$, the area under sesame and $\mathrm{OL_m}$, the area under mustard.

Vegetables are cultivated on accessible land in the village, primarily for local consumption, although after meeting the local needs any remainder is exported. The area under vegetables is therefore fixed at current levels.

Considering the fact that there is an abundance of labour (human as well as animal) in the villages in the Saurashtra region, the sum of human and animal labour requirements of each crop type is restricted to total availability in the village. Since women are normally responsible for the care of the livestock, each animal type is limited to 20% increase over the current level, on the assumption that this would be the maximum acceptable with the present gender division of labour.

$$\sum_{j=1}^{n} A_j \leq 1.2 A_j^* \tag{7}$$

where A_j^* denotes the current total of each livestock type.

Crop nutrient needs have been converted to the energy equivalent of manufactured nitrogen input, because nitrate input can, broadly, be assumed to represent the most significant energy flow involved. These nitrogen needs of the crops are met from animal manure and nitrogen fixed by the leguminous crops cultivated in the village, with the residual provided by external purchased inputs of fertilisers.

$$\sum_{i=1}^{10} C_i d_i - \sum_{j=1}^{3} A_j d_j - M_d \geq 0 \tag{8}$$

where the net nitrogen requirements per hectare of the ith crop (after allowing for fixation by leguminous crops) is d_i; the amount of nitrogen derived from manure per head of the jth animal type is d_j; and the total purchased nitrogenous fertiliser is M_d.

Animal feed requirements are met from a range of sources: crop by-products, fodder crops, and supplies collected from wasteland.

$$\sum_{j=1}^{3} A_j f_j - \sum_{i=1}^{6} C_i f_i - M_f \leq 0 \tag{9}$$

where f_j is the individual fodder consumption requirement of the jth animal type; f_i, the fodder obtained (either directly or as a residue) from each hectare of the ith crop; and M_f, purchased fodder inputs. Grazed fodder is an important constituent in cattle and buffalo diets, and consequently the area of wasteland provides an important constraint on animal numbers; f_j is the minimum fraction of total feed required from wasteland.

$$C_{11} f_{11} - \sum_{j=1}^{n} A_j x_j f_j \leq 0 \tag{10}$$

Only a fairly small quantity of pesticides[5] is used to control aphid attacks on gram, mustard and cotton, and the requirements of these are set equal to, or less than, total purchases. Similarly, the machine labour requirements involved in cultivation and irrigation have been expressed in terms of diesel fuel inputs per hectare, and are also set equal to, or less than, total purchases. We have chosen not to model households directly, for two reasons: firstly, because the magnitude of energy flows involved are relatively small, compared to the crop and livestock systems; and secondly, because households overlap with larger systems, whose effect is to add unnecessary complexity into modelling the sustainability of the agro-ecosystem. However, to complete the account, the removal of fuels from crop residues,[6] animal manure and wastelands need to be included. The total household requirement for energy in each village is derived from the overall population (estimated to be, on average, 428 MJ per person, following Painuly et al. 1995[7]), and is set equal to, or less than, fuel derived from crop residues and animal dung. The majority of requirements for household energy were primarily met from crop residues and animal dung; kerosene and biogas are used in a few households, but their contribution, being negligible, has been ignored.

$$(\mathrm{TP} \cdot R) - \sum_{i=1}^{3} C_i x_i - \sum_{j=1}^{3} A_j v_j - W_x \leq 0 \tag{11}$$

where TP is the population of the village, and R the annual energy requirement per person; x_i, the fuel energy obtained, per hectare, from the ith crop residue; x_j, the fuel energy per head from the dung of the jth livestock type; and W_x, fuel energy obtained from the wood collected from the wastelands.

Consolidating this section, and providing the data used in the examples reported in the next section, constraint matrices for each village are appended to this paper.

5. Trade-offs between solutions for energy and financial optimisation

Multi-Objective Programming (MOP) problems can be tackled in a variety of ways: for example, as a modified form of goal programming, formulating a minimax objective from weighted deviations from the solutions of the respective single objective function problems. However, as Kalrath and Wilson (1997) suggest, great care is required in selecting the nature and form of target variables, and simpler approaches may be preferred. In essence, the MOP approach replaces the traditional concept of optimality with that of efficiency, such that

$$\underline{\mathrm{Eff}}\, Z(x) = \left[Z_1\left(\underline{x}\right), Z_2\left(\underline{x}\right), \ldots, Z_q\left(\underline{x}\right) \right]$$
$$\text{subject to}: \ \underline{x} \in \underline{F} \tag{12}$$

where $\underline{\mathrm{Eff}}$ indicates the search for efficient solutions, and $\underline{F}$ is the feasible set. There are a number of methods by which the efficient set may be calculated; the simplest (especially in a problem involving two objective functions) is the constraint method (Romero and Rehman, 1989) where one of the objective functions is maximised while the other is parameterised and acts as a constraint. For example, when energy is optimised, parameter values for the financial

[5] Pesticide usage in Baghi, Jamanvav and Kundaich in the year of the survey was 0.003, 0.003 and 0.005 t/ha, respectively.

[6] The woody part of the crop plants especially from crops like cotton and sesame are collected from crop fields and used as household fuel, while the dried leaves are left to augment soil organic matter.

[7] Painuly et al. suggested this figure for the southern state of Karnataka; we assume that there is no significant variation in the socio-economic status between the two regions.

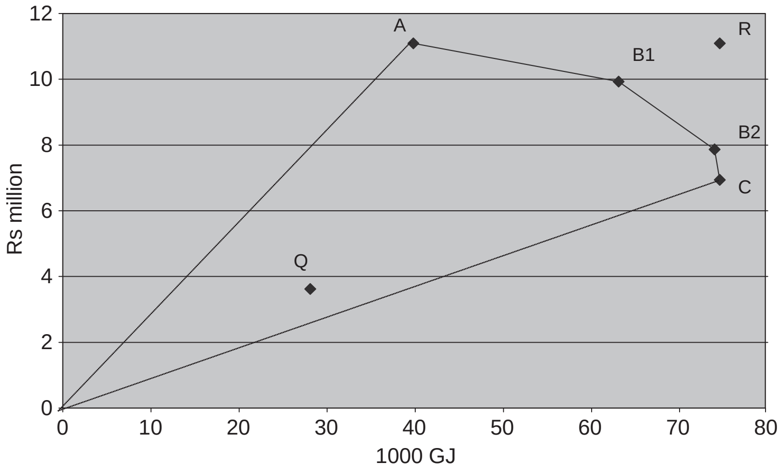

Fig. 2. Efficiency frontier: Baghi. Legend: A (Maximum Net Revenue), B1 (Turning Point 1), B2 (Turning Point 2), C (Maximum Energy Surplus), Q (Existing Position), R (Ideal Point).

constraint range from the total income implied by an optimal solution for energy alone, up to the total income implied by a financially optimal solution alone. This procedure is then reversed, allowing the efficient frontier set to be traced out.

Figs. 2–4, in turn, plot pairs of values of total energy and financial surpluses comprising the efficient set for each village (constraint matrices are appended to the paper). For comparison, each figure shows values for the existing position (labelled Q) and the "ideal" (the values, outside the feasible set, of the model optimised for energy capture and net revenue alone, labelled R). Assuming that equal weight is given to each objective, it is a simple matter to drop a perpendicular from point R to the efficient set, and moving from that point along the set shifts the balance of influence given to either one or other objective.

However, it is perhaps more interesting to examine the behaviour of the underlying activities as the trade-

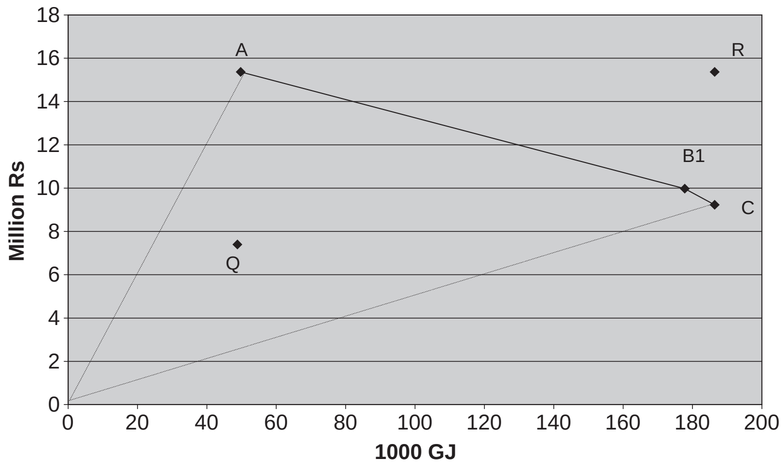

Fig. 3. Efficiency frontier: Jamanvav. Legend: A (Maximum Net Revenue), B1 (Turning Point 1), C (Maximum Energy Surplus), Q (Existing Position), R (Ideal Point).

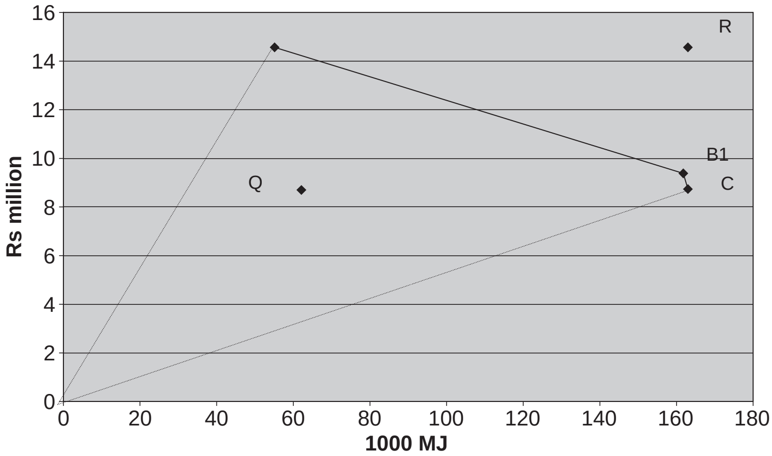

Fig. 4. Efficiency frontier: Kundaich. Legend: A (Maximum Net Revenue), B1 (Turning Point 1), C (Maximum Energy Surplus), Q (Existing Position), R (Ideal Point).

off between net revenue and energy maximisation shifts, and for each village this set has at least one (in the case of Baghi, two) turning points where this nature changes. The labelled points along the frontier, respectively, represent maximum net revenue (A), turning points, (B1, and B2 in the village Baghi), and maximum energy surplus (C).

The frontier for Baghi is the most classical in form, with increasing amounts of one objective having to be given up in order to obtain the other; however, Kundaich, and more especially Jamanvav, have a predominantly linear trade-off except for the portion between points B1 and C, where the amount of income required to be given up to obtain the optimum level of net energy capture intensifies sharply. Table 2 describes the trade-off in numerical terms, showing, for each segment of the efficient set, the amount of net revenue given up to obtain a specific unit of additional energy surplus.

Table 2
Trade-offs between net revenue and energy (Rs given up per GJ)

	A–B1	*B1–B2*	*B2–C*
Baghi	49.83	189.63	1544.74
	A–B1	*B1–C*	
Jamanvav	42.15	86.37	
Kundaich	48.59	538.07	

Table 3 provides original crop areas, livestock numbers and externally purchased inputs, and compares them with the model's optimum solutions for energy and finance at the two maximum points and the turning points. These provide convenient reference points around which to describe the changes in cropping patterns, livestock distributions and input use. Perhaps unsurprisingly, the existing position is far from the efficiency frontier, and in each case further than the frontier is from the ideal point.

In all villages, pearl millet, wheat, gram and sorghum drop out of the crop rotation altogether, reflecting their heavy nutrient demand (fertiliser is costly both in energy terms and finance) and relatively low energy capture and revenue generation. Also, no animal feed is purchased, since with the optimised cropping pattern sufficient feed resources are available from feed crops, cash crop by-products and wasteland grazing. Sesame is not cultivated at all in Baghi, although it appears in Jamanvav and Kundaich only as revenue maximisation receives predominant weighting. Mustard appears sporadically in the rotations of all three villages, but it only appears strongly in Jamanvav, declining after the turning point B1 as the weight of energy maximisation increases. However, for groundnut, cotton, and alfalfa, the patterns between villages are broadly similar. Groundnut, as a crop which is relatively input-efficient, profitable and

Table 3
Comparison of existing system variables with optima and turning points

	Baghi					Jamanvav				Kundaich			
	Q	A	B1	B2	C	Q	A	B1	C	Q	A	B1	C
Energy output (10^3GJ)	29.7	39.8	63.1	74.0	74.6	48.8	49.8	177.8	186.4	62.1	55.1	161.8	163.0
Total income (10^6Rs)	4.8	11.1	9.9	7.9	6.9	7.4	15.4	10.0	9.2	8.7	14.6	9.4	8.7
Land use (ha)													
Pearl millet	67.7	0.0	0.0	0.0	0.0	144.7	0.0	0.0	0.0	80.4	0.0	0.0	0.0
Wheat	44.2	0.0	0.0	0.0	0.0	19.3	0.0	0.0	0.0	53.2	0.0	0.0	0.0
Gram	14.3	0.0	0.0	0.0	0.0	28.7	0.0	0.0	0.0	17.4	0.0	0.0	0.0
Groundnut	275.8	136.0	136.0	136.0	136.0	322.7	356.1	356.1	356.1	783.2	299.7	299.6	299.7
Sesame	21.6	136.0	0.0	0.0	0.0	48.2	356.1	356.1	0.0	33.5	299.7	299.6	0.0
Mustard	32.6	0.0	136.0	136.0	136.0	64.3	0.0	0.0	356.1	26.5	0.0	0.0	299.7
Cotton	13.9	112.9	0.0	0.0	0.0	219.5	641.0	27.4	0.0	28.0	539.4	539.4	0.0
Sorghum	80.3	0.0	0.0	0.0	0.0	166.6	0.0	0.0	0.0	89.2	0.0	0.0	0.0
Alfalfa	23.7	79.2	193.0	271.3	271.1	21.8	0.0	683.5	710.9	38.9	42.3	42.3	596.9
Vegetables	0.7	0.0	0.7	0.7	0.7	1.3	0.0	1.3	1.3	2.3	0.0	0.0	2.3
Uncultivated land	89.6	169.5	167.9	89.6	89.6	150.0	221.2	150.0	150.0	231.5	252.6	252.6	235.1
Animal numbers													
Cows	63	0	13	518	49	313	132	132	0	168	299	299	0
Buffaloes	120	581	569	42	278	148	0	0	68	175	0	0	138
Bullocks	320	21	19	22	22	246	159	58	53	330	9	9	12
							136			343	136	271	277
External inputs													
Diesel (10^3l)	42.3	26.6	31.3	35.9	35.9	34.9	88.3	74.0	94.1	199.8	76.8	76.8	79.1
Fertiliser (t)	51.1	4.1	0.0	0.0	0.0	0.2	36.9	0.0	0	111.8	29.6	30	0.0
Pesticides (t)	0.2	4.0	4.8	4.8	4.8	1.2	22.4	1.0	12.5	3.8	18.9	18.9	10.5
Feed (t)	52.7	0.0	0.0	0.0	0.0	109.5	0.0	0.0	0.0	76.0	0.0	0.0	0.0

rotationally appropriate as a nitrogen-fixing legume, is a prevalent crop across the efficient set, although in Jamanvav and Kundaich its area declines as revenue maximisation is given more weight. Cotton is an important cash crop, and although absent in all three villages between points C to B1, it increases in area in more or less direct proportion to the emphasis on revenue maximisation towards point A. Alfalfa, conversely, from a maximum level between points A and B1, declines towards C. Uncultivated land increases in Baghi between points B1 and B2, having been stable between A and B1 and B2 and C, although at a lower level where energy rather than revenue is maximised. The reverse pattern appears in Jamanvav, where uncultivated land increases as energy maximisation is given more weight. In Kundaich, the model produces a broadly stable area of uncultivated land, comparable with existing levels.

With regard to livestock, far fewer bullocks are kept than at existing levels, with sufficient numbers only to meet cultivation requirements. In Baghi, there is an increase in overall animal numbers, reflecting the availability of uncultivated land for grazing, whereas in Jamanvav and Kundaich, lower overall land availability, relatively, requires a reduction in land area. Buffaloes and cows have an inverse relationship, revolving around the turning points. In Jamanvav and Kundaich, where revenues are maximised at point A, few if any cows are kept in the villages; at point C, the reverse is true, with the changeover occurring at point B1; and in Jamanvav, as uncultivated land rises to a peak prior to revenue maximisation, this provides extra grazing for a corresponding rise in cattle. In Baghi, the situation is more complex due to the greater initial availability of wastelands for grazing; buffaloes are kept at points A and C, but cows begin to displace them at point B1 as emphasis gradually shifts from revenue to energy maximisation, and rise to a peak at point B2 before falling back again at C.

Apart from the absence of feed, other external inputs to the system vary according to the cropping pattern. Diesel use for cultivations and irrigation varies fairly closely with the area of cultivated land, although in all villages, as cotton becomes more important, to some extent more diesel is required. No fertiliser is used in Baghi, reflecting the availability of nutrients from increased numbers of cattle; in Jamanvav and Kundaich, fertiliser use parallels the role of sesame in the rotation, increasing as revenue maximisation becomes dominant. In all three villages, the use of pesticide increases in line with the share of cotton in the cultivated area.

Some further explanation of the behaviour of these variables can be found in an examination of the slack and binding constraints at each point along the efficient set. When net revenue alone is maximised, the availability of sufficient animal feed is a binding constraint in Baghi and Kundaich, despite its availability for purchase externally, which suggests that it is very much more cost-efficient to use fodder crops and by-products for this purpose; at other points along the effective set, it is not a binding constraint. This partly explains the behaviour of cow and buffalo numbers, but the availability of grazing land is always a binding constraint on total animal numbers. Similarly, plant nutrients form a binding constraint in Jamanvav and Kundaich at point A, but not otherwise; other constraints governing the crop rotation become binding, contributing to an explanation of cropping patterns. The need for sufficient household fuel provides a binding constraint in Jamanvav, but only where energy is maximised at point C; animal labour, constrained by grazing resources, also provides a limit in Jamanvav except where net revenues are the maximand.

This clearly demonstrates that the nature of the trade-offs between social interests represented by energy conservation and individual interests represented by smallholder net revenue varies considerably according to land resources (both cultivable and waste), population size, and the way that these interact to produce specific patterns of exploitation under the restrictive assumptions that the multi-objective programming approach requires.

6. Implications for more sustainable smallholder agriculture

At the outset, the limitations of this approach ought to be outlined. Firstly, the case-study approach adopted gives clues to the identification of principal constraints and opportunities rather than contributing to the formulation of general rules and procedures. Second, even for the villages concerned, the models described in this paper cannot be prescriptive; their relatively simple form, particularly the linear character of the constraints, neglects the complex agronomic considerations that determine crop rotations and livestock nutrition. Third, modelling of this type can never hope to encapsulate the complexities of farmer or societal decision-making and reduce them to a finite set of unambiguous optimisable objectives. Whilst developments in expert systems (see, for example, McCown, 2002) might, to some extent, transform the type of information and analysis presented in this paper into practical recommendations for specific locations, our main message concerns the nature and direction of interventions required to make smallholder agriculture more sustainable, in terms of both energy conservation and farmer livelihoods.

In simple terms, the results suggest the need for major changes in current smallholder activity at the village level. The degree to which changes are implied depends largely on the availability of wasteland for livestock ranging, the size of village populations and the demand for household energy (primarily consisting of firewood for cooking purposes). An added emphasis on revenue maximisation features cash crops more strongly in the system (particularly cotton, a crop with significant demand for irrigation) and, at a certain point, a switch between cows and higher-cost, higher milk-yielding buffaloes occurs. With greater emphasis placed on energy maximisation, the shift towards less input-intensive cropping patterns causes, at the extreme, a sharp fall in incomes and scarcity of household fuel from crop residues and animal dung.

To some extent, these results may appear to conflict with the intuition of many anthropological and sociological developmental specialists that traditional cultivators are both 'economically rational' and the guardians of 'ecological wisdom' (see for example CRA, 1987; Cleveland, 1998). However, insights acquired during the survey phase of this study suggest broad reasons for the divergence between current practice and the activity patterns potentially required for overall energy efficiency and net revenue maximisation. As elsewhere, Indian farmers derive a sense of existential security from following the patterns of tradition which to some extent ensure their rationality and wisdom (Holt and Laury, 2002; Binswanger, 1980), but which also in times of rapid circumstantial change (notably in the areas of population growth and ecological pressure) may slow behavioural adaptation. As noted, the region is semi-arid, with irregular rainfall, frequent drought, and limited irrigation resources and facilities. In such conditions, smallholders are naturally risk-averse and more concerned with strategies to minimise crop failure than with optimisation (Huijsman, 1986).

A further facet of tradition is reflected in the livestock population at the time of the survey, and the fact that the model suggests that far fewer draft animals are needed. Therefore, maximisation of either model objective will need to contend with the cultural importance of the cow in the Hindu religious tradition. In fact, sufficient motive power exists within the villages from animal labour alone, and the divergence between current practice and potential energy efficient patterns lies in the observed tendency for smallholders, especially younger ones, to prefer mechanisation to traditional techniques. To some extent, this contradicts the adherence to tradition noted in the area of cropping patterns. Psychologically, however, mechanisation suggests a form of modernity that heightens self-esteem and social status, especially as the general process of development and the broadening of horizons weaken the traditional bonds of belief and culture. Mechanisation often appears irrational in a labour-abundant economy since its economic effect is to augment the productivity of labour. It is increasingly recognised, however, that a realistic understanding of rationality must go beyond economics.

Current policy either directly or indirectly subsidises energy-intensive activities, including fertiliser use, mechanisation and provision of electrical energy for irrigation pumps. In the short term, such actions might be justified in terms of encouraging agricultural modernisation, technical innovation and the spread of the market economy in rural areas. However, if in the medium term the cost of maintaining these subsidies becomes unsupportable, smallholders will be left with a set of technologies and a productive system unsuited to energy-scarce circumstances. This is likely to be particularly the case in terms of water availability. Groundwater resources are being depleted through over-withdrawal[8] and meager recharge from inadequate rainfall: to access groundwater, a tube well as deep as 200–300 m now needs to be drilled in this region, and the groundwater table is depleting at an average rate of 3–3.5 m every year, and in essence, water is starting to look very much like a non-renewable resource in this region, as in most other semi-arid regions with high population densities. Although in principle it is easy to argue that energy is being incorrectly priced in resource cost terms (Majumdar and Parikh, 1996), elimination of such distortions would have significant livelihood implications for agriculture as currently practiced (Singh et al., 1992). Therefore, the implications for policy appear to involve a number of diverse and small interventions which, together, encourage greater overall energy conservation (Parikh et al., 1996), including greater emphasis on nutrient conservation and recycling within the farming system (see for example Sharma et al., 2001; Parikh, 2000); improved efficiency in household fuel utilisation (Parikh and Ramanathan, 1999a,b; Painuly et al., 1992); and the development of greater drought-tolerance in the portfolio of crops available to smallholders. These micro-interventions, in conjunction with closer alignment of energy prices and the resource costs of providing energy, might improve the chances of a sustainable agriculture in an energy-scarce future, in which both energy efficiency and smallholder livelihoods can be simultaneously improved.

[8] Groundwater utilisation in the region stands at 42.56% and the groundwater balance in the region is 3363 MCM/year (MoA, 2001).

Appendix A

Table 1. Objective functions and constraint matrix for Baghi

	Ha											Head			Litres	Tonnes			
	Pearl millet	Wheat	Gram	G'nut	Sesame	Mustard	Cotton	Sorghum	Alfalfa	Vegetables	Waste	Cows	Buffaloes	Bullocks	Diesel	Fertilizer	Pesticides	Feed	
Objective Fn 1 (MJ)	26,147.2	21,096.9	20,312.2	33,746.2	9914.1	38,183.5	54,157.3	72,236.7	225,808.9	283,404.1	50,950.0	1932.4	6405.9	0.0	−38.9	−11,400.0	−363,284	−18,145.0	
Objective Fn 2 (Rs)	3600.0	5100.0	8150.0	9800.0	9500.0	9400.0	13,300.0	2000.0	3500.0	6500.0	0.0	8000.0	12,000.0	0.0	−9.8	−5784.7	−325.0	−35,000.0	
Total land	1	1	1	1	1	1	1	1	1	1	1								< 633.6
Cultivable land	1	1	1	1	1	1	1	1	1	1									< 544.0
Feed	1.50	0.85	0.00	1.02	0.00	0.00	0.00	1.99	6.40	0.00	2.04	−0.98	−1.68	−0.84				1	> 0
Nutrient	−0.045	−0.110	0.030	0.030	−0.045	−0.050	−0.050	−0.045	0.030			0.002	0.002	0.002		1			> 0
Pesticide			−0.007			−0.035	−0.035										1		> 0
Fuel					2.53	4.00	3.71				2.580	0.627	0.725	0.5					> 260.06
Non-legumes											1								> 89.6
Oilseed crops	1	1			1	1	1	1											< 380.8
Oilseed crop ratio				1	1	1													> 272.0
Machine labour				1	−1	−1													< 0
Vegetable limit	−30.0	−117.2	−44.3	−58.6	−30.0	−88.6	−88.6	−60.0	−58.6	−30.0					1				> 0
Animal limit												1	1	1					< 603
Grazing											2.04	−0.29	−0.59	−0.25					> 0
Animal labour	−13	−6	−8	−10	−9	−7	−10	−13	−8	−4				200					> 0
Human labour	370	20	65	685	12	8	140	300	30	105									< 2,240,000

Notes to the constraints: the land, cultivable land and vegetable area constraints are set equal to or less than current areas, whereas the wasteland constraint is set equal to or greater than current area; the feed constraint is set to equal or greater than zero so that the balance between forage from crop by-products and wasteland and animals nutritional needs is made up by purchased inputs; the same principle is applied to the nutrient, pesticide and mechanical energy constraints; the area of non-legumes is constrained to be equal or less than 70% of the cultivable area, and the proportion of oilseed crops to be equal or greater than 50% of the cultivable area; the oilseed crop ratio constraint ensures that groundnut, sesame and mustard are in a 2:1:1 ratio or greater; the animal and human labour constraints are set equal or less than current availability; the grazing constraint ensures that animal numbers are equal to or less than the available uncultivated land; the animal limit constraint constrains total numbers to a figure equal or less than 120% of the current population; and the fuel constraint is set to be equal or greater than current household needs.

Appendix B

Table 2. Objective functions and constraint matrix for Jamanvav

	Ha											Head			Litres	Tonnes				
	Pearl millet	Wheat	Gram	G'nut	Sesame	Mustard	Cotton	Sorghum	Alfalfa	Vegetables	Waste	Cows	Buffaloes	Bullocks	Diesel	Fertilizer	Pesticides	Feed		
Objective Fn 1 (MJ)	26,147.2	21,096.9	20,312.2	33,746.2	9914.1	38,183.5	54,157.3	72,236.7	225,808.9	283,404.1	50,950.0	1932.4	6405.9	0.0	−38.9	−11,400.0	−363,284	−18,145.0		
Objective Fn 2 (Rs)	3600.0	5100.0	8150.0	9800.0	9500.0	9400.0	13,300.0	2000.0	3500.0	6500.0	0.0	8000.0	12,000.0	0.0	−9.8	−5784.7	−325.0	−35,000.0		
Total land	1	1	1	1	1	1	1	1	1	1	1								<	633.6
Cultivable land	1	1	1	1	1	1	1	1	1	1									<	544.0
Feed	1.50	0.85	0.00	1.02	0.00	0.00	0.00	1.99	6.40	0.00	2.04	−0.98	−1.68	−0.84				1	>	0
Nutrient	−0.045	−0.110	0.030	0.030	−0.045	−0.050	−0.050	−0.045	0.030			0.002	0.002	0.002		1			>	0
Pesticide			−0.007			−0.035	−0.035										1		>	0
Fuel					2.53	4.00	3.71				2.580	0.627	0.725	0.5					>	260.06
Wastelands											1								>	89.6
Non-legumes	1	1			1	1	1	1											<	380.8
Oilseed crops				1	1	1													>	272.0
Oilseed crop ratio				1	−1	−1													<	0
Machine labour	−30.0	−117.2	−44.3	−58.6	−30.0	−88.6	−88.6	−60.0	−58.6	−30.0					1				>	0
Vegetable limit												1	1	1					<	603
Animal limit											2.04	−0.29	−0.59	−0.25					>	0
Grazing	−13	−6	−8	−10	−9	−7	−10	−13	−8	−4				200					>	0
Animal labour	370	20	65	685	12	8	140	300	30	105									<	2,240,000
Human labour	26,147.2	21,096.9	20,312.2	33,746.2	9914.1	38,183.5	54,157.3	72,236.7	225,808.9	283,404.1	50,950.0	1932.4	6405.9	0.0	−38.9	−11,400.0	−363,284	−18,145.0		

Notes to the constraints: the land, cultivable land and vegetable area constraints are set equal to or less than current areas, whereas the wasteland constraint is set equal to or greater than current area; the feed constraint is set to equal or greater than zero so that the balance between forage from crop by-products and wasteland and animals nutritional needs is made up by purchased inputs; the same principle is applied to the nutrient, pesticide and mechanical energy constraints; the area of non-legumes is constrained to be equal or less than 70% of the cultivable area, and the proportion of oilseed crops to be equal or greater than 50% of the cultivable area; the oilseed crop ratio constraint ensures that groundnut, sesame and mustard are in a 2:1:1 ratio or greater; the animal and human labour constraints are set equal or less than current availability; the grazing constraint ensures that animal numbers are equal to or less than the available uncultivated land; the animal limit constraint constrains total numbers to a figure equal or less than 120% of the current population; and the fuel constraint is set to be equal or greater than current household needs.

Appendix C

Table 3. Objective functions and constraint matrix for Kundaich

	Ha											Head			Litres	Tonnes			
	Pearl millet	Wheat	Gram	G'nut	Sesame	Mustard	Cotton	Sorghum	Alfalfa	Vegetable	Waste	Cows	Buffaloes	Bullocks	Diesel	Fertilizer	Pesticides	Feed	
Objective Fn 1 (MJ)	26,147.2	21,096.9	20,312.2	33,746.2	9914.1	38,183.5	54,157.3	72,236.7	225,808.9	283,404.1	50,950.0	1932.4	6405.9	0.0	−38.9	−11,400.0	−363,284.0	−18,145.0	
Objective Fn 2 (Rs)	3600.0	5100.0	8150.0	9800.0	9500.0	9400.0	13,300.0	2000.0	3500.0	6500.0	0.0	8000.0	12,000.0	0.0	−9.8	−5784.7	−325.0	−35,000.0	
																			> 55,120,004
Total land	1	1	1	1	1	1	1	1	1	1	1								< 1433.6
Cultivable land	1	1	1	1	1	1	1	1	1	1									< 1198.6
Feed	1	0		0				1	2		0	−1	−2	−1				1	> 0
Nutrient	−0.045	−0.110	0.030	0.030	−0.045	−0.050	−0.050	−0.045	0.030			0.002	0.002	0.002		1			> 0
Pesticide			−0.007			−0.035	−0.035										1		> 0
Fuel					2.51	4.10	3.71				3	1	1	1					> 629.63
Wastelands											1								> 235.1
Non-legumes	1	1			1	1	1	1											< 839.0
Oilseed crops				1	1	1													> 599.3
Oilseed crop ratio				1	−1	−1													> 0
Machine labour	−30.0	−117.2	−44.3	−58.6	−30.0	−88.6	−88.6	−60.0	−58.6	−30.0					1				> 0
Vegetable limit												1	1	1					< 807
Animal limit											0	0	−1	0					> 0
Grazing	−11	−16	0	−4	−2	0	0	−11	−2	0				200					> 0
Animal labour	1250	140	110	2690	55	65	2535	4720	170	0									< 2,430,000
Human labour	26,147.2	21,096.9	20,312.2	33,746.2	9914.1	38,183.5	54,157.3	72,236.7	225,808.9	283,404.1	50,950.0	1932.4	6405.9	0.0	−38.9	−11,400.0	−363,284.0	−18,145.0	

Notes to the constraints: the land, cultivable land and vegetable area constraints are set equal to or less than current areas, whereas the wasteland constraint is set equal to or greater than current area; the feed constraint is set to equal or greater than zero so that the balance between forage from crop by-products and wasteland and animals nutritional needs is made up by purchased inputs; the same principle is applied to the nutrient, pesticide and mechanical energy constraints; the area of non-legumes is constrained to be equal or less than 70% of the cultivable area, and the proportion of oilseed crops to be equal or greater than 50% of the cultivable area; the oilseed crop ratio constraint ensures that groundnut, sesame and mustard are in a 2:1:1 ratio or greater; the animal and human labour constraints are set equal or less than current availability; the grazing constraint ensures that animal numbers are equal to or less than the available uncultivated land; the animal limit constraint constrains total numbers to a figure equal or less than 120% of the current population; and the fuel constraint is set to be equal or greater than current household needs.

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