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Can combining two environmental services under a single PES program result in better environmental outcomes and lower costs?

Ram Ranjan

Department of Economics, School of Humanities and Social Sciences, Shiv Nadar University, Greater Noida, India

Correspondence
Ram Ranjan, Department of Economics, School of Humanities and Social Sciences, Shiv Nadar University, Greater Noida 201314, Uttar Pradesh, India.
Email: ram.ranjan@snu.edu.in

Abstract

This paper develops an integrated framework for modeling payment for ecosystem services (PES) mechanisms that deliver multiple environmental services. Specifically, under a community-led PES, forest conservation is promoted to deliver carbon and stream water benefits. The upstream community is paid for avoided fuelwood harvesting through a United Nations programme on reducing emissions from deforestation and forest degradation (REDD) program, whereas additional income is generated from water sales to the downstream communities. A bio-economic model derives optimal level of fuelwood harvesting, which in conjunction with the changing species composition of forests, streamflow hydrology and fire risks, impacts on the carbon and water generation potential of the PES project. Results indicate that forest conservation outcomes are better when water and carbon services are combined, however overall cost to the program is lower under a carbon-based PES. Changing species composition of forests creates tradeoffs between water and carbon benefits. Forest fires further challenge the viability of PES schemes through reducing streamflow and carbon sequestration potential.

Recommendations for Resource Managers

- Linking two or more environmental services under a single payment for ecosystem services (PES) scheme could improve forest conservation through making it more attractive to the participating communities.
- PES programs that combine multiple environmental services become economically attractive to participating communities through increasing their incomes. For instance, water and carbon driven services complement each other due to the overlapping benefits from improving forest biomass.
- However, fire risks can lower the benefits from PES and dissuade community participation.
- Similarly, the ecological and hydrological dimensions of PES projects that offer carbon and water benefits need to be understood and incorporated within PES framework design to enhance their durability.
- Conservation of mixed forests is more responsive to water-based PES payments, in comparison to monoculture oak forests, however, mixed forests are also more vulnerable to degradation in absence of cooking fuel subsidies.

KEYWORDS
forest carbon sequestration, forest fires, forest water supply, payments for ecosystem services, REDD, stream flow, Uttarakhand forests

1 | INTRODUCTION

Payments for ecosystem services (PES) programs offer an attractive means for conserving the environment. There are currently more than 500 PES programs active across the globe with a combined investment of 36 billion USD (Salzman et al., 2018). However, the market failure problem remains only partially addressed in most PES schemes as the full value of the environmental benefits is rarely accounted for in two-party dealings. This results in an underprovisioning of environmental services. For instance, high opportunity costs of land conversion reduce the attractiveness of United Nations programme on reducing emissions from deforestation and forest degradation (REDD) programs to farmers, resulting in less than satisfactory enrollments. Further, those who benefit only marginally from participation are more likely to exit in future, triggering failure of such PES projects.

There exists an extensive literature documenting the various challenges faced by PES programs. In a study analysing 55 PES projects globally, Ezzine-de-Blas et al. (2016) found that projects that were able to spatially target high-potential areas in terms of environmental services, or offered varying payments to participants, or were more effectively monitored, performed better compared to their counterparts. A lack of well-defined tenure rights and appropriation of benefits by a few have also reduced the effectiveness of PES programs (Chhatre & Agrawal, 2009; Larson, 2011; Larson et al., 2013; Sandbrook et al., 2010). In addition, the issue of leakages has been noted. The Alternative Land Use Service (ALUS) program in Prince Edward Island of Canada incentivizes farmers to set aside land for biodiversity conservation. However, this has led to an increase in agricultural production costs and reduced profit margins. Farmers have ended up using land elsewhere to make up for forgone productivity or taken to intensifying production on their remaining parcels of lands (Vijay et al., 2019).

The Conservation Reserve Program (CRP) in the United States is a good example of a government-led initiative which pays farmers for adopting best land use practices that generate various types of environmental benefits. However, the costs are borne by the government (and hence indirectly by taxpayers), and there is no targeting of individual beneficiaries for bearing costs (Claassen et al., 2008). The total amount budgeted in 2004 towards implementing CRP was 2 billion USD, and at that time had about 40 million acres of private land enrolled into the program (Claassen et al., 2008). However, the U.S. accountability office noted that due to a lack of cross compliance requirements and monitoring, the actual compliance level by farmers had been less than hundred percent. PES programs in Vietnam have seen significant involvement by the state but there is also high level of corruption and poor management of forests (To & Dressler, 2019). Higher state involvement excludes deserving participants and reduces the effectiveness of such programs. The Wimmera catchment pilot program in Victoria, Australia, is another example of a government involvement to incentivize land use practices on 28,000 ha of upstream farms that would lead to salinity reduction in downstream watersheds in the most cost-effective way. Instead of downstream users of water bearing the costs of upstream land use changes, the Australian catchment management authority pays participants through an inverse auction mechanism (Wunder et al., 2008).

The experience with carbon-focussed PES schemes has been mixed. Ferraro et al. (2015) estimate that protected areas in Thailand, Costa Rica, Indonesia, and Brazil have led to additional storage of 1 billion ton of carbon and 5 billion USD worth of ecosystem services. However, the opportunity costs of carbon-based PES vary considerably across countries (Larjavaara et al., 2018). The costs of avoided deforestation range between 0.4 and 171 USD/ton, with a mean value of 26.2 USD/ton. Indonesia, which has a large forest area, is also a major palm oil producer. The net present value of returns from palm forests has been estimated between 4000 and 10,000 USD/ha, in comparison to carbon benefits which only yield 600 to 1000 USD/ha (Butler et al., 2009). In developing countries, there is also a demand pressure on forests resulting in excessive and illegal harvesting. India has currently 70 M ha of forests, which is roughly one-fifth of its geographical area. However, a large proportion of the population is dependent on forests for meeting livelihood needs, resulting in their heavy degradation. It is estimated that there is 228 MT of annual fuelwood demand from forests, whereas, sustainable harvesting can only supply 128 MT (Aggarwal & Das, 2009).

Like carbon-based PES projects, water-based PES schemes have also been promoted globally. Along with PES projects that monetize water provisioning services, there is additional 170 million dollars invested through Investment in Watershed Services (IWS) programs globally covering 43 Million ha of watersheds and affecting 230 million people (Romulo et al., 2018). Challenges faced in implementation of water-based PES projects have been discussed in the literature (Hansen et al., 2013; Hayes & Murtinho, 2018). The success of water-based PES programs has been affected by whether participants received payments individually or collectively, how well the communal governance mechanisms were organized, and by the opportunity cost of land.

There exist only a few examples of water-based PES based programs in India. The Fair Deals project in Himachal Pradesh (which borders Uttarakhand) was based on downstream communities in the Kuhan village paying upstream communities in Kalan village for grazing restrictions, which helped with improving drinking water supply and reduced siltation in the Kuhan watershed (Kissinger et al., 2013). While the downstream communities agreed to pay in-kind support for upstream grazing restrictions, construction of a road above the catchment region negated most of the conservation benefits through causing excessive siltation in the dams (Kissinger et al., 2013). In another example, Palampur, which is a hill station in the Kangra valley of Himachal Pradesh, draws 15% of its drinking water from a spring originating in Bohal, Mandai, and Odi villages upstream. Roughly 60 households reside in the upstream region. Upstream villages collect 3700 kg of firewood per household annually and 1100 kg of leaf fodder from forests that feed rainwater to the springs (Kovacs et al., 2016). Under the PES agreement, Palampur town agreed to pay 10,000 INR per year to the upstream women's organization (known as *Mahila Mandal*) for protecting the forests. However, Kovacs et al. (2016) point out several practical challenges that arose in the post-contract stage due to discontent within the upstream community members over hardships resulting from restrictions placed on logging and uneven sharing of monitoring costs to deter illegal logging.

In India, currently there exists only one large-scale project, in the Khasi hills of Meghalaya, that delivers both carbon and water services through community conservation of forests. Sixty-two villages have come together to protect their forests and help sequester carbon through assisted natural regeneration. It is expected that over a 30-year period, the project will sequester 20,000–50,000 tons of carbon resulting in 0.1–0.2 million USD of income to the community. Through reduced fuelwood harvesting and control of slash and burn method of farming, communities have significantly reduced forest fires in the region (Poffeberger, 2015). The scheme is recognized as a REDD project under Plan Vivo and receives additional PES for improving forest water supply to the city of Shilong. In 2013, the village federation received carbon credits for roughly 22,000 tons, which were sold for 6–7 USD/ton. In principle, such PES programs offer multiple benefits including enhanced social capital, environmental improvement, enterprise development, development of secure land tenure rights, gender equality, and enhanced socio-cultural values (Poffenberger, 2015). Alix-Garcia et al. (2018) measured the impact of Mexico's conservation payment programs on community social capital and prosocial behavior. Their study suggested that PES programs improved social capital by about 10% and land management activities, including construction of firebreaks and soil conservation, increased by 50%.

In this paper, the potential environmental and cost-saving benefits of combining two ecosystem services under a single PES scheme are explored. Specifically, water generation and carbon sequestration benefits of forests are optimized through a community led PES project. There exist examples in the literature where multiple environmental objectives and tradeoffs have been addressed under single conservation projects (for instance, see Schroder et al., 2016). There are practical benefits from promoting linked PES projects. A water-based PES or a carbon-based REDD project by itself may not provide sufficient incentives to restore forests and undertake long-term conservation efforts to avoid risks of future fires or illegal clearing. In case of fire, water quality and quantity would decline, and forest carbon would get released. Coupled PES programs whereas can provide synergistic benefits in terms of environmental services as well as monetary support to local communities. Community participation could increase due to higher monetary incentives and side benefits such as augmented nontimber forest products (NTFP) due to higher conservation. Coupled PES programs can also help generate positive institutional externalities through removing obstacles to participation and creating examples for replication elsewhere. In this paper, we link a streamflow related PES program to carbon sequestration-based REDD mechanism in a forestry-dependent community. The community is offered PES for water and carbon benefits generated from conservation of degraded forests. These monetary incentives help the community switch away from fuelwood harvesting and use cooking gas for their daily energy needs. An optimal harvesting rule is determined through maximizing long-term returns to the community under varying combinations of water and carbon-based PES payments. Further, the risk to the project from future fires is modeled, accounting for the possibility of reduced streamflow in the postfire scenario. An application of the model is presented for the Uttarakhand region of India.

2 | STUDY AREA BACKGROUND AND MODEL

Uttarakhand has 60% of its physical area covered with forests (Forest Department, 2016). The state is characterized by persistent water scarcity (Sarma, 2016). Climate change is further predicted to reduce groundwater and surface water supply by 30% in the region (Kelkar et al., 2008). In addition to water stress, traditional-livelihood avenues can no longer support local communities. Uttarakhand forests cannot sustainably meet the fuelwood needs of local communities (Germain et al., 2017), which has resulted in high degradation through excessive harvesting (Baland et al., 2010). Per capita average annual fuelwood extraction in the communities is 900 kg (Germain et al., 2017), which further increases with altitude. Excessive harvesting aggravates water scarcity through increasing runoffs and reducing infiltration. In addition, the risk of forest fires increases through illegal clearing of forests and changing species composition from oak to pine trees (Babu et al., 2016; Singh & Singh, 1992). Pine forests are 7–10 times more prone to fire compared to oak (Babu et al., 2016). Due to a rapid replacement of oak forests by pine, and a general degradation in forest quality, more than 90% of drinking water streams in the villages of Almora district have gone dry (Prasad, 2010). This has prompted community-led afforestation initiatives in the region. Uttarakhand, in fact, has a unique “Van Panchayat” community system which is noted for its forest management outcomes (Baland et al., 2010).

With this background, we develop the formal model next. The forest growth and hydrological models build on Ranjan (2019a, 2019b). However, the current model differs from the previous studies in many significant ways. First, this paper integrates biomass carbon sequestration and stream water generation benefits of forests in a single PES model. Whereas previous works have considered them individually. Importantly, it demonstrates how tradeoffs may arise between carbon sequestration, fuelwood consumption and water provisioning goals of a PES program offering two environmental services when species composition of forests is dynamic. Second, this study considers the impact of forest fires on streamflow and the success of PES programs. Finally, it derives the cheapest combinations of carbon and water PES payments that lead to highest environmental benefits.

Consider a forestry-based community that owns mixed forests comprising oak and pine trees. Trees are harvested for fuelwood. The community has fixed per capital fuelwood needs and any shortfall is met through liquified petroleum gas (lpg) substitution. The biomass in oak trees $x_{\text{oak}}(t)$ follows logistic growth (refer to Ranjan, 2019a, for further details), given as follows:

$$\dot{x}_{\text{oak}}(t) = \rho_{\text{oak}} x_{\text{oak}}(t)\left(1 - \frac{x_{\text{oak}}(t)}{k_{\text{oak}}(t)}\right) - h_{\text{oak}}(t); \rho_{\text{oak}} > 0, h_{\text{oak}}(t) < x_{\text{oak}}(t), \tag{1}$$

where ρ_{oak} is the intrinsic growth rate of oak trees, $k_{\text{oak}}(t)$ carrying capacity of a unit area of land, and $h_{\text{oak}}(t)$ the level of fuelwood harvesting at time t. Similarly, pine biomass $x_{\text{pine}}(t)$ grows as:

$$\dot{x}_{\text{pine}}(t) = \rho_{\text{pine}} \cdot x_{\text{pine}}(t) \cdot \left(1 - \frac{x_{\text{pine}}(t)}{k_{\text{pine}}(t)}\right) - h_{\text{pine}}(t); \rho_{\text{pine}} > 0, h_{\text{pine}}(t) < x_{\text{pine}}(t), \tag{2}$$

where ρ_{pine} is the intrinsic growth rate of pine trees, $k_{\text{pine}}(t)$ carrying capacity of a unit area of land, and $h_{\text{pine}}(t)$ the fuelwood harvesting at t.

Pine trees act as invader species, replacing oak trees, owing to their superior advantage in terms of stress tolerance and seed dispersal (Connell & Slatyer, 1977; Nautiyal, 2015). Further, oak regeneration in cleared forests is adversely affected by grazing, lopping, and fires (Nautiyal, 2015). Therefore, any reduction in carrying capacity of oak trees results in an increase in the same for pine trees. The carrying capacity $k_{\text{oak}}(t)$ of oak trees is assumed to get reduced through harvesting as:

$$\dot{k}_{\text{oak}}(t) = -h_{\text{oak}}(t) \cdot d; 1 > d > 0, \tag{3}$$

where d is the displacement coefficient measuring a proportional rate of loss in carrying capacity of oak trees from harvesting. Loss in carrying capacity of oak results in a gain to the pine's carrying capacity $k_{\text{pine}}(t)$ as follows:

$$\dot{k}_{\text{pine}}(t) = h_{\text{oak}}(t) \cdot d. \tag{4}$$

Forests help improve stream flow. Oak trees have been noted to result in higher stream water flow compared to pines (Lewis & Likens, 2000; Swank & Miner, 1968; Thompson et al., 2011). In the context of the study region, it is assumed that stream flow in downstream communities is generated through water infiltration in subsurface layers of upstream forests. Stream water flow $w_{\text{oak}}(t)$ from oak forests is modeled (following Ranjan, 2019b) as follows:

$$w_{\text{oak}}(t) = \left(w_0 \cdot \frac{x_{\text{oak}}(t)^{w_1}}{x_{\text{oak}}(t)^{w_1} + w_2}\right) \cdot a \cdot \text{rain}; \; a > 0, \text{rain} > 0, w_0 > 0, w_1 > 0, w_2 > 0, \tag{5}$$

where parameter w_0 measures the maximum streamflow per unit area, a total area of the forest, and rain denotes annual rainfall in inches. Parameters w_1 and w_2 nonlinearly relate the impact of forest degradation on water flow. Stream flow $w_{\text{pine}}(t)$ from pine forests is modeled as follows:

$$w_{\text{pine}}(t) = \left(w_3 \cdot \frac{x_{\text{pine}}(t)^{w_4}}{x_{\text{pine}}(t)^{w_4} + w_5} - w_6 \cdot \frac{x_{\text{pine}}(t)^{w_7}}{x_{\text{pine}}(t)^{w_7} + w_8}\right) \cdot a \cdot \text{rain}; \; w_3, w_4, w_5, w_6, w_7 \text{ and } w_8 > 0. \tag{6}$$

Parameters w_3, w_4, and w_5 have similar interpretation as their respective counterparts in Equation (5). The additional negative term in Equation (6) reflects the fact that as pine volume increases, stream flow declines, where parameters w_6, w_7, and w_8 determine the rate of decline.

Total water generation $w_{pes}(t)$ from oak and pine is derived as:

$$w_{pes}(t) = w_{oak}(t) + w_{pine}(t). \tag{7}$$

Income $i_{pes}(t)$ from water-based PES payments is further given as:

$$i_{pes}(t) = k_{pes} \cdot w_{pes}(t), \tag{8}$$

where $k_{pes} > 0$ is the price of water negotiated under PES.

Next, we model the impact on carbon sequestration and carbon incomes from conservation efforts. Carbon sequestration $s_{oak}(t)$ in oak forests is a function of biomass growth net of harvesting $h_{oak}(t)$ as:

$$s_{oak}(t) = \left(\rho_{oak} \cdot x_{oak}(t) \cdot \left(1 - \frac{x_{oak}(t)}{k_{oak}(t)}\right) - h_{oak}(t)\right) \cdot c_{carbon} \cdot a; c_{carbon} > 0, \tag{9}$$

where c_{carbon} is the conversion factor relating biomass to sequestered carbon. Similarly, carbon sequestration $s_{pine}(t)$ in pines is given as:

$$s_{pine}(t) = \left(\rho_{pine} \cdot x_{pine}(t) \cdot \left(1 - \frac{x_{pine}(t)}{k_{pine}(t)}\right) - h_{pine}(t)\right) \cdot c_{carbon} \cdot a. \tag{10}$$

Total carbon-based PES income $i_{carbon}(t)$ becomes:

$$i_{carbon}(t) = (s_{oak}(t) + s_{pine}) \cdot p_{carbon}, \tag{11}$$

where $p_{carbon} > 0$ is the price of carbon negotiated under PES.

Any conservation comes at the cost of forgone harvesting. Resulting shortfall $f_{res}(t)$ in fuelwood supply can be derived as:

$$f_{res}(t) = f_{dem} \cdot n - h_{oak}(t) \cdot m_{oak} \cdot a - h_{pine}(t) \cdot m_{pine} \cdot a, \tag{12}$$

where $f_{dem} > 0$ is per capita annual fuelwood demand and n the community population. Parameters $m_{oak} > 0$ and $m_{pine} > 0$ are masses of unit volumes of oak and pine trees, respectively. Any shortfall in fuelwood supply would require use of lpg ($g(t)$) so that demand equals supply:

$$h_{oak}(t) \cdot m_{oak} \cdot a + h_{pine}(t) \cdot m_{pine} \cdot a + g(t) = f_{dem} \cdot n. \tag{13}$$

Cost $c_g(t)$ of lpg substitution is assumed nonlinear given inaccessibility of higher altitude regions and less than 100% substitutability of lpg with fuelwood:

$$c_g(t) = p_g \cdot \left(1 + g_1 \cdot \frac{g^{g_2}(t)}{g^{g_2}(t) + g_3}\right) \cdot (1 - sub); 1 > sub > 0, g_1, g_2, g_3 > 0, \tag{14}$$

where p_g is the market price of lpg and parameters g_1, g_2, and g_3 incorporate a nonlinear cost of substitution. Parameter sub reflects government subsidy on lpg.

Communities may earn additional income $i_{ntf}(t)$ through nontimber forest products (NTFP), which is higher in healthier forest stocks. This is modeled as:

$$i_{ntf}(t) = f_0 \cdot \left(1 + f_1 \cdot \frac{(x_{oak} + x_{pine})^{f_2}}{(x_{oak} + x_{pine})^{f_2} + f_3}\right) \cdot n; f_0 > 0, f_1 > 0, f_2 > 0, f_3 > 0, \tag{15}$$

where f_0 is the NTFP income possible in absence of any forests and f_1, f_2, f_3 are parameters relating the health of the forests to NTFP yield.

Total community income $i_{com}(t)$ is the sum of carbon and water driven PES and NTFP incomes, net of fuelwood substitution costs as:

$$i_{com}(t) = i_{pes}(t) + i_{carbon}(t) + i_{ntf}(t) - c_g(t). \tag{16}$$

Communities also earn incomes from farming, migration, and salaried employment, which are not included here for simplicity.

The community maximizes long-term utility U as:

$$U = \max \int_0^{\infty} log(i_{com}(t)) \cdot exp(-r \cdot t) dt, \tag{17}$$

where r is the rate of time preference.

Next, we model risk of forest fires, which causes loss of $\Omega\%$ in forest stock and an equal amount in carrying capacity. Fire risk may emanate from various sources. Herein, we focus on a specific fire hazard $\dot{\lambda}(t)$, which can be managed through keeping the stock of pine forests lower. The fire hazard evolves as:

$$\dot{\lambda}(t) = \lambda_0 \cdot \left(1 + \underbrace{\frac{\left(\frac{x_{pine}}{x_{oak}}\right)^{\lambda_1}}{\left(\frac{x_{pine}}{x_{oak}}\right)^{\lambda_1} + \lambda_2}}_{\text{endogenous} \cdot \text{risk}} \right); \lambda_0 > 0, \lambda_1 > 0, \lambda_2 > 0, \tag{18}$$

where λ_0 is the exogenous component of fire hazard, and the endogenous component can also reach a maximum value of λ_0 when the ratio of pine to oak volume increases. The endogenous component affects $\dot{\lambda}(t)$ nonlinearly through parameters λ_1 and λ_2.

Forest fires can affect stream flow. In the literature, the impact of forest fires on stream flow and infiltration rates has been noted to both increase and decrease. However, most studies have observed a decline in infiltration rate following fire due to an increase in water repellency of surface soils (Martin & Moody, 2001; Robichaud et al., 2016). Here, it is assumed that water infiltration would fall immediately after a fire, however, there would be an improvement as biomass recovers. Following observations in Robichaud et al. (2016), the loss $l(t)$ in infiltration rate, measured as a percentage decline in infiltration compared to that in unburned forests, is modeled as:

$$l(t) = l_0 \cdot e^{-l_1 \cdot \frac{x(t)}{x_{max}}}; l_0 > 0; l_1 > 0, \tag{19}$$

where l_0 is the maximum infiltration loss rate and parameter l_1 governs the improvement in infiltration rate as forest biomass recovers over time. The resulting stream flow from oak and pine trees in the postfire scenario is given as:

$$w_{oak}(t) = \left(w_0 \cdot \frac{x_{oak}(t)^{w_1}}{x_{oak}(t)^{w_1} + w_2} \right) \cdot a \cdot \text{rain} \cdot (1 - l(t)), \tag{20}$$

$$w_{pine}(t) = \left(w_3 \cdot \frac{x_{pine}(t)^{w_4}}{x_{pine}(t)^{w_4} + w_5} - w_6 \cdot \frac{x_{pine}(t)^{w_7}}{x_{pine}(t)^{w_7} + w_8} \right) \cdot a \cdot \text{rain} \cdot (1 - l(t)). \tag{21}$$

The community's optimization plan under risk of fire can be written (following Reed & Heras, 1992) as:

$$\max \int_0^\infty \begin{pmatrix} \log(i_{\text{com}}(t))\exp(-\lambda(t))\exp(-rt)+ \\ V_{\text{postfire}}\dot{\lambda}(t)\exp(-\lambda(t))\exp(-rt) \end{pmatrix} dt. \tag{22}$$

The term $\int_0^\infty \log(i_{\text{com}}(t)\cdot\exp(-\lambda(t))\cdot\exp(-r\cdot t)dt$ in Equation (22) is a reduced form of expected utility from income obtained until the time of fire. The expanded version of the expression for expected utility until the time of fire can be written as:

$$\int_0^\infty \dot{\lambda}(t)\exp(-\lambda(t))\int_0^t \log(i_{\text{com}}(z))\exp(-rz)dzdt, \tag{23}$$

where $\dot{\lambda}(t)\cdot\exp(-\lambda(t))$ is the instantaneous probability of fire occurring at time t, and $\int_0^t \log(i_{\text{com}}(z))\exp(-rz)dz$ is the sum of utilities derived from incomes until time t. The first integral up to infinity accounts for the possibility that fire could occur at any time between zero and infinity. Equation (23), after integration by parts, yields the first term of (22). The second term in (22) is the expected value obtained in the postfire scenario, where V_{postfire} is the value obtained after optimizing community's postfire utility function. Fire could lead to a loss of biomass and carrying capacity of the forests. Let ξ be the proportion of biomass and carrying capacity lost in fire. The postfire value is solved through optimizing Equation (17) with the reduced water generation capacities as given by Equations (20) and (21). The above optimization framework assumes a single fire event. Cases with multiple fire events can be handled through solving a postfire value function for each fire incident. For instance, to solve for a postfire value function $V_{fire}(n)$, where n represents the nth fire event, the optimization problem would be given as:

$$V_{\text{postfire}}(n) = \max \int_0^\infty (\log(i_{\text{com}}(t))\cdot\exp(-r\cdot t)\cdot\exp(-\lambda(t)) + V_{\text{postfire}}(n+1)\cdot\exp(-r\cdot t)\cdot\dot{\lambda}(t)\cdot \exp(-\lambda(t)))dt. \tag{24}$$

For simplicity, we present a numerical example involving a single fire-event as the intuition derived through the results can be easily extended to cases involving multiple fires. The next section presents a numerical application of the optimization model.

3 | NUMERICAL EXAMPLE

The numerical example uses Uttarakhand as a context for parametrizing model equations. Appendix A and Table 1 provides the rationale for parameters used in the model. The model is run in general algebraic modeling systems (GAMS 24.7.4) software, using a time horizon of 150 years and discount rate of 3%. The postfire value function is solved through deriving utility values for various starting levels of state variables and calibrating the value function in STATA15 using a nonlinear regression command. The estimated postfire value is presented in Table 1.

We start with a base case scenario that assumes no carbon or water-based PES payment and a community that owns only oak forests (Section 3.1). Sensitivity of base case results to

TABLE 1 Parameter values selected for the base case model

Equation	Parameter value	No.
$\dot{x}_{\text{oak}}(t) = \rho_{\text{oak}} \cdot x_{\text{oak}}(t) \cdot \left(1 - \frac{x_{\text{oak}}(t)}{k_{\text{oak}}(t)}\right) - h_{\text{oak}}(t)$	$\rho_{\text{oak}} = 0.53$, $k_{\text{oak}}(0) = 450{,}200\ \text{m}^3/\text{ha}$	1
$\dot{x}_{\text{pine}}(t) = \rho_{\text{pine}} \cdot x_{\text{pine}}(t) \cdot \left(1 - \frac{x_{\text{pine}}(t)}{k_{\text{pine}}(t)}\right) - h_{\text{pine}}(t)$	$\rho_{\text{pine}} = 0.53$, $k_{\text{pine}}(0) = 0{,}200\ \text{m}^3/\text{ha}$	2
$\dot{k}_{\text{oak}}(t) = -h_{\text{oak}}(t) \cdot d$, $\dot{k}_{\text{pine}}(t) = h_{\text{pine}}(t) \cdot d$	$d = 0.5$	3
$w_{\text{oak}}(t) = \left(w_0 \cdot \frac{x_{\text{oak}}(t)^{w_1}}{x_{\text{oak}}(t)^{w_1} + w_2}\right) \cdot a \cdot \text{rain}$	$w_0 = 0.116; w_1 = 3; w_2 = 10^7$; $\text{rain} = 50\,\text{inch}$; $a = 50\,\text{ha}$	5
$w_{\text{pine}}(t) = \left(w_3 \cdot \frac{x_{\text{pine}}(t)^{w_4}}{x_{\text{pine}}(t)^{w_4} + w_5} - w_6 \cdot \frac{x_{\text{pine}}(t)^{w_7}}{x_{\text{pine}}(t)^{w_7} + w_8}\right) \cdot a \cdot \text{rain}$	$w_3 = 0.14; w_4 = 3; w_5 = 10^7$; $w_6 = 0.12; w_7 = 3; w_8 = 10^8$; $\text{rain} = 50\,\text{inch}$; $a = 50\,\text{ha}$	6
$i_{\text{pes}}(t) = p_{\text{water}} \cdot w_{\text{pes}}(t)$	$p_{\text{water}} = 0{,}0.0001{,}0.001$ (INR/L)	8
$s_{\text{oak}}(t) = \dot{x}_{\text{oak}}(t) \cdot m_{\text{oak}} \cdot c_{\text{carbon}} \cdot a$	$f_d = 1200\,\text{kg}$; $m = 600\,\text{kg/m}^3$; $c_{\text{carbon}} = 0.5$	9
$s_{\text{pine}}(t) = \dot{x}_{\text{pine}}(t) \cdot m_{\text{pine}} \cdot c_{\text{carbon}} \cdot a$	$f_d = 1200\,\text{kg}$; $m_{\text{pine}} = 330\,\text{kg/m}^3$; $c_{\text{carbon}} = 0.5$	10
$i_{\text{carbon}}(t) = (s_{\text{oak}}(t) + s_{\text{pine}}) \cdot p_{\text{carbon}}$	$p_{\text{carbon}} = 0$, 280 INR/ton	11
$i_{\text{ntf}}(t) = f_0 \cdot \left(1 + f_1 \cdot \frac{(x_{\text{oak}} + x_{\text{pine}})^{f_2}}{(x_{\text{oak}} + x_{\text{pine}})^{f_2} + f_3}\right) \cdot n$	$f_0 = 1000; f_1 = 50; f_2 = 2; f_3 = 10^6$; $n = 100$	15
$\dot{\lambda}(t) = \lambda_0 \cdot \left(1 + \frac{\left(\frac{x_{\text{pine}}}{x_{\text{oak}}}\right)^{\lambda_1}}{\left(\frac{x_{\text{pine}}}{x_{\text{oak}}}\right)^{\lambda_1} + \lambda_2}\right)$	$\lambda_0 = 0.01, 0.02$; $\lambda_1 = 4; \lambda_2 = 3$	18
$l(t) = l_0 \cdot e^{-l_1 \cdot \frac{x(t)}{x_{\max}}}$	$l_0 = 0.5$; $l_1 = 4$	19
V_{postfire}	$196.60 \cdot x_{\text{oak}}(t)^{0.0327} \cdot x_{\text{pine}}(t)^{0.0308} \cdot k_{\text{oak}}(t)^{0.049} \cdot k_{\text{pine}}(t)^{0.048}$	24

bio-physical parameters is explored next. Following that, we take up scenarios where there is either a water or carbon-based PES or a combination of the two. Combinations of water and carbon PES payments which minimize overall costs to the program while maximizing water and carbon benefits are derived. Sensitivity analysis is performed with respect to lpg subsidy and rainfall. This is followed by scenarios where the community owns mixed forests. Under these scenarios, tradeoffs are explored between water generating benefits of pine trees and fuelwood benefits of oak trees when the community faces high lpg costs. Finally, the influence of fire risks on management of mixed forests is considered.

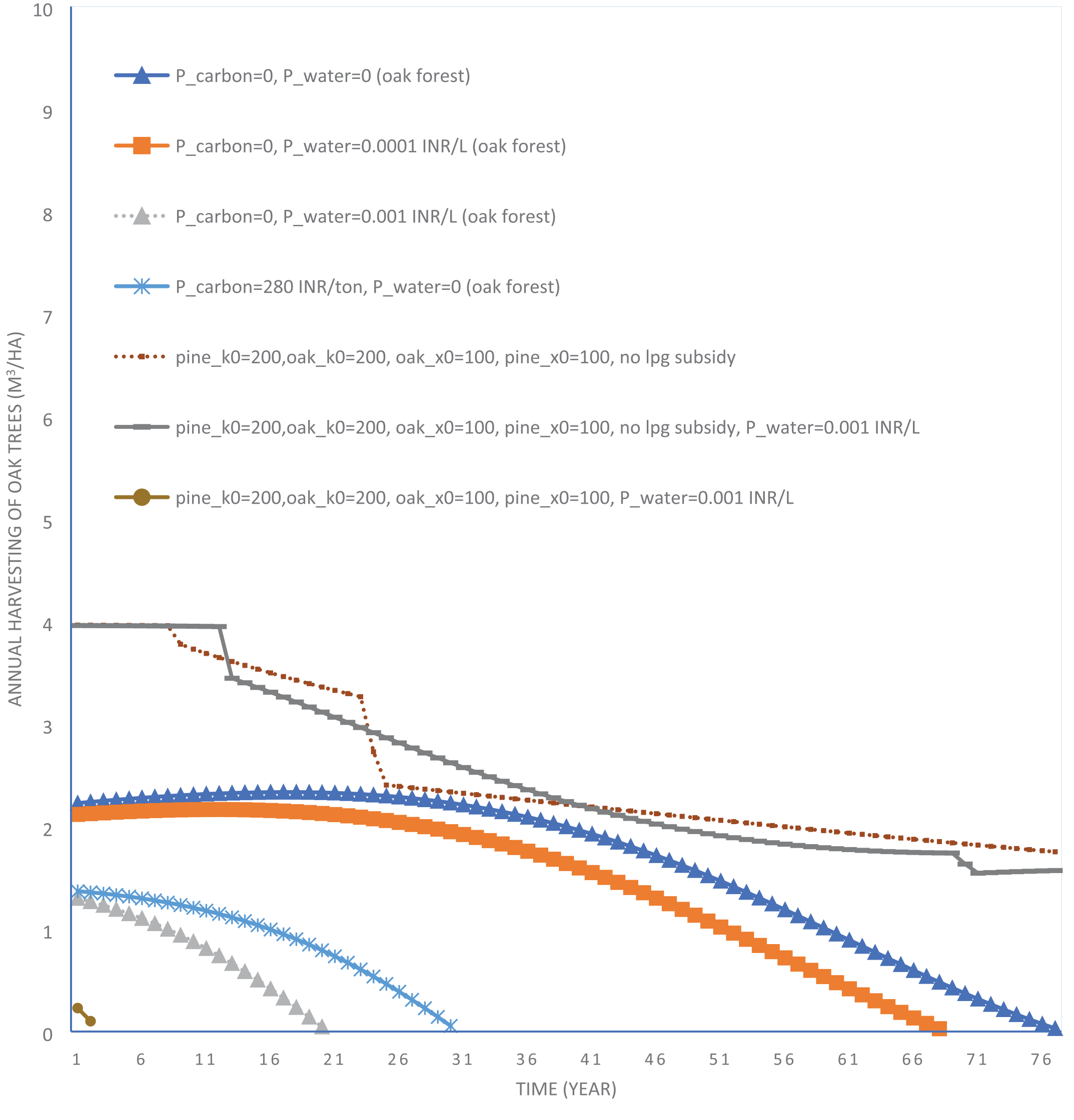

FIGURE 1 Time path of annual fuelwood harvesting (per ha) in oak and mixed forests under various scenarios

3.1 | Results for oak forests

The base case derives harvesting decisions when no carbon or water-based PES is available and no fire risk is present. The community owns 50 ha of oak forests. There is harvesting of 2.3 m^3/ha in the initial years (Figure 1). However, this results in 44% fuelwood shortage, which further increases after 30 years as harvesting declines over time (Figure 2). Any shortfall in fuelwood is met through lpg, which is available at 50% subsidy. To have zero-fuelwood shortage, there needs to be harvesting of 4 m^3/ha. However, even without carbon or water income, the base case results in 44% switch from fuelwood to lpg. This happens primarily to increase the sustainability of oak forests (which helps with NTFP incomes). Due to lower harvesting, forest biomass improves and gradually reaches carrying capacity in 150 years (Figure 3).

Next, we explore sensitivity of results to biophysical parameters. When initial biomass stock is increased from base case value of 100 to 200 m^3/ha, there is further reduction in harvesting.

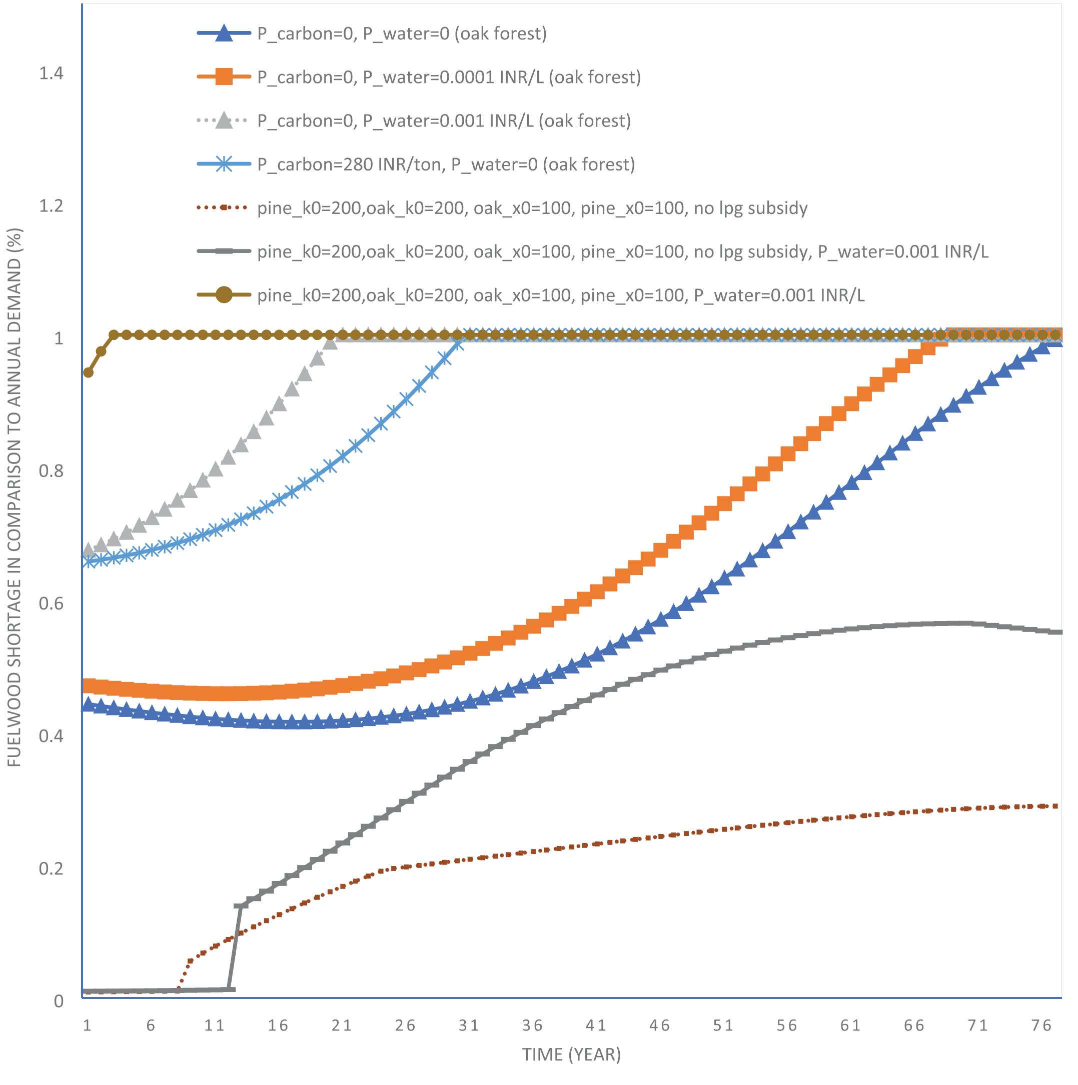

FIGURE 2 Shortfall in fuelwood supply due to reduced optimal harvesting under various scenarios

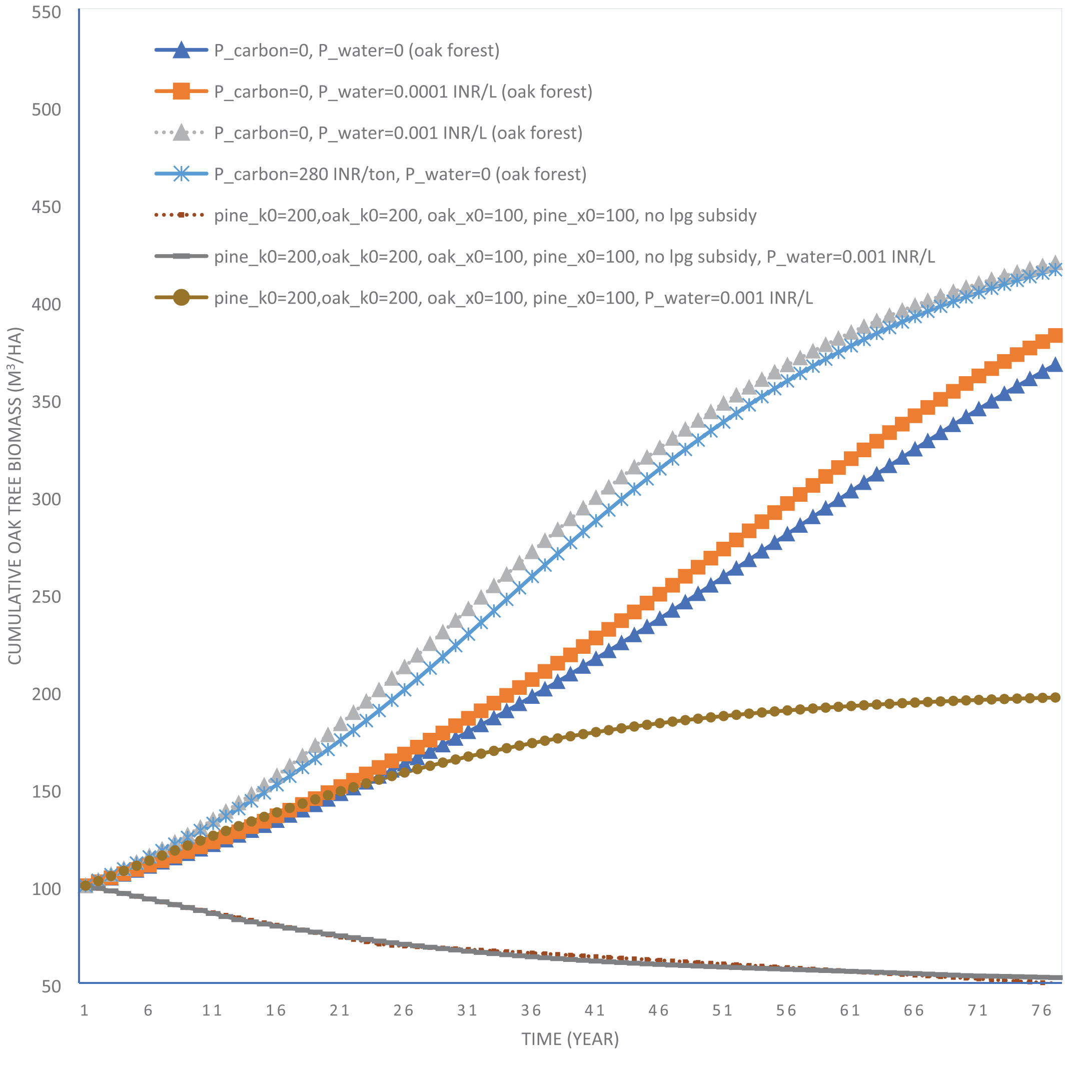

FIGURE 3 Time paths of oak forest biomass (per ha) under various scenarios

The benefits of forgoing fuelwood consumption materialize through higher NTFP incomes that result from faster forest growth when initial stocks are higher. The base case assumes low discount rate of 3%. At 6% discounting, there is constant harvesting of 4 m^3/ha resulting in zero fuelwood shortage. Therefore, higher discounting adversely affects the sustainability of forests. Whereas a higher intrinsic growth of forests (ρ_{oak} of 0.073 compared to 0.053) results in higher harvesting, yet the long-term stock of forests exceeds the base case. Similarly, a community that has a 33% lower annual fuelwood requirement at 800 kg per capita, harvests less than the base case (i.e., it conserves more) and has better long-term forest biomass as a result. Finally, in a degraded forest with lower carrying capacity of 250 m^3/ha, compared to base case value of 450 m^3/ha, there is higher harvesting resulting in rapid extinction of forests. Therefore, sensitivity analysis (not shown in the figures) indicates that, good quality forests with high carrying capacity and high initial stocks, forests with high growth rates, areas receiving higher rainfall, and communities with lower fuelwood requirements and lower time discounting, result in better forest management and hence would be more conducive to the success of PES initiatives.

Now, consider scenarios where the community receives PES for water. A water price of 0.0001 INR/L leads to a marginal reduction in harvesting compared to base case. Fuelwood shortage in initial years is 47%. As a result, oak tree volume is marginally better compared to base case. Total water generated under this scenario is roughly 26 ML/yr in initial years, but gradually increases to 245 ML/yr as tree volume improves from 100 to 375 m^3/ha in about 70 years. Another scenario, where PES payment is increased to 0.001 INR/L, leads to significant cutback in harvesting (to 1.3 m^3/ha) which further declines to zero by year 21. As a result, oak forest growth is the highest of all scenarios. Fuelwood shortage is 65% in initial years and increases to 100% by year 21. Stream-water volume (Figure 4) under this scenario is significantly higher in the first 30 years, however,

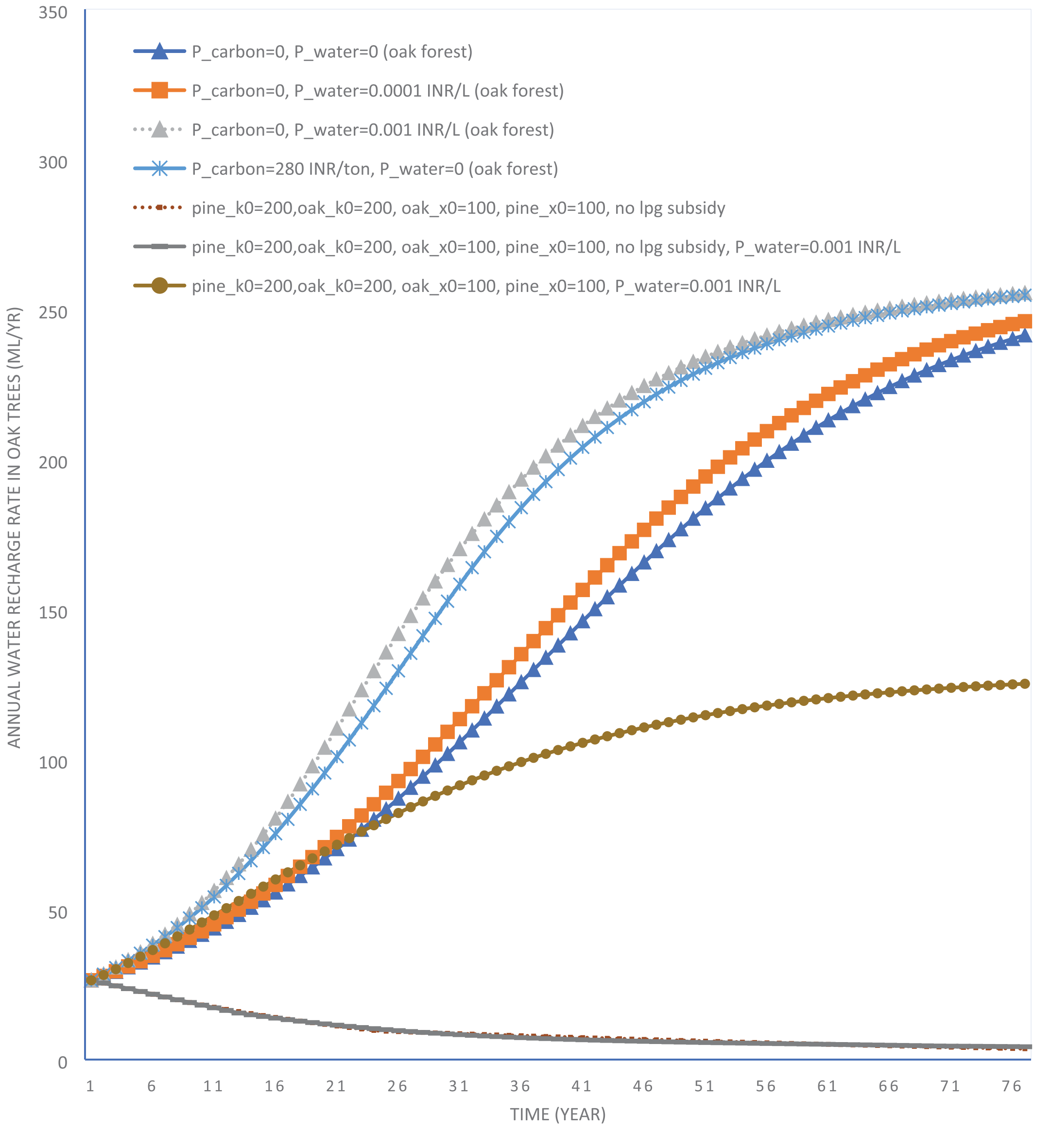

FIGURE 4 Annual water recharge rate in oak and mixed forests under varying payment for ecosystem services-based water prices and liquified petroleum gas subsidy levels

TABLE 2A Combinations of carbon and water prices leading to complete switch to lpg from year 1

50% lpg subsidy		25% lpg subsidy		0 subsidy	
p_{carbon} (INR/ton)	p_w (INR/L)	p_{carbon} (INR/ton)	p_w (INR/L)	p_{carbon} (INR/ton)	p_w (INR/L)
0	0.003	0	0.0065	1950	0
70	0.00255	280	0.00525	0	0.011
140	0.00217	710	0.0029		
300	0.00135	1050	0.0012		
465	0.0005	1260	0		
548	0.0001				
569	0				

the difference compared to base case becomes smaller in later years due to declining marginal productivity of forests as biomass reaches close to carrying capacity. The base case assumes an annual rainfall of 50 inches. When rainfall is increased to 100 inches, there is higher cutback in harvesting, which results in further improvement in biomass. Whereas reduction in annual rainfall from 50 to 30 inches, results in marginally higher harvesting and lower long run biomass (this sensitivity scenario is not depicted in the figures). Therefore, more rainfall is better for the success of water-based PES mechanisms.

Next, consider the impact of carbon payments on inducing lower harvesting. A carbon price of 280 INR/ton (4 USD/ton) leads to similar outcomes as the previous scenario (of a higher PES for water of 0.001 INR/L). This suggests that combining carbon and water payments could induce a much larger level of fuelwood substitution to lpg, resulting in higher water and carbon benefits to society. In fact, the highest carbon and water benefits would arise when fuelwood harvesting is completely stopped. We find combinations of PES for water and carbon prices that lead to zero harvesting right from year 1. Table 2A depicts these combinations. When carbon price offered is zero, it would require a water price of 3 INR/KL to induce complete switch to lpg. Whereas, on the other extreme, when water-based PES payment is zero, it requires a carbon price of 569 INR/ton (8 USD/ton) to achieve the same outcome. In between the two extremes, there are various combinations possible that result in zero fuelwood harvesting. Results are also displayed for a lower subsidy of 25% and when no subsidy is provided. Table 2B presents total costs of achieving zero harvesting under a 50% lpg subsidy scenario. Figure 5 presents the isoquants for ensuring zero harvesting for 0%, 25%, and 50% lpg subsidies. It is also found that total costs decline when carbon PES is increased and water PES is lowered, suggesting that the community responds more to carbon payments than water payments. The reason for this is that carbon-based PES provides immediate payments from curtailing harvesting through higher sequestration, whereas water-based PES gradually improves in the long run with forest biomass (Figure 6). Therefore, compensation required for reducing harvesting is higher under water-based PES as most of the payment occurs in the future.

3.2 | Results for mixed forests

Next, consider scenarios where the community owns a mixed forest comprising oak and pine. The assumption here is that mixed forests are more likely to be degraded and hence would have

TABLE 2B Total cost of ensuring zero fuel harvesting under combinations of carbon and water prices at 50% lpg subsidy

50% lpg subsidy		
p_{carbon} (INR/ton)	p_w (INR/L)	Total cost (million INR)
0	0.003	98.8
70	0.00255	84.5
140	0.00217	72.6
300	0.00135	46.8
465	0.0005	20.0
548	0.0001	7.47
569	0	4.33

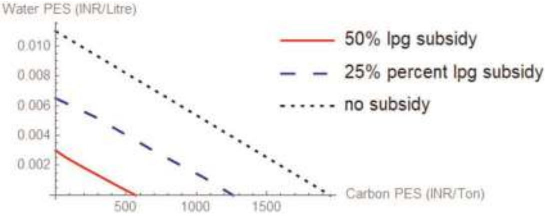

FIGURE 5 Isoquants that would be necessary to achieve zero fuel wood harvesting given varying levels of lpg subsidy. lpg, liquified petroleum gas; PES, payment for ecosystem service

lower carrying capacities for both types of trees. Pine trees generate lower fuelwood for the community and are less desirable from a livelihood perspective. From an environmental viewpoint too, they have less to offer compared to oak. Pine trees support lower biodiversity richness compared to oak. Further, they generate relatively lower stream water and are more prone to fire. Given a lower mass of wood per unit volume (330 kg/m^3 compared to 600 kg/m^3 in oak), they also sequester less carbon. Therefore, overall, pine trees provide lower carbon and water benefits to the community. In a scenario where the community owns equal measures of pine and oak forests (100 m^3/ha each), its optimal response varies considerably compared to base case. In a new scenario where oak and pines have an initial biomass of 100 m^3/ha each (and carrying capacities of 200 m^3/ha each) and PES payment for water is offered at 0.001 INR/L, there is almost no harvesting. There is some harvesting in the first 2 years after which the community completely switches to lpg. Whereas in a previous scenario where a PES was offered at 0.001 INR/L, but the community owned only oak forests, there was 70% fuel-wood shortage and harvesting of oak trees lasted until 20 years. There are several factors in the new scenario that lead to zero harvesting. First, there is the displacement effect, which leads to pines growing in areas cleared of oak trees. Therefore, harvesting of oak not only lowers current carbon and water-based PES earnings (Figure 6), but also lowers future earnings through replacement by pine. Despite lower harvesting, the long-term oak biomass is reduced under this scenario due to lower initial volume. Pine biomass (see Figure 7) growth is also low. However, note that despite the lower water and carbon benefits of pine trees, it may not be optimal to harvest pines immediately and replace it with oak trees. If the community harvested

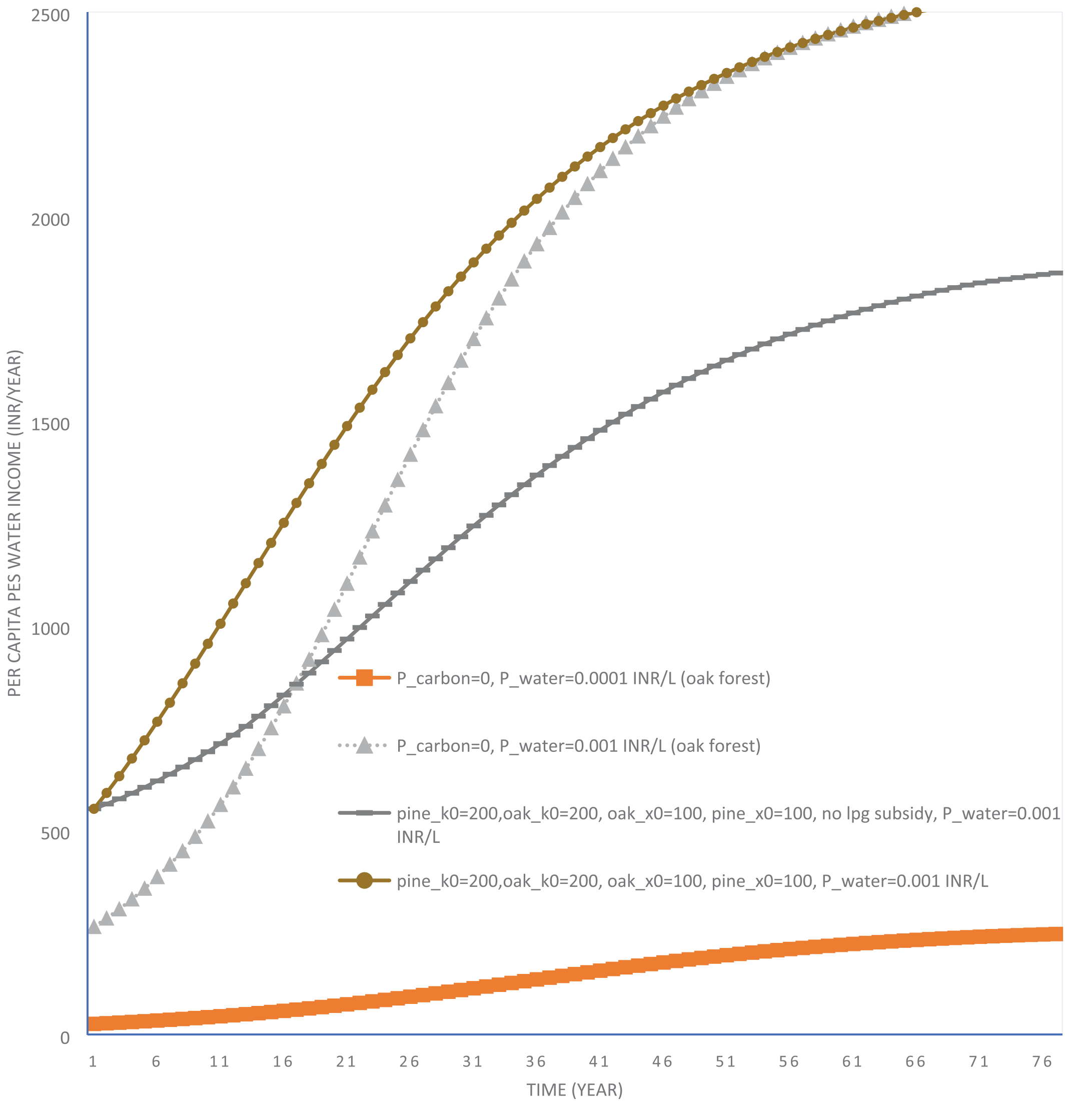

FIGURE 6 Per capita PES water income in oak and mixed forests at a water price of 1 INR/kL. PES, payment for ecosystem service

all the pines and planted oaks, it would be costly in terms of forgone water and carbon benefits from the current stand of pines. The newly planted oak trees would start to offer similar benefits only after 10 to 15 years when biomass grows to significant levels.

In another scenario, where there is no lpg subsidy, the community prefers to go for maximum harvesting of oak trees as the costs of lpg substitution are high. Harvesting of oak leads to their decimation in the long term due to displacement by pine. Figure 8 shows carbon sequestration under all scenarios. Under no lpg subsidy, carbon sequestration in oak forests is negative as the community loses oak forests. Under no subsidy, oak water generation also drops to zero. Pine water generation whereas improves over time, as pine volume improves. In another scenario, where there is no lpg subsidy but a PES of 0.001 INR/L for water is offered, there is no difference made to the time path of oak

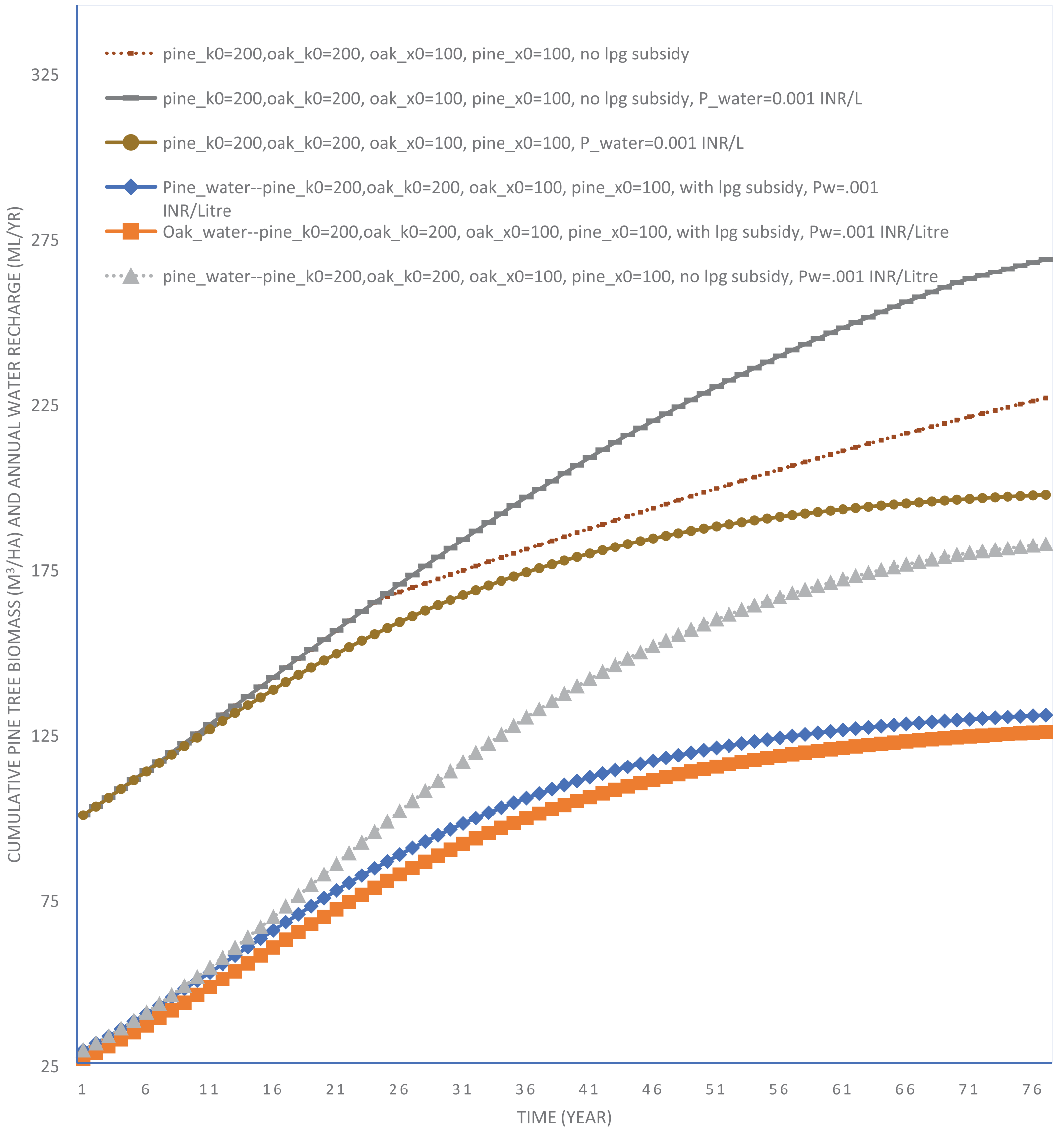

FIGURE 7 Time paths of cumulative pine biomass (per ha) and water recharge under various scenarios

biomass. The high cost of lpg is the overriding influence in deciding whether to preserve oak forests. However, under monoculture oak forests, not providing lpg subsidy does not lead to negative sequestration. This suggests that preservation of mixed forests is more sensitive to lpg subsidies. Finally, it is also worth comparing tradeoffs that are created by a water-based PES due to the sensitivity of community's harvesting decisions to lpg subsidies. As was observed above, in a mixed forest, absence of lpg subsidy leads to maximum harvesting of the oak forests. However, pine forests are not harvested heavily when lpg subsidy is lacking. This is depicted in Figure 9. There is lower harvesting compared to oak forests but harvesting increases over time as pine biomass improves (in comparison to oak biomass which declines over time). However, when there is water-based PES of

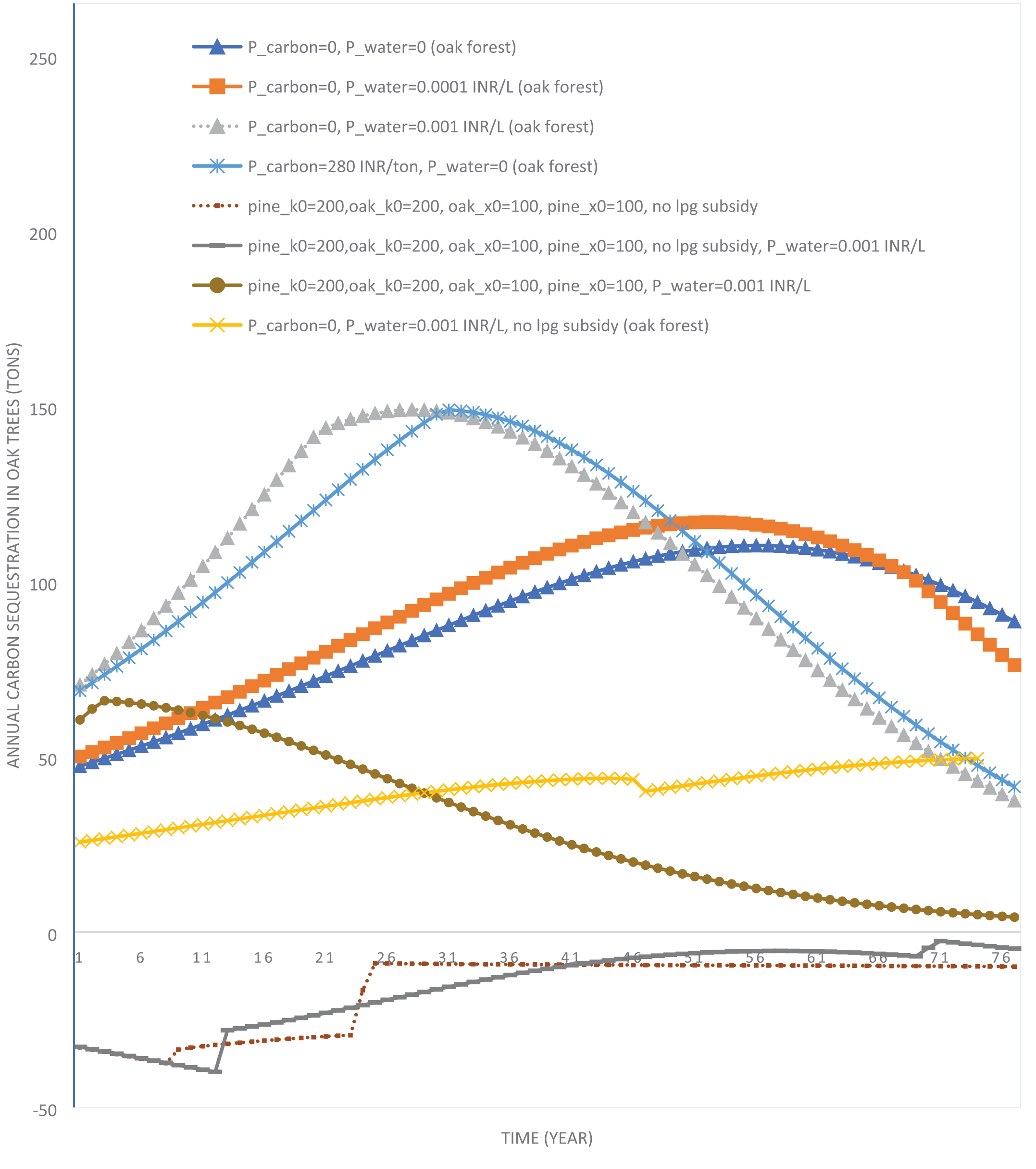

FIGURE 8 Total annual carbon sequestration in oak forests for various scenarios

0.001 INR/L provided (and no lpg subsidy), pine harvesting is postponed and does not begin until year 70. The reason for this delay is that the fuelwood benefits from pines in a mixed forest are not enough to warrant their harvesting, so harvesting is optimal only under zero lpg subsidy. However, in presence of a water-based PES payment, the water generation benefits of pines exceed the fuelwood benefits and improve over time due to an increase in their biomass. Therefore, harvesting becomes optimal only in later years when oak forests are completely decimated. This intuition is further confirmed by considering a scenario where lpg subsidy is present along with a water-based PES, which leads to zero harvesting of pine forests.

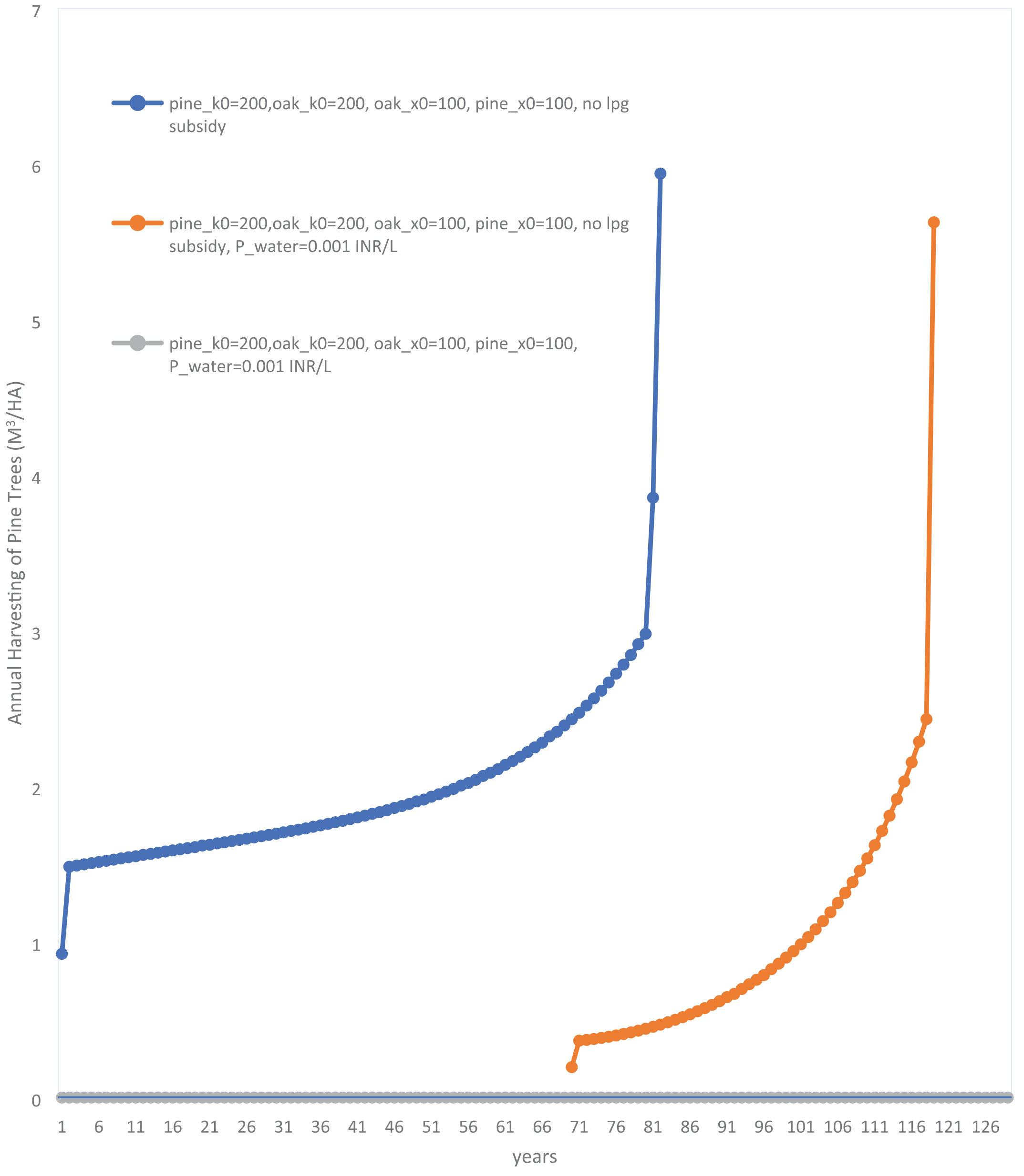

FIGURE 9 Annual harvesting of pine trees compared for scenarios where lpg subsidy is varied. lpg, liquified petroleum gas

3.3 | Risk of forest fires

Next, consider scenarios where there exists a fire risk. The postfire value function is calibrated assuming a PES of 0.001 INR/L in the postfire scenario. Further, in the postfire scenario there is reduced infiltration in forests due to a loss in forest biomass and carrying capacities of 20%. The calibrated postfire value function is presented in Table 1. We first consider a low fire risk

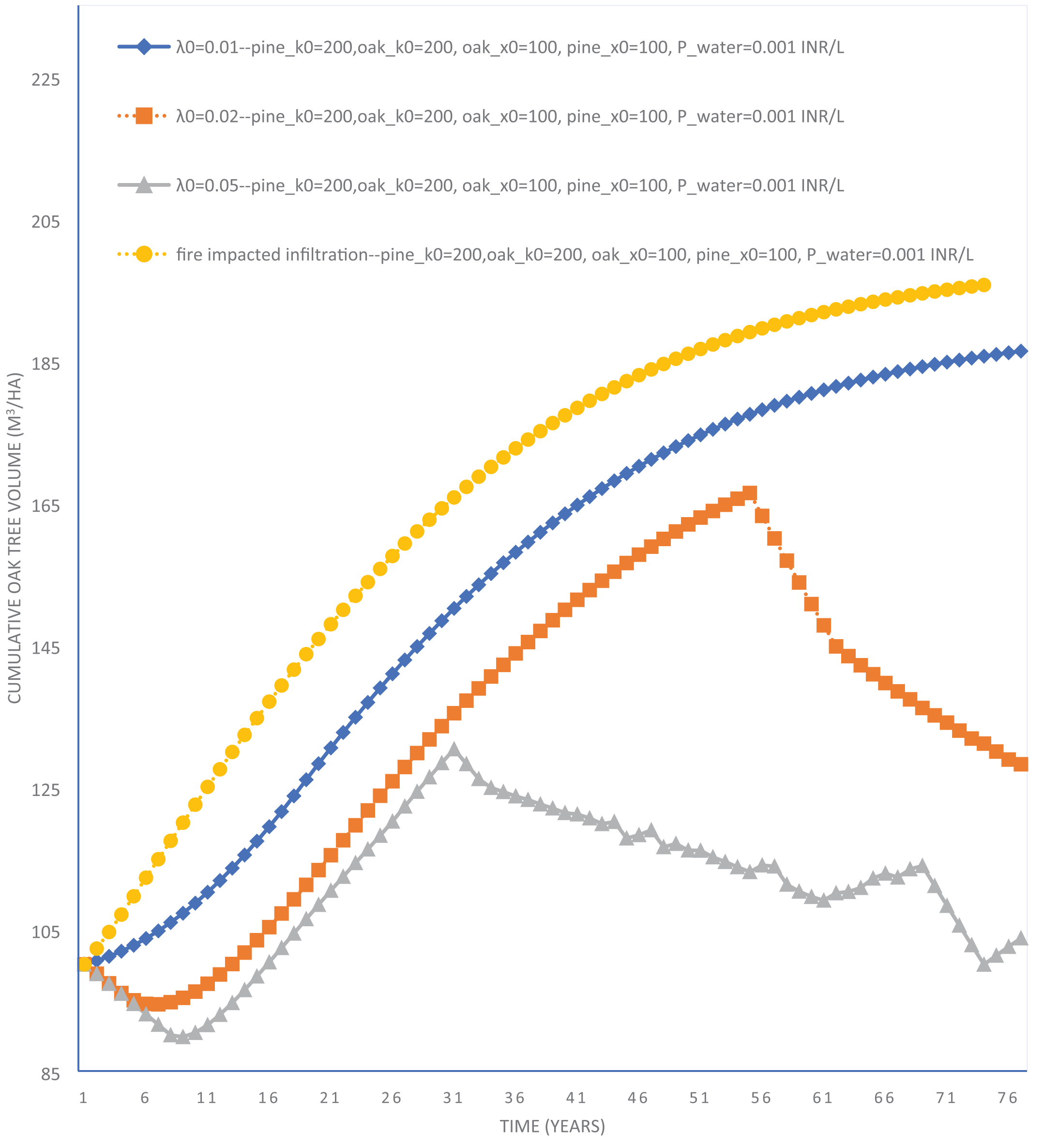

FIGURE 10 Cumulative oak tree volume time paths compared for fire-risk scenarios

scenario ($\lambda_0 = 0.01$). The community increases harvesting in initial years due to resource discounting effect. In the latter years, there is curtailment of oak harvesting and switch to lpg to stabilize oak biomass and to reduce the risk of fires (Figure 10). Therefore, compared to a no-risk scenario where a community manages mixed forests (but with PES of 0.001 INR/L and reduced infiltration due to fires), oak volume is worse under the scenario with a fire risk. An increase in fire risks however further aggravates this resource discounting effect as the long run oak biomass is significantly reduced. Another interesting aspect to note is that while pine biomass (Figure 11) keeps increasing under a low fire risk scenario due to displacement effect, the presence of higher fire risk leads to harvesting of pine trees to stabilize their biomass. This helps with managing fire risks, albeit at the cost of forgone PES incomes from water.

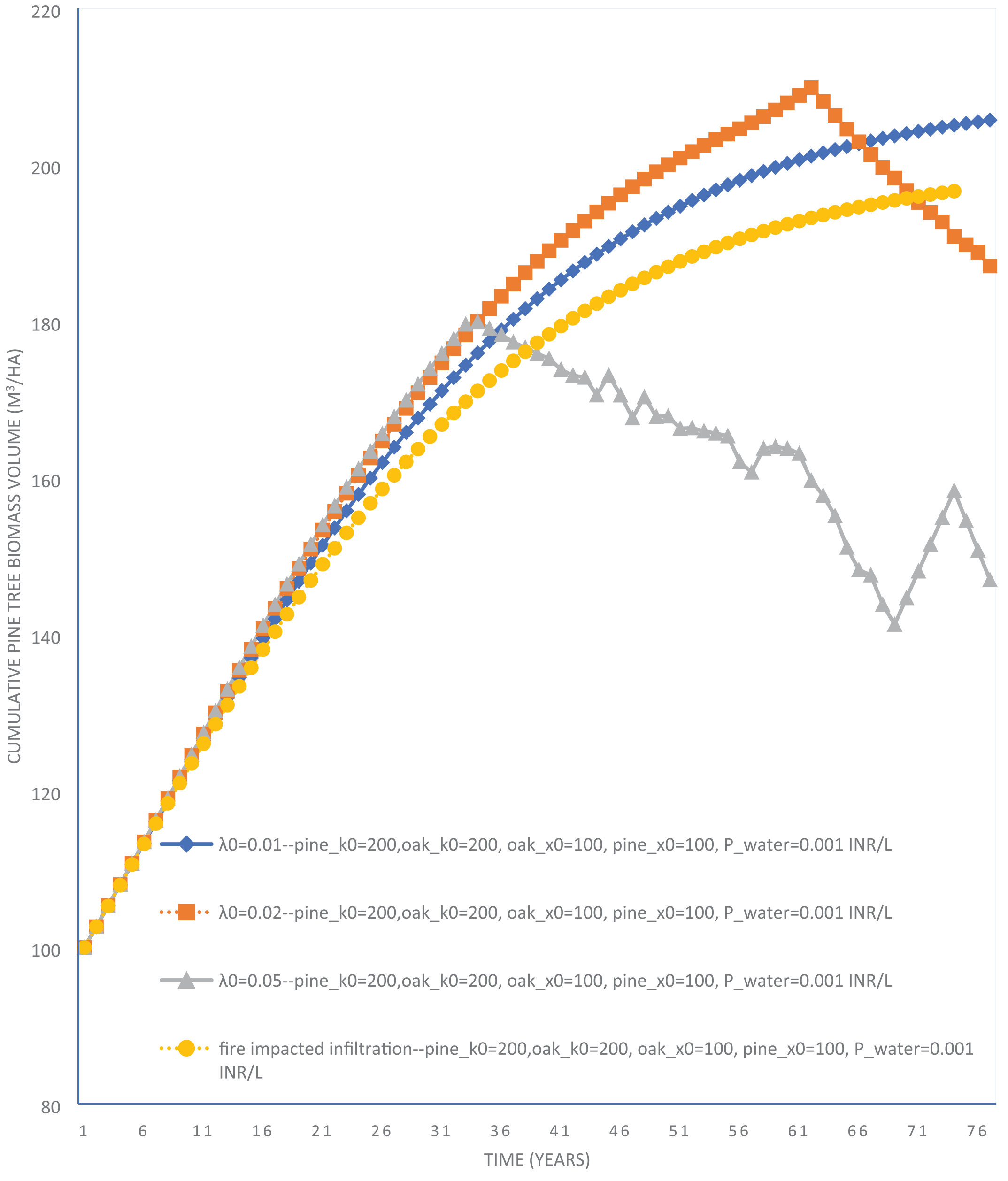

FIGURE 11 Cumulative pine biomass volume (per ha) compared across fire-risk scenarios

4 | LIMITATIONS

Limitations related to model assumptions and parameter estimation are worthwhile noting. Infiltration rate in forests is not derived using a regional hydrological model, rather, estimates are borrowed from existing global literature. The risk of forest fires is modeled endogenous to species composition effect only. There are other factors that cause frequent fires in the region. Frequent droughts, population pressure, illegal harvesting, and deliberate fires are some other notable sources of fires. There would be operational costs associated with monitoring forests for illegal harvesting and hiring staff for PES measurement and accounting. Long-term sustenance of such linked PES projects would therefore require an external facilitator and stable institutional and community involvement. Where such support is lacking, it would become harder to promote coupled PES programs. Finally, this study does not consider the carbon emission implications of switching to lpg on global carbon mitigation objectives.

5 | CONCLUSION

Key results from this study can be summarized as follows. A sustainable management of oak forests does not provide enough fuelwood to meet community's annual energy needs. The community uses subsidized lpg to make up for a shortfall in fuelwood supply. In absence of lpg subsidy or a constant supply of lpg in the high-altitude regions, there would be higher pressure on forests for meeting fuelwood needs. Under a PES mechanism, a water price of 1 INR/kL can lead to significant cutback in harvesting, and a complete switch to lpg in the long run may be possible. Whereas, just using REDD payments as an incentive for forest conservation would require a carbon price of 280 INR/ton ($4/ton) to achieve similar forest biomass outcomes as a water price of 1 INR/kL. Also, to achieve zero fuelwood harvesting right from the first year would require either a water price of 3 INR/kL or a carbon price of 569 INR/ton ($8/ton).

For incentivizing zero fuelwood harvesting, carbon-based PES payments prove more cost effective. At a lpg subsidy of 50%, zero harvesting can be achieved at 569 INR/ton, whereas at 25% subsidy, carbon price needs to be 1260 INR/ton, and at no subsidy the required price is 1950 INR/ton. The overall costs to the carbon-based PES program for achieving zero harvesting for the next 150 years are 4.3, 8.5 and 17 million INR, at 50%, 25%, and 0% lpg subsidy, respectively. Whereas the same corresponding costs for a water-based PES are 99 million, 212 million, and 3.6 billion INR. In terms of affordability of such PES schemes to the local community, PES costs at 3 INR/kL are much cheaper than municipal water supply, which charges a flat rate of 150 INR/month and supplies 40 lpcd (World Bank, 2017). The municipal water costs turn out to be 125 INR/kL. Similarly, carbon-based PES payments of 569 INR/ton (or 8 USD/ton) are comparable to existing PES program in the Khasi hills region of Meghalaya at 6–7 USD/ton (Poffenberger, 2015). Given their low costs, such multi-PES arrangements could be financed under Plan Vivo certification and REDD + schemes.

Management of mixed forests gets complicated by several factors. First, the displacement effect of pine trees requires oakwood harvesting to be reduced compared to that in a monoculture oak forests. Even as pine trees provide lower fuelwood support, it is not optimal to harvest them as this would impact on water recharge rate. In mixed forests, a lack of lpg subsidy can lead to heavy harvesting of the oak forests for fuelwood even under a high PES for water. Whereas, in monoculture oak forests, a lack of lpg subsidy does not lead to a reduction in biomass over time. Therefore, while PES payment can encourage conservation of mixed forests through reduced fuelwood harvesting, their sustainability is far more sensitive to lpg subsidies compared to monoculture oak forests.

In presence of fire risks, that lead to partial loss of biomass and carrying capacity, there is a resource discounting effect present even under a high water-based PES. This results in higher oak harvesting for fuelwood compared to the no-risk case. The loss in water infiltration rate in the postfire scenario creates additional incentive to harvest. When faced with low fire risks, the community harvests more oak forests, which then get replaced by pine forests. However, despite their contribution to increasing fire risks, pines are not harvested and instead allowed to displace oak forests at low fire risks due to their contribution to stream flow. Whereas, when fire risks are higher, it becomes optimal to harvest both forest types.

From a policy perspective, combining multiple environmental services under a single PES project can be challenging due to additional contract and negotiation requirements, and also monitoring challenges may increase. However, given the fact that communities have a higher incentive to conserve their forests when incomes from combined PES are higher (in comparison to individual PES schemes), there is also a possibility that endogenous institutional strengthening could result over time. Combining two ES has a practical advantage as their beneficiaries are different. Carbon payments could be made by international programs such as REDD under Plan Vivo certification, whereas local communities would pay for water services. The results from this study indicate that paying for water in addition to carbon credits leads to additional conservation. However, the lowest cost to society of attaining zero harvesting is possible through higher carbon prices. In reality, higher carbon prices may not materialize in absence of a willing buyer. Whereas a lower carbon price coupled with water payments can be equally effective in achieving higher conservation targets.

It is feasible to implement the proposed PES mechanism in Uttarakhand as there is a ready market for water services generated by the program given the persistent water scarcity faced in the region. The low carbon and water costs associated with generating environmental services make it an attractive option for communities with limited alternatives. The government's ongoing lpg subsidies help mitigate cost shocks to fuelwood-dependent PES schemes. Further improving lpg reliability and accessibility in high altitude areas would go a long way towards supporting forest conservation efforts.

AUTHOR CONTRIBUTIONS

Ram Ranjan: conceptualization (lead); data curation (lead); formal analysis (lead); investigation (lead); methodology (lead); project administration (lead); resources (lead); software (lead); supervision (lead); validation (lead); visualization (lead); writing original draft (lead); writing review and editing (lead).

ORCID

Ram Ranjan http://orcid.org/0000-0002-8756-9392

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APPENDIX A: DISCUSSION OF PARAMETER ESTIMATION

Stream water infiltration rate is higher in oak forests compared to pine forests. Thompson et al. (2011) measured infiltration rate to be higher in hardwood oak forests of North

Carolina (at 14.55 mm/h) in comparison to pine forests (5.3 mm/h) within the same region. In the Uttarakhand region, water recharge rate in pine forests has been estimated to be lower at 8 percent compared to 23% in oak forests (Agarwal et al., 2018). A much earlier experimental study conducted in the southern Appalachian region of North Carolina compared water recharge in pine and oak forests that received an annual rainfall of 68 inches. Oak forests led to an annual stream flow of 31 inches. However, after clearing the land and allowing pine to grow on the same site, it was noted that annual stream flow reduced to 5.6 inches over a 10-year period. In another study in California oak woodland rangelands, a mean rainfall (over a 20-year period) of 734 mm/year resulted in a mean annual stream flow of 353 mm/year (Lewis & Likens, 2000). These observations are used in our study to calibrate differential stream flow rates from pine and oak forests. For further details, the reader is referred to Ranjan (2019b).

Fires affect volume and quality of water generated from forests. The forest floor comprises litter and duff layers which help with rainwater infiltration, storage, and reduced runoff. After severe fire, the organic matter in litter gets charred and turns into ash and charcoal. Further burning of organic matter releases gases which make the forest floor water-repellent leading to reduced infiltration (Martin & Moody, 2001). Martin and Moody (2001) measured infiltration rates in severely burned New Mexico Pine and mixed conifer forests using artificial annual rainfall between 97 and 440 mm/h. The steady state ratio of burned to unburned sites′ infiltration rates was 0.15 for pine forests and 0.38 for mixed conifer forests. Further, the steady state infiltration rates between granitic and volcanic soils were found to be similar. Robichaud et al. (2016) measured infiltration rates following severe fires in 2000 in the montane forests of western Montana. Fire in burned sites led to higher water repellency (88%) and reduced infiltration rate (of 30 mm/h) compared to control sites where infiltration rate was higher at 44–48 mm/h. However, they also observed that after 5 years of fire, infiltration rate in burned sites had increased to 84 mm/h and fire altered repellency had reduced to 48%. Fire related infiltration loss in our study is estimated using observations in Robichaud et al. (2016). Pine trees are relatively more fire prone (risk is seven times higher) compared to oak trees (Babu et al., 2016). Between 1998 and 2012, 13,000 ha of Uttarakhand forests were destroyed by fires. In our model, it is assumed that in the postfire scenario, oak and pine biomasses as well as the carrying capacities would be lost by 20%.

For estimation of oak and pine biomass growth rates, carbon sequestration rates in Uttarakhand forests, annual fuelwood consumption in the study area and use of lpg among communities, the reader is referred to Ranjan (2019a).