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Multi-objective spatial design principles for rural biomass energy planning

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Abstract Rural energy systems in India and much of the developing world continue to be dominated by subsistence biomass energy use. Participatory community-managed forestry practices such as joint forest management will be increasingly important for ensuring that the community commons and local biomass energy resources are sustainably managed. This paper demonstrates the use of remotely sensed landscape information, geographic information systems analysis, spatial optimization, and landscape ecology design principles for decentralized landscape-based biomass energy systems planning. The design process is illustrated with a case study from the Shivalik Hills of Haryana, India. The design objectives are improved accessibility and improved ecological sustainability of the biomass resource base.

Introduction

Rural energy is re-asserting itself at the top of the global sustainable development agenda. A spate of new reports by reputed development agencies recognize rural energy as the link between poverty alleviation, gender equity, sustainable livelihoods promotion, and even biodiversity loss and climate change mitigation—all aspects of sustainable development. *The Challenge of Rural Energy Poverty in Developing Countries*, a co-publication of the WEC (World Energy Council) and the FAO (Food and Agricultural Organization), states that sustainable development of the traditional energy sector could improve environmental sustainability, both locally and globally, mitigate desertification, alleviate rural poverty, and lead to energy and economic efficiency, and possibly even greater gender equity.

The World Energy Assessment: energy and the challenge of sustainability, a UNDP (United Nations Development Programme) and WEC co-publication (UNDP 2000), examines the inter-relationship between sustainable patterns of energy production, distribution, and consumption and the quality of life. Saying that 2 billion people have no access to commercial energy and that women and children are greatly taxed while procuring increasingly scarce biomass energy, the study advocates the efficient use of locally available resources.

Among the major hurdles to implementing rural energy on a large scale are (1) lack of institutional reform to channel credit and extension services to rural communities to facilitate technological transition and (2) lack of integrated conceptual models for intervention planning and design that address the scope of potential benefits. This paper introduces an integrated conceptual model for rural energy development using geographical design principles, which addresses the basic development objectives of improved physical access to biomass energy resources and minimal landscape-level ecological degradation. The design principles are illustrated with a case study from Haryana, India. We focus on improved biomass systems design because rural areas continue to depend greatly on biomass energy and because improved biomass management can bring various socio-ecological benefits (Ravindranath and Hall 1995). Our design methodology does not preclude the complimentary use of other locally available renewable energy technologies such as solar photovoltaics or micro-hydel.

Background

Energy in rural India

Officially, 86% of the villages in India are electrified. However, just over 30% of the rural households have electricity (TERI 1999a, p.270). More than 99% of rural electricity energy is consumed as shaft power, primarily for pumping water in the fields. Grid energy is highly unreliable and results in chronic equipment failure, an unwillingness to invest in agro-industrial post-harvest processing, and generally stunted rural socio-economic development (*The Economist* 2000; Ravindranath and Hall 1995).

Thus, rural households rely greatly on the traditional energy resource, biomass. Over 90% of the energy used by rural households for all uses (primarily cooking, space heating, and lighting) comes from biomass (Bose, Puri, and Joshi 1991; Ravindranath and Hall 1995; Shankar, Hegde, and Bawa 1998). The generally preferred fuel choice, fuelwood, supplies the largest fraction of biomass energy (56%), followed by animal dung (21%) and crop residues (16%). Kerosene supplies about 9% of the total rural primary energy, mostly for lighting (UNEP 1995). Only 2%–3% rural households have access to or can afford commercial cooking fuels like kerosene or LPG (liquefied petroleum gas) (TERI 1999a).

The overwhelming dependence of the rural sector on primitive biomass combustion for primary energy requirements is unsustainable, and pressure on the land to procure biomass resources, particularly fuelwood, is acute. India supports 18% and 15% of the global human and livestock populations respectively, with 2% of the world's landmass, 1% of the world's forest area, and 0.5% of the world's pasture land. Forest availability has decreased from 0.2 ha/person to 0.07 ha/person (700 m^2) (GoI 1999). The Indian Ministry of Environment and Forests (MoEF) estimates the annual sustainable yield from all forests at 115 million cubic metres and the demand at 200 million cubic metres (GoI 1999). Though logging and extension of agricultural land also lead to deforestation (World Bank 1996), biomass energy procurement is a major cause of incremental forest degradation and ultimately loss of biodiversity (D'Silva, Appanah, and Kariyawasam 1994; Ravindranath and Hall 1995; Shankar, Hegde, and Bawa 1998). If people do not have access to productive forests, they are forced to use lower quality biomass (animal dung and crop residue), which raises a host of ecological and gender-based health and equity issues (Cecelski 1987; Smith 1993).

Mahapatra and Mitchell (1999) describe the effects of decreased access to forests for fuelwood on households in 24 villages in two districts of Orissa. They considered the distance travelled to collect fuelwood as a proxy for scarcity and the effects of deforestation. The average distance travelled by people to procure fuelwood was 4.86 km, with 43.7% households in one district and 27.1% households in the other travelling more than 8 km to procure fuelwood. They urged a holistic look at the rural energy sector, which addresses the continued dependence of the rural populace on biomass energy, particularly fuelwood, and integrates energy and forestry issues. Others have advocated integrated rural energy and forestry policy (Revelle 1976; Agarwal 1989; Sarin 1995a; Sarin 1999), but community-based forest management strategies that actually succeed are new.

Integrating decentralized energy and forestry management

One of the bright spots in the last decade of environmental management in India is the afforestation of degraded common lands through community-based management known as JFM (joint forest management). Successful JFM projects (notably Sukhomajri Village in Haryana and Jhabua District in Madhya Pradesh) demonstrate that communities can improve the ecological resilience of their local landscape, increase food, fodder, and fuel production, and even improve biodiversity if they are allowed the greatest degree of self-governance and control over the regenerated resource (Sarin 1995b; Singh and Varalakshmi 1998a; CSE 1999). JFM is a historic policy shift towards democratic, decentralized resource management in India. Such a style of forest management is also increasingly being recognized as a key institutional model for rural energy design and a pre-requisite to successful rural electrification (WEC 1999). Expanding the mandate of decentralized community forest management to the wider objectives of integrated rural energy management requires a clear conception of institutional and physical design objectives. Shukla (1996) says the geographic design perspectives required for integrated rural energy planning are still lamentably lacking. Shukla states that locational optimization of infrastructure, land-use planning, decentralization, and major penetration of renewable energy can lead to a very low resource and emissions intensive economy. These measures, which have the most potential for climate change mitigation and sustainable development, are also, however, those least amenable – indeed effectively intractable – to conventional energy sector analysis.

Methodology

Overview

This paper introduces the use of modern geomatics technology (remote sensing and

GIS, or geographic information systems) and design principles based on location optimization and landscape ecology to tackle the geographic complexity of multi-objective rural energy planning. Assuming the fundamental intervention objective is to improve accessibility to biomass resources (Mahapatra and Mitchell 1999), the authors hope to develop ecologically sustainable designs of the biomass resource supply within the larger landscape context (CSE 1989, Pachauri 1993).

A pre-requisite to the design process is a JFM-style participatory rural extension programme engaging the target rural population. The assumed outcomes of this process are (1) an expression of community willingness to participate in a JFM-style afforestation programme and (2) a cadastral survey of the landscape, supplemented by remote sensing analysis, indicating the location of all villages, the existing forest structure, and appropriate locations for afforestation. Identifying priority afforestation areas should also consider improved watershed management, for example, by targeting high-risk erosion zones. Figure 1 gives a schematic representation of the results of such a survey.

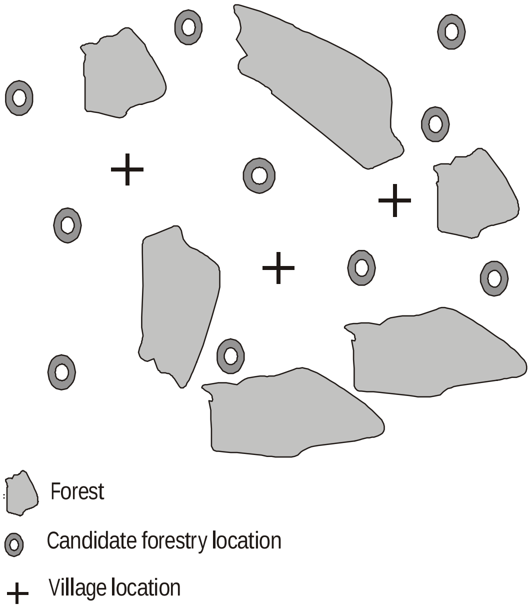


Figure 1 Schematic cadastral survey

Objective 1: improved accessibility

Objective 1 is readily formulated as a location–allocation exercise (described in the operations research literature as the ‘*p*-median problem’) (Love, Morris, and Wesolowsky 1988), wherein the objective is to improve the access to the biomass resource by reducing distances between the village and the resource. As stated earlier, Mahapatra and Mitchell (1999) provide the rationale for this design criterion. Figure 2 gives a schematic of such an accessibility-based design, which ignores the forest structure present on the landscape and seeks only to improve (by minimizing) this total distance criterion. The required size of the afforested area is determined by the total popu-

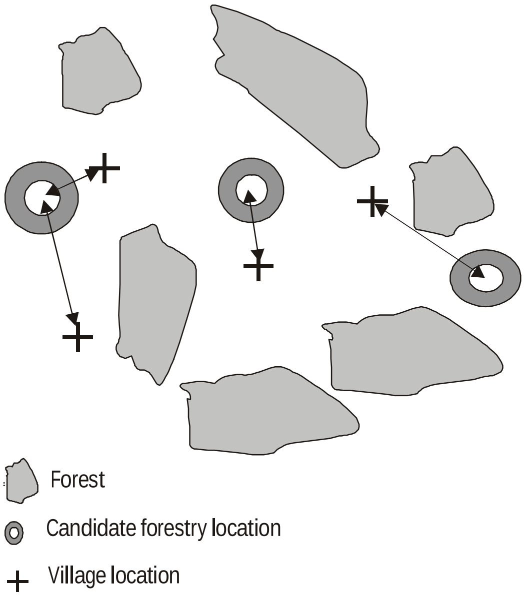


Figure 2 Schematic improved biomass accessibility

lation in all the villages that will be accessing it for domestic biomass requirements.

Objective 2: sustainable design of biomass resource

Ensuring the sustainability of the biomass resource within the landscape is not readily formulated as a variant of a classical operations research or location science problem. The problem is instead conceived as a 'landscape ecology' design problem, wherein the afforestation programme should enhance the ecological integrity of the existing forest. Landscape ecology provides a theoretical foundation for understanding the forest mosaic as an ecological process and structure and provides tools for measuring the degree of forest fragmentation (Forman 1995). Mitigating forest fragmentation is increasingly being recognized as critical for halting biodiversity loss (Franklin 1996). Indeed, the modern consensus in conservation biology and systems ecology is that species-specific conservation schemes are futile if the larger issue of habitat destruction is not addressed (Noss, LaRoe, and Scott 1995; Jennings 1995).

India is home to seven per cent of the total global biodiversity (GOI 1999), yet this invaluable resource is under unrelenting stress. Menon and Bawa (1997) documented the extent of forest fragmentation in the Western Ghats by measuring the breaking up and isolation of forest fragments using remote sensing and GIS-based quantitative landscape ecology. The severe threat to biodiversity conservation that Menon and Bawa describe is ubiquitous in India. The MoEF estimates that 42% of India's forests have already been degraded (GOI 1999). Retarding the cause of biodiversity loss – the continued loss and fragmentation of existing forest cover – is a stated objective of the National Forestry Action Programme (GoI 1999). This can be closely coupled to community-level biomass energy planning. Figure 3 gives a schematic of an afforestation scheme to minimize forest fragmentation.

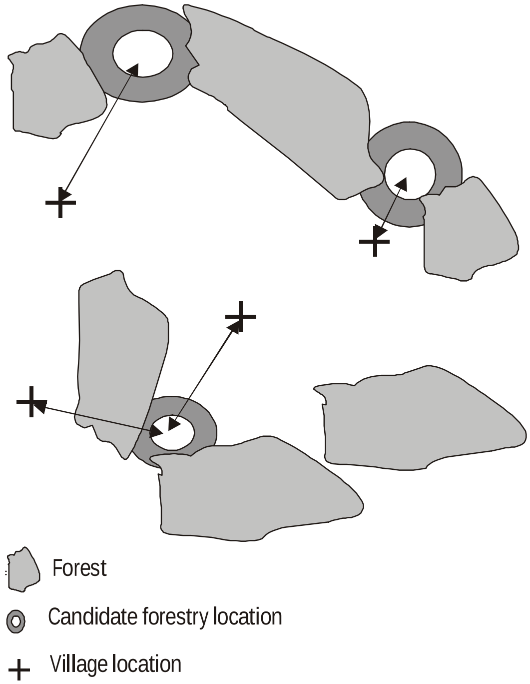


Figure 3 Schematic minimized forest fragmentation

Application: the Shivalik hills study area

Historical and socio-ecological context

We apply spatial design principles to a rural energy planning exercise in a semi-mountainous region, the Shivalik Hills, in Haryana. The Shivaliks span about 20 000 km^2 across Punjab, Haryana, and Himachal Pradesh, in the sub-montane ecological zone of the Himalayan foothills. The region is characterized by erratic rainfall, extremes in temperature, and unreliable hydrology. Thus, it is essential to maintain vegetative cover to mitigate the risk of erosion. Figure 4 shows the location of Haryana and the Shivaliks.

Figure 4 Location map: Haryana; Shivalik Hills

Historically, the Shivaliks supported dense forest. In 1806, British administrators began managing the Shivalik forests to extract large quantities of timber for the Royal Navy. In 1822, the hillsides were divided among the villages, and the subsequent forest clearing for cultivation and intensified grazing severely degraded the hills ecosystem. In 1916, a traveller, Patrick Fagan, said the Shivaliks were 'as barren as the mountains of the moon' (cited in Singh and Varalakshmi 1998a, p.27).

The Punjab Land Preservation Act (1900), which aimed to slow down landscape degradation in the hills ecosystem, open grazing in fragile areas, and the lopping of trees, annulled traditional rights of pasture, wood-cutting, and conversion of forest lands for cultivation. The Act was largely ineffective, and only escalated tensions between the forest department and the hill communities. In 1939, the Ambala Soil Conservation Division, a special branch of the forest department, was established to control soil erosion and restore vegetation. The Soil Conservation Division can be credited with the first attempt at participatory resource management in the hills. Government policy focused on forcing people to accept voluntary forest closure. By 1942, the government resorted to compulsory forest closure, again inciting conflicts with the hill communities over usufruct to fuel, fodder, and pasturage.

In the 1970s, the Sukhna Lake catchment in the Shivaliks was heavily silted, underlining the severity of landscape degradation in the region and motivating another concerted effort at participatory forest management (Singh and Varalakshmi 1998a). The Chandigarh Centre of Central Soil and Water Conservation Research and Training Institute and the HFD (Haryana Forest Department) pioneered participatory watershed rehabilitation techniques. Water harvesting methods in the Sukhomajri watershed (and later replicated at Nada Village) raised agricultural productivity to such an extent that it boosted community confidence and interest in forest protection measures.

The success of Sukhomajri in community-based natural resource management is well documented: between 1976 and 1992 average tree density rose from 13/ha to 1272/ha (CSE 1999). Singh and Varalakshmi (1998a) attribute the success to HFD's recognition that increased forest productivity had to be shared with the villages. Sukhomajri demonstrates that communities can break free from the vicious cycle of ecological and socio-economic impoverishment. Among the most notable successes at Sukhomajri is the advent of HRMS (hill resource management societies), community institutions that delineate responsibilities and distribute benefits of ecosystem regeneration.

The HFD has since attempted to replicate the successes of Sukhomajri and Nada in 39 Shivalik villages. Only 20% of the target villages have managed to establish HRMSs and secure benefit-sharing agreements with the HFD. Singh and Varalakshmi (1998a) say these villages lacked the cooperative spirit of Sukhomajri and Nada and that these experiments failed largely because community rights and responsibilities were poorly defined and there was no clear policy regarding benefit sharing.

Current status of Shivalik land resources

Figure 5 gives the current status of forests in the Shivalik Hills in Haryana (TERI 1999b). The information has been aquired from multispectral imagery via the IRS 1B LISS - II satellite system (imagery acquisition dates: 5 and 6 April 1999; sensor resolution: 36.2 metres). The imagery covers a 2091-km^2 region in the districts of Ambala and Yamunanagar. The border with Himachal Pradesh defines the northern boundary of the study area. The region's most notable feature is the very small amount of extant non-degraded forest. The landscape planning process focuses on these

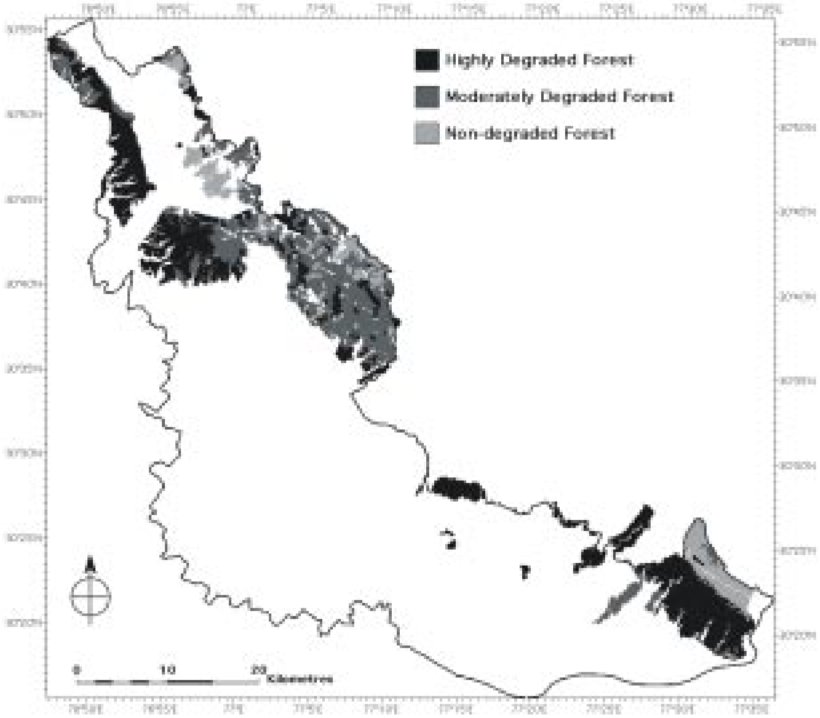


Figure 5 Haryana Shivaliks: forest status

remaining forest fragments as the 'ecological nuclei', providing the basis for afforestation systems planning.

Spatial decomposition

For institutional and computational tractability, the landscape design process requires a spatial decomposition of the entire region into smaller planning units. The concept of 'spatial energy catchment' is introduced. It is based on the notion that an energy demand centroid (defined as the population weighted centroid of a village cluster) exerts a radial zone of influence that defines the geographic region from which the village centroid can economically acquire biomass. Voronoi polygons describe such zones of influence and are defined by mapping the regions that contain all locations closer to its centroid than any other centroid (Okabe, Boots, and Sugihara 1992). Molecular physics, astrophysics, materials science, biochemistry, geology, ecology, and archaeology, all of which require some definition of point pattern regions of influence, apply Voronoi analysis. The Voronoi description is practical for systems that rely strongly on biomass. A fundamental process in such systems will be the flow of biomass along the shortest path distances towards the energy demand centroid, irrespective of watershed or jurisdictional boundaries (Joshi and Sinha 1993).

Current biomass energy systems planning practice implicitly recognizes the spatial zone of influence governing biomass flow. In a biomass resource study in Haryana for the Ministry of Non-conventional Energy Sources, TERI (1999c) drew attention to the artificiality of imposed political jurisdiction (block) boundaries on the resource assessment: 'an informal market exists in the area, which operates much beyond the study area, to bring in the biomass'. In a similar study in a hilly region of Arunchal Pradesh, TERI (1999d) assumed a radial 'zone of influence' (15–20 km) on biomass supply for a proposed 1-MW rural power project. The spatial generalization of these radial zones of influence is in fact a 'spatial tesselation' (Okabe, Boots, and Sugihara 1992) that generates Voronoi polygons. This concept has not yet entered the rural energy literature or rural energy planning practice.

A '*k*-means' clustering algorithm (Griffith and Amrheim 1997) based on the size and location of villages within the greater study area is used to identify demand centroid locations. Figure 6 illustrates the resulting spatial tesselation and highlights the region-of-interest and the remaining non-degraded forest fragments within it. The region-of-interest was extracted for detailed design. It straddles the districts of Panchkula and Ambala and is known locally as the Morni Hills. The villages and the non-degraded forest in the Morni Hills catchment are shown in Figure 7. The Morni Hills catchment contains some of the few remaining non-degraded forest fragments in the entire greater study area. The people of Ambala and Yamunanagar districts are more dependant on fuelwood than the rest of Haryana (TERI 1999a). The Morni Hills catchment will be used to illustrate the essential biomass system design concepts.

Figure 6 Haryana Shivaliks: spatial tesselation and region-of-interest (Morni Hills) extraction

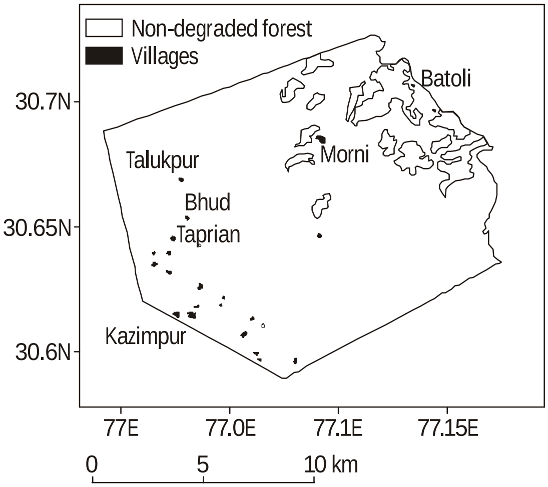


Figure 7 Morni Hills: villages and non-degraded forests

Accessibility design

The *p*-median accessibility problem is constructed by generating candidate afforestation zones from the patches of degraded forests and generating demand points at the centroids of the villages. The afforestation zones will be the places from where the communities will acquire their biomass energy supply. In practice, selecting candidate zones for afforestation should be closely coupled with watershed development planning, ideally using GIS-based analysis. Figure 8 illustrates the village supply allocations for the *p*-median solutions (the $p=3$ and $p=7$ cases), the improvement in the total accessibility (measured as a decrease in population-weighted distance), and the average biomass supply distance. The average biomass supply distance is related to the total accessibility and decreases as the accessibility improves, but is not weighted by the population of individual villages. The existing non-degraded forest is shown in the *p*-median solutions for perspective. The *p*-median algorithm attempts to minimize the population-weighted distance (the total accessibility) by optimally selecting candidate afforestation sites. Selecting the best candidate supply zones by 'brute force' enumeration of possibilities is computationally intractable even for relatively small problems such as these (40 candidate afforestation sites)—requiring the evaluation of 54 000 and 94 billion scenarios for the $p=3$ and $p=7$ cases respectively. It is a modern and flexible approach to solve combinatorial problems such as the *p*-median problem. The use of 'genetic algorithms' is adopted for this analysis.

The *p*-median solutions in Figure 8 indicate that villages will effectively share the forest resource. The 'real-world' practicality of such designs can only be evaluated through field extension. In many cases, sociocultural divisions between villages will preclude cooperative resource management. However, as Singh and Varalakshmi (1998b) note, the sociocultural divisions between villages may be no more acute than within villages, and JFM success stories indicate that such differences can be surmounted by clearly defining rights and responsibilities. When demarcating the forests falling under the protection and jurisdiction of local JFM resource management societies (such as the HRMSs in the Shivaliks), 'neighbouring villages which have traditionally been using the same forest area' must be consulted. Cooperative forest use is not only possible—it is historically the rule. Clear and equitable demarcation of forest access rights to the same forest is essential for cooperative forest management. Singh and Varalakshmi (1998b), in fact, advocate engaging all neighbouring stakeholders in defining access rights: 'conflicts over access between neighbouring villages to the same forest resource may be lessened if both villages participate in the protection and regeneration of presently degraded forest, cultivating a sense of joint ownership'.

Landscape impact of afforestation / biomass energy supply programmes

The accessibility-based design methodology looks only at improved access to domestic

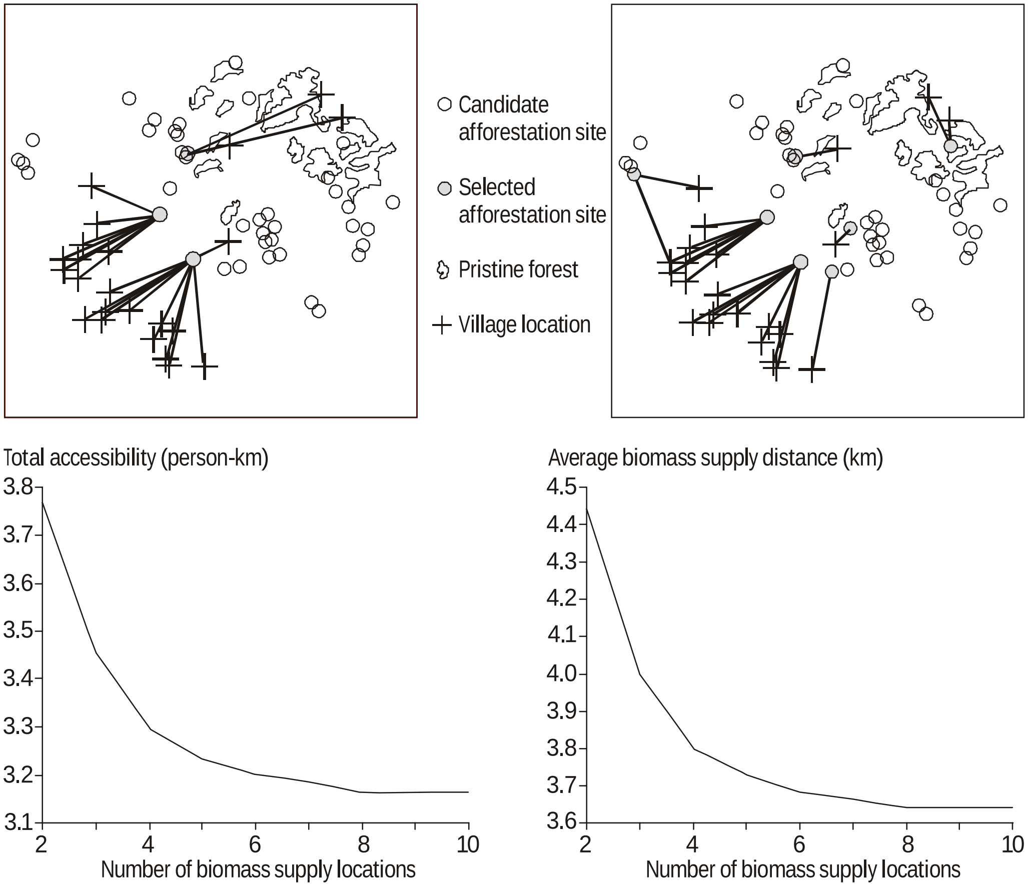


Figure 8 *p*-median optimization results

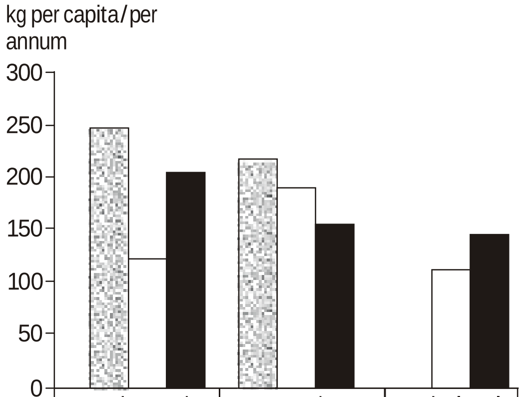
biomass energy supplies. High efficiency conversion of biomass to electrical energy through a gasification–combustion process is a promising technology with wide applicability for decentralized rural power, and it is the second key conceptual component of integrated rural energy design (Ravindranath and Hall 1995). The basic conversion technology has been known for decades; however, poor reliability has delayed wide-scale field deployment. This may soon change: sustained research and development in biomass gasifiers has demonstrated robust designs well suited for rural power applications (Ravindranath and Hall 1995, Khosla 1999). Rural biomass power installations can potentially give the economic rationale for JFM-style afforestation programmes to provide the requisite gasifier feedstock (Jain 1996). The upfront investment costs remain onerous for rural applications in developing countries. However, a new multilateral investment source, called the CDM (Clean Development Mechanism), is evolving.

Rural biomass energy and climate change mitigation

The CDM, proposed under the Kyoto Protocol of the UN FCCC (United Nations Framework Convention on Climate Change), enables developing countries to sell GHG (greenhouse gas) emissions credits to emitters of GHGs in the developed world who are obliged to reduce emissions under the Kyoto Protocol (Khosla 1999). In principle, afforestation (which sequesters atmospheric CO_2) and biomass gasification (which reduces dependence on fossil fuels) are eligible investment vehicles under the CDM. DESI Power Pvt. (India), a not-for-profit agency, currently manages the installation and operation of six village-based biomass gasifiers, financed by the Dutch government through the prototype CDM. In 3 years of operational experience, DESI has demonstrated that introducing reliable biomass energy will stimulate artisanal industry and employment (Khosla 1999).

The landscape impact of forests managed by the community for both domestic and commercial energy will be significant. Ecologically sustainable forest management practice typically assumes that no more than the MAI (mean annual increment) is harvestable in a given year. The MAI is defined as biomass growth (in tonnes/hectare) as a percentage of the standing forest biomass stock (tonnes/hectare). The MAI varies as a function of species type, climatic zone, soil and hydrological conditions, and forest health. Some generalizations are possible however: for natural forests of mixed species the MAI will be 1%–2%, while the MAI for a managed plantation forests will be 2%–4% (Shankar, Hegde, and Bawa 1998). For the Shivalik case, the standing biomass growing stock is assumed at 160 tonnes/hectare and MAI at 2%, resulting in a net sustainable wood supply of 3.2 tonnes/hectare/year.

The landscape impact of afforestation programmes will depend on both the forest productivity and the demand for fuelwood. The typical rural biomass energy demand pattern in Ambala and Yamunanagar districts, all-Haryana, and all-India is shown in Figure 9. Figure 10 shows three landscape impact cases (p=5), relative to the existing non-degraded forest, of afforestation schemes designed to supply (1) a basic fuelwood demand of 200 kg/person/year, (2) 200 kg plus 100 kWh/person/year electrical energy, and (3) 200 kg plus



	Firewood	Dungcake	Agricultural residue
▨ Ambala and Yamunanagar	250.4	219.7	0.0
☐ Haryana average	124.1	191.4	113.8
■ All India average	206.8	157.6	147.2

Figure 9 Biomass energy consumption (TERI 1999a)

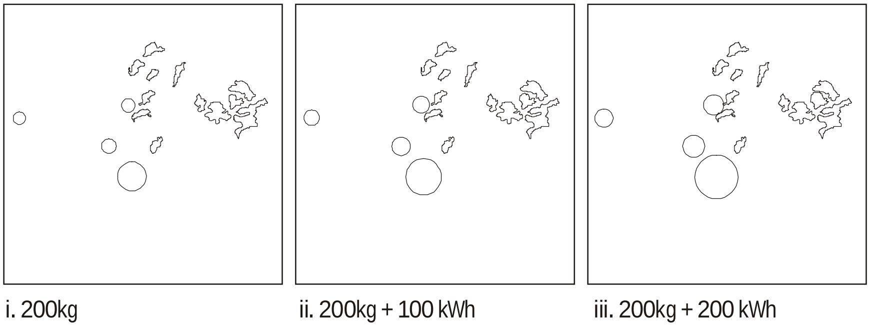

i. 200kg
ii. 200kg + 100 kWh
iii. 200kg + 200 kWh

Figure 10 Landscape design: spatial impact

200 kWh electrical energy through a rural biomass gasification scheme. The assumed wood energy content is 30 GJ/tonne and total conversion efficiency is 30% (Bain, Overend and Craig 1997). The large spatial impact in the last two cases is in part attributable to an assumed 50% ecological reserve requirement, but it would be large even without it. The reserve requirement allows forest harvest for electrical energy from only 50% of the total growing area, which is intended as 'insurance' for ecological sustainability. The reserve requirement is similar in concept to the multiple-use-module in conservation biology planning, wherein an inner forest core area is restricted and multiple uses, including energy harvest in this case, are permitted in the outer forest zones (Noss 1986).

Biomass energy and landscape ecology

Rural electrification schemes based on community forest management and biomass gasification will, evidently, exert a large landscape impact even at very modest electrical energy demand levels. The impact on the local ecosystem and local biodiversity will be significant and generally positive, particularly if sound landscape design principles are followed (Paine, Peterson, Undersander et al. 1996; Bell 1994). Ravindranath and Hall (1995) and Agarwal (1987) caution against the use of monoculture energy forestry plantations, as several decades of experience in social forestry indicates that monoculture plantations are socially and ecologically harmful. Bell (1994, p. 57) stresses the need to integrate the energy harvesting regions smoothly within the existing forest structure 'tying them into the landscape'. Bell also advocates the use of curvilinear, rather than rectilinear, forest features. This ecological design principle is usually attributed to Diamond's (1975) original studies in island biogeography wherein he argues that a circular shape provides the most dispersal opportunities for species, thus minimizing local extinctions. Apart from these largely qualitative design criteria, literature on formal landscape design principles for biomass energy systems planning is scant. The quantitative revolution in landscape ecology, however, provides modern analytical tools to formalize the design process.

Quantitative landscape ecology is revolutionizing forest management, contributing new spatially-based concepts, which, in essence, relate forest ecosystem health to the spatial configuration of forest patches on the landscape. The first available suite of landscape ecology indicators, *Fragstats* (Marks and McGarigal 1994), provided forest planners with a consistent set of measurements for analysing increasingly ubiquitous remotely sensed forest data. Forest planners could now manage (and in principle, optimally design) forests to minimize fragmentation, which research has increasingly identified as the underlying cause of habitat and biodiversity loss (Jennings 1995).

The biomass energy landscape design process demonstrated in the Shivalik Hills focuses on the MPI (mean proximity indicator), one of several dozen *Fragstats* indicators documented by Marks and McGarigal (1994). Other landscape ecology indicators, such as the perimeter/area ratio used by Menon and Bawa (1997) in their biodiversity conservation planning exercise in the Western Ghats, are equally valid. The MPI is a strong indicator of the degree of forest fragmentation, increasing as forest patches become less isolated and their distribution less fragmented (Marks and McGarigal 1994). The MPI (dimensionless) is defined for a particular land class such forest, as

$$\mathrm{MPI} = \frac{\displaystyle\sum_{j=1}^{n}\sum_{s=1}^{n}\frac{a_{js}}{h_{js}^{2}}}{n}$$

where a_j is the area of the jth patch of forest and s denotes all patches other forest patches within a threshold distance, d of the jth patch, h_{js} is the edge-to-edge distance between patches and n is the total number of patches on the landscape. The MPI thus increases as both the average patch size increases and the average proximity of patches increases. The threshold distance d, in this case, is set to a large value so the entire landscape is considered in all analyses.

Participatory multi-objective landscape design

Two competing objectives for community-managed afforestation design have thus been defined. A design optimized for accessibility will tend to disperse the forest resource base, while a design based on landscape ecology will tend to maximize the compactness of the forest. Multi-objective analysis (Jannsen 1992) can help formalize the process of selecting between alternative designs. The genetic algorithm, spatial optimization (accessibility), and landscape ecology evaluation modules were all implemented as linked routines in the Matlab™ programming environment (MathWorks 2000). Candidate designs were ranked according to their accessibility and MPI performance. The best-performing candidate designs were then selected by the genetic algorithm and used to generate better candidate designs according to standard genetic algorithm operations (Holland 1992).

Figure 11 illustrates the essence of multi-objective analysis. If the optimization weights the first objective at 100% and the second objective at 0%, the solution will lie on the horizontal axis in Figure 11 and will have the best possible performance for respect to Objective 1, but the poorest performance for objective 2. Similarly, if the second objective is weighted at 100% and the first at 0%, the solution will lie on the vertical axis. Weighting solutions between 0% and 100% will produce solutions

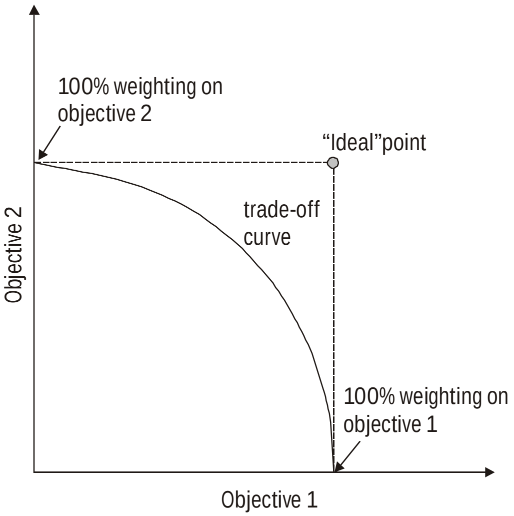


Figure 11 Schematic multi-objective analysis space (two-dimensional)

on the 'trade-off curve' or the 'efficient frontier', defined as the locus of solutions that can improve with respect to one objective only if a decrease is accepted in the other objective. The 'ideal' point represents the best possible performance with respect to both objectives, but is not a feasible solution. The multi-objective analysis essentially means deciding where along the efficient frontier the acceptable compromise between objectives lies. Table 1 shows the results for four different cases ranging from 100% priority weighting on accessibility maximization (total weighted distance minimization) to 100% priority weighting on landscape ecology (MPI) maximization. The performance scores are normalized in Table 1 for the multi-objective analysis, with 1.00 representing the best possible score and 0.00 representing the worst possible score for both the accessibility and the landscape ecology criteria. Figure 12 shows the corresponding landscape designs for the four cases.

All cases illustrate the landscape impact of an afforestation design to sustainably supply per capita demands of 200 kg wood and 200 kWh electrical energy, and show the euclidean (straight line) accessibility distance. Figure 13 illustrates the trade-off curve for this analysis. Design 4 is clearly unacceptable as accessibility is greatly compromised to maximize forest compactness. Design 1 is a poor candidate design as well. Designs 2 and 3 provide a large gain in MPI with little penalty in total accessibility. The appropriate design decision in this case would likely be to explore other cases between 2 and 4 in consultation with the affected communities.

Table 1 Multi-objective optimization results

	Objective weighing		*Performance*			
			Accessibility		*Landscape ecology*	
Case	*Accessibility (%)*	*Landscape ecology (%)*	*Person-km*	*Normalized person-km*	*MPI*	*Normalized MPI*
1	100	0	32 536	1.0000	285	0.0000
2	75	25	32 901	0.9919	779	0.3284
3	50	50	37 451	0.8912	993	0.4707
4	0	100	77 719	0.0000	1789	1.0000

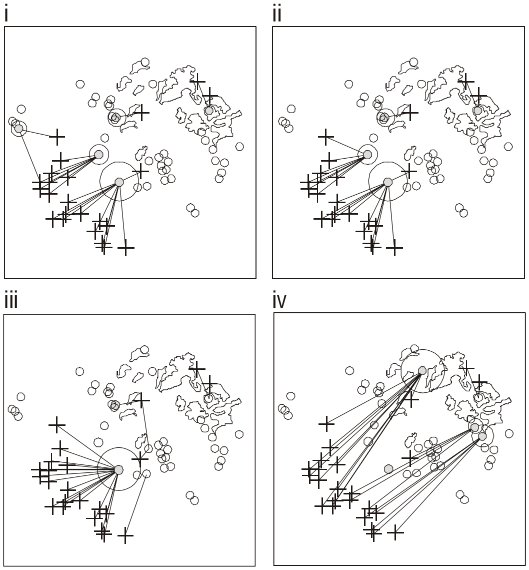


Figure 12 Schematic multi-objective analysis space (two-dimensional)

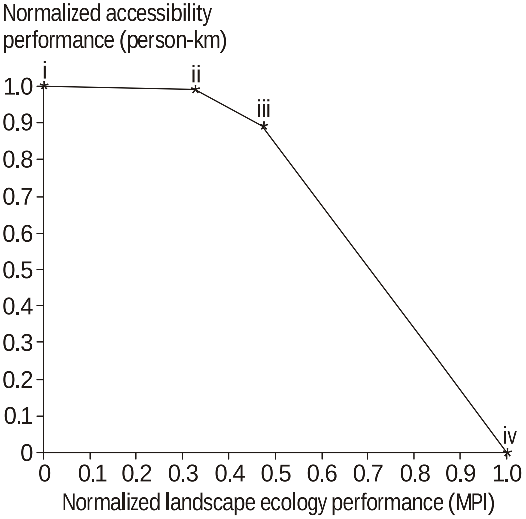


Figure 13 Trade-off curve

The multi-objective analysis formalizes and rationalizes the complex evaluation process of the socio-economic and socio-ecological issues inherent in rural energy design. The design process illustrated here, however, cannot be considered complete without extensive community participation in defining objectives and choosing between alternative designs. Decades of experience in social and community forestry indicate participatory methods are the only path to project success.

Conclusions

Poor access to biomass energy, ongoing ecosystem degradation, and very low penetration of modern energy systems characterize the landscape, the ecology, and the economy of rural India. A renewed vision for integrated rural development must therefore start with revitalizing rural biomass-based energy economies. Community-based forest management and high-efficiency conversion of biomass to electricity form the basis for this new integrated rural development vision. Forest systems managed for energy will exert a large landscape impact, the design of which will therefore require detailed geographical analysis. A case study in the Shivalik Hills (Haryana, India) demonstrates a new forest planning approach utilizing remote sensing, GIS, and design principles derived from spatial optimization and landscape ecology. The multi-objective analysis framework illustrated can assist community-based forest planning and management in maximizing socio-economic and ecological benefits. Community-based forest management or JFM is indeed one of the few success stories in rural environmental management in India. Enhanced JFM planning for basic human development and ecosystem objectives such as high quality energy provision and improved biodiversity should be at the centre of integrated rural development policy. The authors hope that this research makes a conceptual and analytical contribution to understanding this new rural planning paradigm.

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