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Mitigating vector-borne pathogen spread risks through promoting Gmelina arborea-based afforestation and agroforestry on private farms

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A B S T R A C T

Bat-borne pathogens such as Nipah virus, SARS-CoV2, and Ebola have been causing significant losses to the global economy and human lives. In this paper, the role of afforestation and agroforestry in mitigating risk of bat-borne disease transmission to humans is explored using an epidemiological-agroforestry model of land use decision on private farms. Farmers owning land in fragmented forest areas are financially incentivized to grow Gmelina arborea-based forests or intermix them with agricultural crops. This reduces forest fragmentation through creating connectivity between forest patches. While agroforestry may increase the chances of contact between bats and humans, a reduction in forest fragmentation improves the carrying capacity of bats and reduces their risk of migration and roosting near human dwellings. Results indicate that afforestation on private lands or promoting agroforestry can help reduce the risk of virus transmission to humans. A small sum paid under a payment for ecosystem services (PES) scheme would be sufficient to incentivize farmers to convert their farmlands into Gmelina arborea-based agroforestry or forests. In absence of substantial PES incentives, private landowners may delay land conversion when financial benefits generated through agroforestry timber sales carry higher weight in their optimization decisions. Whereas the socially optimal land use option would be to immediately convert farmland in affected areas to agroforestry or forests. Therefore, from a policy perspective, promoting PES-based forestry and agroforestry in fragmented bat habitats can help prevent spread of deadly viruses in the future.

1. Introduction

Bats are known to be carriers of several zoonotic pathogens (Letko et al., 2020; O’Shea, 2014) even though they remain unaffected by them (Irving et al., 2021). Despite bats being major vectors, the transmission of pathogens from bats to humans is considered a rare event (Streicker et al., 2010). However, lately there has been a spike in bat-borne disease transfers to humans. Amongst the many deadly diseases carried by bats are Hendra virus, Marburg, Nipah virus, Ebola, SARS CoV, SARS-CoV-2 and SARS (Berge et al., 2017; Letko et al., 2020). Viruses are transmitted mainly through bat saliva, urine and feces. In Asia, Nipah virus spread from bats to humans and pigs has been periodically occurring since 2010 (Subudhi et al., 2019). Similarly, Hendra virus has spread from bats to horses and humans in Australia (Subudhi et al., 2019).

A reason bats remain immune to viruses despite harboring them in their bodies lifelong is their ability to suppress inflammation caused by virus-induced immune response. This ability to suppress inflammation is further attributed to their evolution. Constant flight in bats leads to damaged DNA which would normally result in inflammation. However, prolonged immune response through inflammation is costly and bats have evolved to suppress it (Sheldon and Verhulst, 1996; Subudhi et al., 2019). This ability to suppress inflammation helps them survive the many viruses they harbor.

Our understanding of the zoonotic risks posed by bats as well as their behavior with respect to the environment is limited (Letko et al., 2020). Several studies have tried to understand the process of virus shedding amongst bats in order to predict periods of high spread risk to the host environments. Bats may be persistently infected by zoonotic viruses and shed them episodically, especially when stressed (Plowright et al., 2016; Rahman et al., 2010; Sohayati et al., 2011). In some bats, viral shedding is associated with hibernation. Big brown bats (Eptesicus fuscus) undergo a suppression of their immune response and a reduction in antibody levels at the end of the hibernation period, which results in viruses reactivating from latency (Gerow et al., 2018; Subudhi et al., 2019). Other stressors may include habitat loss and competition for resources. Subudhi et al. (2019) recommend further exploring the role of habitat destruction through deforestation in causing stress induced virus shedding in bats. Human intervention through anthropization of natural
environments has played a major role in destroying bat habitats. SARSCoV-2 (COVID-19) outbreak emerged in late 2019. WHO declared it a pandemic in March 2020. At the time of writing, it was still prevalent in many countries around the world, including India. However, following the outbreak the focus on bats has intensified globally, as agricultural expansion is a key driver of deforestation, the reduction in bats and humans is linked with an agroforestry-based land use model to explore the possibility of incentivizing private participation towards contagious disease risk mitigation. There is no dearth of mathematical models exploring disease transmission and spread dynamics between bats and humans. Similarly, the beneficial impact of afforestation and agroforestry on the environment is also well established. However, the use of afforestation or agroforestry on private lands to provide connectivity to threatened species and mitigate disease spread risks while simultaneously addressing conservation objectives has not been explored thus far. The model developed in this study addresses this gap in the literature. The key contribution of this study is that through linking an epidemiological model of pathogen transfer to land use decisions, it provides a framework for incentivizing private participation in environmental restoration and disease spread prevention efforts. In addition, through applying the model to a local context, it demonstrates how restoring fragmented habitats can be an effective way of managing bat-borne diseases such as Nipah virus or SARS.

An extensive review of mathematical models dealing with zoonotic pathogen dynamics can be found in Allen et al. (2012). Examples of mathematical models of Nipah virus infection and spread also exist in the literature (Sinha and Sinha, 2019; Sultana and Podder, 2016). Chen et al. (2020) used a Bat-Hosts-Reservoir-People linkage model for exploring SARS-CoV-2 spread dynamics. Under such models, human and bat populations are generally divided into susceptible, exposed, infected (asymptomatic as well as symptomatic) and recovered categories (Chen et al., 2020). Based upon virus transmission rates between these categories as well as the birth and mortality rates of hosts, one can derive the basic reproduction number ($R_0$). This number measures the number of secondary infections caused by a single infected individual. A low $R_0$ ensures that disease spread can be contained. Other relevant examples of mathematical models exploring host-pathogen disease dynamics can be found in Hethcote et al. (2005) and Brauer (2008).

Agroforestry systems have been found to mitigate the effects of habitat conversion and agricultural intensification on bats assemblage (Williams-Guillen et al., 2015). While there are no known studies exploring the role of afforestation and agroforestry in mitigating bat-borne disease risks, their benefits in other areas have been widely acknowledged. The spread of Ebola virus disease (EVD) in West Africa was found to be higher in forest regions that were heavily fragmented (Rulli et al., 2017). Other benefits of agroforestry trees include lowering ambient temperatures (Kanzler et al., 2019), preventing soil erosion, sequestering soil carbon, and enhancing soil fertility (Cardinael et al., 2017). They also help with protecting biodiversity, mitigating groundwater pollution, and flooding prevention (Patel-Weynard et al., 2017). As some agroforestry trees can grow quickly, they make ideal candidates for short-rotation coppice harvesting, generating substantial revenues to the farmers (Gunter et al., 2011). Agroforestry has been found to improve species richness of trees to the same extent as forests (Harvey and Villalobos, 2007). Pest control benefits of agroforestry trees have also been recognized. Agroforestry has also been promoted in some countries, such as Nepal, to provide resilience against climate change (Arval et al., 2019).

With this background, we turn to developing the formal model next. We first develop an epidemiological model of virus transmission between bats and humans in section 2.1. This model is then linked to an agroforestry model in section 2.2. A representative farmer first optimizes long run income from land use allocation, without considering the impact of agroforestry on disease risk mitigation. The farmer receives PES payments for the benefits provided by agroforestry towards reducing forest fragmentation and risk of virus spread. However, PES
payments are determined exogenous to the model. Finally, land use allocation is also derived from the perspective of a social planner who is primarily concerned with the disease prevention benefits of agroforestry. The model (in section 2) is presented in the context of India, where many species of bats are found and there have been cases of bat-borne diseases in the recent past. In section 3, a numerical example is presented using the Nipah virus as a case study, however, the findings of the model (as presented and discussed in sections 3 and 4) are applicable to all potential diseases carried by bats, including SARS-CoV.

2. Model

Consider a farming community, represented by a single farmer, that optimizes over its land use allocation between open farming of wheat crop and wheat and gamhar based agroforestry. Wheat can be intermixed with agroforestry trees such as gamhar (G. arboresa) or poplar (P. deloides). Further, agroforestry is an attractive option for the farmer. The farmer harvests mature gamhar trees and replants new ones at regular intervals. However, benefits from agroforestry are affected by timber prices, the impact of tree shading on wheat productivity as well as any PES payments that the farmer receives. Forest fragmentation results in a higher rate of bat-borne virus transmission, as in absence of forest habitat bats tend to roost near human habitations. Planting agroforestry trees along with crops can be an effective way of mitigating virus spread risk, for which the farmer receives additional PES payments. When the farmer plants only trees, and no crops, the risk of spread can be further reduced as the chances of contact with bats during planting and harvesting are reduced.

2.1. An epidemiological model of bat-borne disease spread

Let $s_{\text{hum}}$, $i_{\text{hum}}$, $r_{\text{hum}}$, $p_{\text{hum}}$ be the susceptible, infected, recovered, and total human populations at time $t$. Similarly, $s_{\text{bat}}$ and $i_{\text{bat}}$ are susceptible and infected bat populations at time $t$. Further, let $\beta_{bh}$ and $\beta_{hh}$ be bat to human, and human to human disease transmission rates. Also, $\alpha_{\text{hum}}$ is the death rate of infected humans and $\gamma$ is the recovery rate of infected humans. The infected bat population never completely recovers from the virus. Following the literature on bat epidemiology (Allen et al., 2012; Sinha and Sinha, 2019; Chen et al., 2020), the rate of change in susceptible human population is given as:

$$\dot{s}_{\text{hum}} = -\beta_{bh} \frac{s_{\text{hum}} i_{\text{bat}}}{p_{\text{hum}}} - \beta_{hh} \frac{s_{\text{hum}} i_{\text{hum}}}{p_{\text{hum}}}$$ (1)

Fig. 1. Time paths of cumulative human populations susceptible to virus infection under the base case scenario and scenarios without the agroforestry option involving varying levels of initial bat population sizes, bat-to-human transmission rates, human-to-human transmission rates and bat mortality rates.

The rate of virus transmission from bats to humans varies over time. Those who get infected by the bat virus join the infected population, the rate of growth of which is given as:
\dot{i}_{hum} = \beta_{bh} \frac{s_{hum} i_{hum}}{p_{hum}} + \beta_{hh} \frac{s_{hum} i_{hum}}{p_{hum}} - \alpha_{hum} i_{hum} - \gamma i_{hum} \tag{2}

A proportion of the infected population, after recovering, joins the recovered population whose rate of change is given as:

\dot{h}_{hum} = \gamma i_{hum} \tag{3}

For simplicity, and without any loss in generality, no birth or death or immigration is assumed for the human population. Total population is the sum of susceptible, infected and recovered humans, given as:

\begin{align*}
    p_{hum} &= s_{hum} + i_{hum} + h_{hum} \tag{4}
\end{align*}

Likewise, bat population dynamics is modeled next. The population of susceptible bats grows following a logistic function (see Hethcote et al., 2005 for example of an epidemiological model using logistic growth rate in the host population) as:

\begin{align*}
    \dot{s}_{bat} &= \rho_{bat} (s_{bat} + (1 - \phi) i_{bat}) \left(1 - \frac{p_{bat}}{k_{bat}} \right) - \alpha_{bat} s_{bat} - \beta_{bb} \frac{s_{bat} i_{bat}}{p_{bat}} \tag{5}
\end{align*}

where \(\rho_{bat}\) is the intrinsic growth rate of bats. Infected bats are assumed to have a marginally lower growth rate, which is reflected through the additional parameter \(\phi\). Offsprings of infected bats join the susceptible population. A portion of susceptible population moves into the infected category due to disease transmission from infected bats. The natural death rate of bats is given by the parameter \(\alpha_{bat}\). Bat population growth is constrained by the carrying capacity of their habitat (Brauer, 2008; Clement and Castleberry, 2013). Carrying capacity \(k_{bat}\) is modeled as:

\begin{align*}
    k_{bat} &= \text{den}_{bat} (a_{gamhar} + f_0) \tag{6}
\end{align*}

Carrying capacity is a function of the existing forest area \(f_0\) which is assumed to remain unchanged. Carrying capacity can also be increased through agroforestry or afforestation on private farms represented by area \(a_{gamhar}\). Parameter \(\text{den}_{bat}\) is the bat density in a hectare of forests, which is assumed constant. The rate of change in infected bat population is defined as:

\begin{align*}
    \dot{i}_{bat} &= \beta_{bb} \frac{s_{bat} i_{bat}}{p_{bat}} - \alpha_{bat} i_{bat} \tag{7}
\end{align*}

Finally, total bat population comprises the sum of infected and susceptible bats:

\begin{align*}
    p_{bat} &= s_{bat} + i_{bat} \tag{8}
\end{align*}

Next, we set up an agroforestry model that helps determine the rate of bat-human virus spread through affecting forest fragmentation.

2.2. A forestry and agroforestry model of virus risk mitigation

Forest fragmentation in the context of bat habitats has not been modeled in the literature. The chances of wild animals coming in contact with humans increases with the length of forest edges (Pfeifer et al., 2017). However, in case of bats, the risks increase significantly when their habitat is destroyed due to agricultural intensification and they are
forced to migrate closer to human settlements. Therefore, when fragmented forests are restored through afforestation and agroforestry, it helps reduce the risk of infection through connecting forests and increasing the carrying capacity of bats. As a result, we do not adopt a forest edge effect related risk pathway in our study. Further, it is assumed here that the increase in risk of virus spreading to the farmers working in close proximity to the agroforestry trees is insignificant in comparison to the reduction in risk of spread through a lower bat migration rate to human settlements.

We construct a fragmentation variable \( g_t \) in natural forests \( (f_0) \), which is defined as:

\[
g_t = 1 - \frac{(a_{gamhar}a_{gamhar})g_1}{(a_{gamhar}a_{gamhar})g_1 + g_2}
\]  

(9)

where \( a_{gamhar} \) is the area of private farms under gamhar tree based agroforestry and \( a_{gamhar} \) is the average age of the gamhar trees. Parameters \( g_1 > 0 \) and \( g_2 > 0 \) influence the nature of the relation between forest area and age and the level of fragmentation. The product of the area and age of trees defines the fragmentation variable \( g_t \) which ranges between 0 and 1. When the product of age and area of trees increases, the level of forest fragmentation is reduced. The assumption here is that original forests of size \( f_0 \) are scattered in patches due to anthropization. When the level of fragmentation is high, the risk of infection spreading from bats to humans is also high. Converting farmland into agroforestry helps connect these fragmented patches and reduces the risk of disease spread, \( \beta_{bh} \) (Estrada et al., 1993), which is defined as:

\[
\beta_{bh} = \beta_0 \left( 1 + \frac{g_3}{g_3 + g_4} \right)
\]  

(10)

The risk of spread may evolve non-linearly with fragmentation as determined by parameters \( g_3 > 0 \) and \( g_4 > 0 \). Parameter \( \beta_0 \) is half of the highest rate of infection possible when fragmentation level reaches its maximum value of 1. Further, \( \beta_0 \) is also the exogenous component of infection which is independent of forest fragmentation. \( \beta_{bh} \) has also been modeled in the literature as a function of the density of human population (for instance Brauer, 2008). However, in this study, it is assumed that higher fragmentation would automatically result in higher contact with the existing population. Further, it is also possible for humans to come in contact with the bats while harvesting crops in the agroforestry regions, however, such risks of infection from agroforestry regions are likely to be low. We incorporate this possibility through considering a case of restoration of fragmented habitat through afforestation where the farmer plants arborea trees but no agricultural crops.
and hence there is a reduced chance of their coming in contact with bats. The assumption here is that under afforestation without intercropping with agricultural crops, the value of $\beta_0$ is lower than that under agro-forestry, as under the latter, chances of humans coming in contact with the bats increase. However, even under agroforestry, when the average age of gamhar trees increases, there is a mitigation of bat to human infection rate due to increase in the carrying capacity of the forests.

The average gamhar age $age_{gamhar}$ is further expressed as a function of land conversion in each year as well as harvesting of mature gamhar trees (following Ranjan, 2021) as:

$$age_{gamhar} = \int_0^t \frac{y_z}{a_{gamhar}} \mod ((t-z), T) dz$$  \hspace{1cm} \text{(11)}$$

where $y_z$ is the area converted into gamhar trees in year $z$ and $T$ the rotation period for harvesting mature age gamhar trees. The $\mod((t-z), T)$ function represents the difference left after dividing $t-z$ by $T$ and measures the age of trees at time $t$ planted on area converted in year $z$, after accounting for previous rotations. For example, if current year is 9 and rotation length is 7, a tree that was planted on area converted in year 1, would be $\mod(9-1, 7)$ or 1 year old, as it would have already gone through 1 rotation in year 8. The multiplication by the ratio of area planted in year $z$ to total area at time $t$, $\frac{y_z}{a_{gamhar}}$, further adjusts this age.

Agroforestry trees can generate substantial revenues to the farmers through harvesting of mature trees for timber. The total timber biomass in gamhar trees grows non-linearly, initially increasing at a rapid rate but slowing down after 7 or 8 years. Accordingly, biomass $m_{gamhar}$ in a stand of gamhar trees at $t$ can be expressed as:

$$m_{gamhar} = m_{max} \left( \frac{(t-z)^{b_1}}{(t-z)^{b_1} + b_2} \right)$$  \hspace{1cm} \text{(12)}$$

where $b_2 > 0$ and $b_1 > 0$ are parameters that determine an initially increasing growth rate in biomass which later plateaus with age, $m_{max}$ is the maximum biomass accumulation on a unit hectare of land for trees of any age, and $z$ is the time of initial planting of trees. The term $\left( \frac{(t-z)^{b_1}}{(t-z)^{b_1} + b_2} \right)$ ranges between 0 and 1. Assuming a constant price of timber $Price_{gamhar}$, the farmer can earn income $inc_{gamhar}$ from harvesting $h_{gamhar}$.
Assuming that only mature age gamhar is harvested to maximize profits, the farmer would be able to harvest a total volume of gamhar timber in year $t$, given by the expression:

$$h_{\text{gamhar}} = m_{\text{max}} \left( \frac{T^n}{T^n + b_2} \right) \left( y_{t-2T} + y_{t-2T} + y_{t-3T} ... + y_{t-nT} \right)$$

(14)

If a farmer planted an area $y_t$, $3T$ years ago, it would be harvested in years $2T$ and $T$. Further, trees in that area would also become mature in year $t$. Using similar argument, all trees planted in $T$, $2T$, $3T$ ... until $nT$ years ago would become mature for harvesting in year $t$, where $n$ is equal to $\frac{t}{T}$.

The farmer can grow wheat in the gamhar tree areas as trees would only occupy land equal to their total basal area. However, wheat planted close to gamhar would also suffer from a shading effect. Further, gamhar roots would compete for water and other nutrients, reducing the availability of the same for wheat crops. Agroforestry trees, such as poplar and gamhar, cause more losses to crops when their canopies are bigger and when they are older. We need to account for this productivity loss adjusted output through the variable $\theta_{\text{wheat}}$. $\theta_{\text{wheat}}$ is measured as a function of the average age of gamhar trees (following Ranjan, 2021):

$$\theta_{\text{wheat}} = \left( \theta_0 - \theta_1 \frac{\text{age}_{\text{gamhar}}}{\text{age}_{\text{gamhar}} + \theta_2} \right)$$

(15)

where $\theta_1 > 0$, $\theta_2 > 0$, $\theta_3 > 0$ are parameters relating the effect of age of gamhar trees on productivity loss. When gamhar trees are not planted, their average age would be zero, which would result in a constant productivity parameter $\theta_0$. However, the adverse effect $\theta_{\text{wheat}}$ is only on area $(a_{\text{gamhar}} - \text{tree area} a_{\text{gamhar}})$, where tree area is the basal area of a single gamhar tree.

Now, one can write the total wheat income of the farmer as a function of area under gamhar trees and area that has not yet been converted into gamhar plantations as:

$$\text{inc}_{\text{wheat}} = \theta_{\text{wheat}} \text{wheat}_0 \left( a_{\text{gamhar}} - \text{tree area} a_{\text{gamhar}} \right) + \text{wheat}_0 (A_1 - a_{\text{gamhar}})$$

(16)

In equation (16), wheat$_0$ represents the fixed wheat income per ha earned in absence of shading effect and net of all input costs. $A_1$ is the total farm size. The area $(A_1 - a_{\text{gamhar}})$ has not yet been converted into gamhar plantations, as a result, wheat crops grown on this area are not affected by gamhar shading effect and competition for nutrients and...
water. The rate of change in area under gamhar is given as:

$$\dot{a}_{\text{gamhar}} = y_t$$

(17)

Whereas the rate of loss in total area under wheat crops is given as:

$$\dot{a}_{\text{wheat}} = -y_t \text{tree}_{\text{area}}$$

(18)

where \text{tree}_{\text{area}} is the basal area of a single tree. Finally, we can set up the utility maximization problem of the farmer who maximizes his/her sum total of utility \(U\) from total income \(\text{inc}_{\text{tot}}\) over time as:

$$U = \int \log (\text{inc}_{\text{tot}}) \exp(-\rho t) dt$$

(19)

where \(\rho\) is the rate of time preference, \(\text{inc}_{\text{tot}}\) is the sum of incomes obtained from wheat farming \(\text{inc}_{\text{wheat}},\) timber sales \(\text{inc}_{\text{gamhar}},\) and any PES income \(\text{inc}_{\text{pes}},\) that they receive for helping reduce the risk of disease spread. PES income could be simply a function of the total area under gamhar trees in any given year, given as:

$$\text{inc}_{\text{pes}} = \text{pes}_0 \text{a}_{\text{gamhar}}$$

(20)

where \(\text{pes}_0\) is an exogenously determined PES payment per hectare of farmland converted into agroforestry.

If instead of the representative farmer, a social planner optimizes over land use decisions, taking into account only the value of human lives saved, one can represent societal utility as declining in human mortality. Accordingly, we specify a hypothetical social utility function as:

$$U = \int \log \left( \frac{\text{val}_0}{\text{val}_0 \alpha_{\text{hum}} + c_1} \right) \exp(-\rho t) dt$$

(21)

where \(\text{val}_0\) is the fixed value derived per period by the planner when there is no mortality and \(c_1\) is a small constant. The above utility function assumption implies that utility declines considerably even if only a few human lives are lost. Next, we present an empirical application of the above model.

### 3. Numerical example

The numerical example presents a case study of Nipah virus spread in Fig. 6.
India. Nipah virus, which has been recurring in India and Bangladesh since 2001, causes a high fatality of about 78% in humans (Wenzel, 2014). Examples of mathematical models of Nipah virus infection and spread dynamics can be found in the literature (Sinha and Sinha, 2019; Sultana and Podder, 2016). A much broader review of various types of mathematical models dealing with Zoonotic pathogens is presented in Allen et al. (2012).

Pteropus giganteus (flying fox bats), a frugivorous species of bats, is considered the main carrier of Nipah viruses in India and Bangladesh. Bats are also the carriers of other deadly viruses such as Ebola and SARS-CoV2 (Nabi et al., 2020). In India, 11 bat species have been identified as potential Nipah virus carriers (Plowright et al., 2019). Due to the loss of forests, that serve as their main habitat, bats have been forced to seek alternative roosting places in anthropized areas. This increased proximity between bat and human populations has resulted in a significant spike in virus transmission to humans in Bangladesh (Nabi et al., 2020). Bats normally forage within 1 km radius from their roosts (Clement and Castleberry, 2013). The growth rate in bat populations is usually low as an adult pair produces only one bat a year. The intrinsic growth rate of bats is small and has been estimated at about 0.1 (Haider et al., 2017). Bat density varies considerably in the forests. In the Yasawa archipelago of Fiji, mean bat density was 0.43 bats/ha, whereas in the forested areas it was as high as 9.5 bats/ha (Luskin, 2010). Big-eared bats, C. rafinesquei, found in the US, have a density ranging between 0.07 adult bats/ha to 1.18 adult bats/ha (Clement and Castleberry, 2013). Bat population density is also affected by forest type and age. There were 2–14 times more bats detected in old growth pine forests compared to other forests in central Ontario (Jung et al., 1999). Bat population growth can be adversely affected by habitat destruction. Forest fragmentation, in particular, has an adverse impact on species richness in bats. A negative relationship was observed between bat species richness and isolating distance of forest fragments in tropical rainforests of southern Veracruz Mexico (Estrada et al., 1993). Man-made islands of vegetation have been recommended as a potential way to improve bat populations as this helps with reducing the distance between two forest patches (Estrada et al., 1993). Forest fragmentation also results in concentration of bat populations, which increases virus spread risks (Estrada et al., 1993). Forest fragmentation has been identified as one of the major determinants of Nipah virus spread in Bangladesh. Nipah virus infection rate in Bangladesh was higher in regions with higher human

Fig. 7. Total bat population over time (including both susceptible and infected bats) for the base case and the no-agroforestry scenarios involving varying levels of initial bat populations and bat mortality rates.
population density and also higher in areas that had more fragmented forests. Villages that had more forest patches (at 0.5 per km$^2$) had a higher infection rate compared to those with less patches (at 0.32/km$^2$). Further, villages with a higher number of forest fragments also had a higher number of roosts (Hahn et al., 2014). Nipah virus spread rate related parameter values for this study are adapted from Sinha and Sinha (2019), who do a comparison of spread rates across India, Bangladesh and Malaysia.

In the numerical example, gamhar trees are used, as gamhar based agroforestry is considered a viable option in India. On agroforestry farms, an average of 600 trees per ha can be planted. Biomass accumulation in $G.\ arborea$ increases from 40 tons/ha in year 5 to 85 tons/ha in year 10, before plateauing to 448 tons/ha in year 28 (Gunter et al., 2011). Gamhar timber can fetch a decent price in the range of 8,000–10,000 inr/ton. Gamhar trees are also suitable as bat habitats. $P.\ giganteus$ prefers taller trees with bigger canopy and its density is higher in dense forests compared to flood affected areas (Hahn et al., 2014). Flying foxes in India roost in Mango, Sheesham, Peepal, Eucalyptus, Banyan, Tamarind and Gmelina arborea (gamhar) trees (Bhushan n.d.). With this background, we next present results from the numerical example. Parameter values used in the numerical example are presented in Table 1.

4. Results

The numerical example is performed using the general algebraic modeling systems (GAMS) software with a time horizon of 150 years and discount rate of 3%. Optimization over 150 years mimics an infinite horizon problem. The base case and its variant scenarios are run (in section 4.1) without the agroforestry option. In the base case, it is assumed that there is 2000 ha of old growth forest which serves as a natural habitat for bats. The forest is fragmented, having several patches, which results in higher frequency of disease transfer to humans. Modeling the spatial distribution of forest fragments is not considered in this study. The spatial aspects related to various forest patches and their connectedness through agroforestry are incorporated through the

![Graph](image_url)  
**Fig. 8.** Total susceptible human population time paths under the base case and agroforestry scenarios involving varying levels of PES payments, lower timber prices and land sizes.
assumption that as area under agroforestry increases, fragmentation gets reduced in a non-linear fashion. The base case and its variant scenarios concentrate purely on understanding the epidemiological aspect of the model where the effects of a higher disease transmission rate between humans and between bats and humans are explored. These scenarios assess virus transmission dynamics between susceptible and infected human populations and linkages between infection-led mortality and recovery rates. Similarly, infection transmission dynamics between susceptible and infected bats is also explored. Section 4.2 then presents results including the agroforestry and afforestation options.

Under the agroforestry scenarios, a farming community owning 200 ha of farmland allocates its land into agroforestry over time. Agroforestry helps reduce fragmentation in bat habitats through providing continuity between old forest patches. This lowers disease transmission rates between bats and humans. The results further explore optimal land use allocation decisions for private farmers when faced with PES incentives, and also for a social planner. Finally, a scenario where farmers plant trees on their farms without undertaking cropping is also explored.

4.1. Base case results

We first consider scenarios in absence of any agroforestry uptake by the farming community. In the base case, the susceptible human population continuously declines over time as it gets gradually infected by the virus (Fig. 1). The infected population (Fig. 2) whereas increases in the initial years and then starts to decline after reaching a peak. The decline in infected population is determined by a reduction in the susceptible population as those that are infected either suffer mortality (Fig. 3) or recover. As the recovered population (Fig. 4) is assumed to acquire immunity, there is a reduction in the total population that can get infected as time progresses. This explains the non-linear shape of the infected population over time. The recovered population gradually increases to cover the entire population in the long run.

Bat population is divided into susceptible and infected categories (Fig. 5 and Fig. 6). The susceptible population increases over time as the carrying capacity of bats in old forests is about 800. However, the growth rate in overall bat population is hampered by the infection rate as infected bats are assumed to have a lower growth rate. The infected
bat population continues to increase over time as the total bat population also increases (Fig. 7). In a scenario where the maximum infection rate of humans by bats ($\beta_0$) is higher at 0.75 (compared to the base case value of 0.5), there is a steeper decline in the susceptible population and a higher rate of infection in the initial years. However, in the latter years (after year 36) the infection rate under a higher $\beta_0$ scenario falls below the base case due to a reduction in the susceptible population. This can be confirmed through comparing the recovered populations for the two scenarios, which is higher under the higher $\beta_0$ scenario. Human mortality is also higher under a higher infection rate scenario, however, in the long run, it falls below the base case due to a faster reduction in the susceptible population. Likewise, when the infection rate from bats to humans is lower compared to the base case ($\beta_0=0.25$), the susceptible human population declines at a lower rate and the infection rate is also lower. However, in the long run, the infection and death rates surpass the base case as well as the higher infection rate scenarios. A higher bat-human infection rate combined with a higher human-human transmission rate leads to a very steep decline in the susceptible population due to very high infection rate amongst humans. This results in a higher death rate in the early years compared to previous scenarios, however the long run death rate is one of the lowest. The recovered population under this scenario improves faster than all previous scenarios due to a higher infection rate. A scenario where susceptible bat population is higher at 1000 (compared to the base case susceptible population of 100), there is a steep decline in susceptible human population compared to the base case due to marginally higher infection rate. This leads to a higher death rate as well as a higher recovery rate in the human population. In another scenario where bat mortality rate is higher, there is a lower infection and death rate in humans as bats are the primary vectors of the virus. Finally, consider a scenario where the infected bat population is much higher at 100. That is, hundred bats are infected and 100 others are susceptible in a total population of 200 bats. Under this scenario, the human infection rate peaks in just 6 years and begins to decline from there onwards as the susceptible population declines steeply. Human death rate follows a similar pattern as the infection rate, however, after peaking, the death rate falls to the lowest levels amongst all scenarios considered so far. The rate of growth of recovered humans is also the steepest under this scenario. The susceptible and infected bat populations are depicted in Figs. 5 and 6. The susceptible bat population increases at a steeper rate when there are 100 infected bats compared to
the base case scenario where there are only 10 infected bats. However, as the infected bat population increases due to a higher rate of infection, the growth rate of bats declines. When the total number of susceptible bats is higher at 1000 bats (compared to 100 bats in the base case), there is a steeper decline in susceptible bat population due to a higher rate of infection amongst bats as well as due to higher competition for food as the carrying capacity of the forests is low. This is evident through the total bat population dynamics depicted in Fig. 7. Bat population in most scenarios settles at about 433 bats, whereas under a higher mortality scenario their long run population is much lower.

4.2. Results for the agroforestry model

Having understood how the epidemiological model behaves, we now run the full model where the farmer is allowed to convert farmland into forests and benefit from PES payments. PES payment determination is considered exogenous to the model. Compared to the base case, when the agroforestry option is allowed, it results in a less steep rate of infection due to the impact of agroforestry on reducing forest fragmentation. The rate of decline in the susceptible population (Fig. 8) is less steep compared to the base case scenario (with no agroforestry option). The human infection rate is lower as a consequence (Fig. 9).

In another scenario, when the farmer receives less money from gamhar timber sale (gamhar price = 1000 inr/ton), there is no afforestation, which increases the infection rate compared to the previous scenario. As there is no reduction in forest fragmentation (Fig. 10) the infection rate is same as the base case (which has no agroforestry option). When the farmer receives a PES payment of 2850 inr/ha for forest area under agroforestry in each year (but there is low income from sale of timber), the rate of afforestation is much faster compared to the base case with agroforestry option (Fig. 11). This scenario demonstrates how much PES payment would be required to incentivize high afforestation rate when the farmer does not benefit significantly from timber sales. When there is less agricultural area available for conversion to forests, the infection rate is higher for the first 50 years. This suggests that forests play a positive role in limiting infection spread through reducing fragmentation. For a scenario where gamhar price is lower at 1000 inr/ton and a PES payment of 2850 inr/ha is made, there is periodic fluctuation observed in the infection rate among humans. As a result, harvesting of mature trees results in significant reduction in forest cover compared to scenarios where farmland is gradually converted. Note that fragmentation is a function of the product of forest area and forest age. When most standing gamhar trees are harvested in a particular area, the average age of remaining trees also declines, which results...
in increased fragmentation. When PES payment is higher at 30,000 inr/ha and timber prices are low at 1000 inr/ton, afforestation rate is even higher than the previous scenario. This scenario is also conducive to bat population improvement as the long run stock abundance of bats reaches close to 500 (Fig. 12).

Sensitivity analysis with respect to variation in other key parameters is also performed. An increase in the adverse impact of shading, through the $\theta_1$ parameter, slows down the rate of agroforestry adoption. At a higher shading related adverse impact on wheat productivity, land use decisions are more sensitive to agricultural incomes. Specifically, when shading effect on crop productivity is high, the rate of afforestation is much slower for a higher price of the agricultural produce. A higher land size, whereas, improves the rate of afforestation. Similarly, an increase in the discount rate results in faster rate of conversion of open farming to agroforestry. An increase in land conversion cost does not affect the rate of afforestation, as the benefits from conversion far outweigh the costs.

In another scenario, where there is no wheat farming and only gamhar trees are planted (and periodically harvested), the rate of decline in susceptible population is less steep compared to the wheat-gamhar based agroforestry scenarios. This is due to the additional assumption that the rate of bat to human infection (parameter $\beta_0 = 0.25$) gets reduced to half when there is no cropping in the fragmented area, as this lowers the chances of humans coming in contact with the bats. Under this scenario, the susceptible human population time path is higher than the base case agroforestry scenario (Fig. 13), suggesting a lower rate of virus transmission to humans. Finally, we also consider optimization from a social planner’s perspective. Under this scenario, afforestation happens the fastest of all scenarios. This should be intuitive, as agroforestry helps lower human mortality and thus it would become desirable to reduce forest fragmentation as soon as possible. It is also worth mentioning here that when the planner includes farm and timber incomes in their optimization problem, the resulting afforestation time path is only marginally higher than the base case (where agroforestry option is also included). As timber sales and farm incomes can be significant, their weight in the utility function increases, creating tradeoffs with the earlier objective of solely saving human lives.

5. Discussion

The base case scenario demonstrated that, over time, the entire human population in the community could acquire immunity through infection and subsequent recovery. However, the cost of this immunity would be a loss of human lives during the initial stages. In some scenarios, infection rate is high, which results in steep recovery but also higher mortality rate in the early stages. However, as the susceptible population declines due to an increase in the recovered population, there is a lower infection rate in the long run and lower mortality as well, until both are reduced to zero. For bats, as there is no recovery from the disease, the susceptible population never declines. In fact, it increases in most scenarios due to a growth in the bat population. As infected bats
have lower fertility compared to healthy bats, scenarios that lead to higher rate of infection can also affect bat stock abundance in the long term. When infection transmission rates between humans and between bats and humans are both high, infection and mortality rates are amongst the highest. However, the recovered population also increases at a steep rate under this scenario. When the entire bat population is infected, again, human infection and mortality is very high in the early years.

Agroforestry helps with reducing infection and mortality rates among humans compared to when the option is not used. When benefits from timber sales are lower, the farmer does not have enough incentives to convert farmland into agroforestry, which results in a higher infection rate. An exogenously determined PES payment of 2850 inr/ha in each year is found to be sufficient to incentivize rapid and complete conversion to agroforestry. Further, a low timber sale price combined with PES payments results in fluctuations in forest fragmentation rates due to higher harvesting of forest biomass. Under these scenarios there is steeper afforestation, which significantly reduces standing biomass stocks when mature trees are harvested. Results also demonstrate that when farmland area is small, forest fragmentation cannot be reduced to zero. This would aggravate the disease spread rate. Whereas planting only trees in fragmented areas instead of practicing agroforestry can result in an even lower rate of infection from bats to humans. Finally, from a societal perspective, it would be optimal to immediately convert farmlands in fragmented areas into agroforestry if the objective is solely to protect human lives. However, when farm and timber incomes are also taken into consideration, the rate of afforestation is not considerably different from a privately optimal outcome. This suggests that tradeoffs exist in the path to managing deadly diseases which need to be overcome through taking on board the interests of all stakeholders.

Findings from this study support the existing wisdom regarding conserving our forests for stopping the spread of zoonotic diseases. For instance, Brock et al. (2019) found that zoonotic malaria spread chances among households living in proximity of fragmented forests increased in proportion to the size of cleared land. Similarly, in case of the Hendra virus, forest fragmentation can result in reduction in habitat necessary for supporting, feeding, and sheltering bats during winter and spring seasons, resulting in higher shedding of zoonotic viruses (Eby et al., 1999; Plowright et al., 2015). Gibb et al. (2020) argue that intensity of land use change globally, particularly conversion of forests into agricultural areas, is increasing the interface between humans and zoonotic virus carriers. Conceptual frameworks linking deforestation to COVID-19 also exist in the literature (Brancalion et al., 2020). It is important to further highlight the benefits of conserving forests, as during the COVID-19 pandemic, there has been an opportunistic clearing of forests under the false assumption that trees increase the risk of virus spread. While there are no studies currently that have applied agroforestry for virus risk mitigation and with which the results from this study could be compared, there has been some work exploring the possibility of COVID pandemic adversely affecting agroforestry (Duguma et al., 2021). Similarly, Baudron & Liégeois (2020) argue that though agriculture is responsible for most biodiversity losses on the planet that result in deadly disease outbreaks, farmers would require market-based incentives for adopting more sustainable practices.

The results derived in this study should be understood in light of some key limitations of the model. The model ignores changes in bat
populations due to outside entry or exit of bats. Similarly, susceptible and infected human populations could increase through outside arrivals. There is also the possibility of new mutations of viruses affecting recovered populations. If farmers grow agroforestry trees that yield edible fruits (such as mangos and date palm), chances of interaction between bats and humans may increase. However, such risks are still lower compared to fragmentation related bat migration to human settlement areas. Bat density was assumed fixed in this study, however bats being gregarious creatures can be found in higher numbers even when their habitat shrinks. Parameters related to infection rate among bats, among humans, and between humans and bats are likely to vary considerably from region to region. Changing climate, such as droughts, warming, and high frequency precipitation, may all affect bat population dynamics and their adaptation to new environments. Finally, the exact impact of forest fragmentation on pathogen spread rate is difficult to quantify and model.

6. Conclusion

In this paper, we integrated vector-borne zoonotic disease transfer dynamics within an agroforestry land use model to address the challenge of increasing rates of bat to human disease transmissions caused by anthropization of natural environments. Agroforestry and afforestation on private farmlands can reduce forest fragmentation and help lower the possibility of bats migrating and roosting in rural or urbanized areas, where the chances of disease transmission increase manifold. Results from this study demonstrate that agroforestry and afforestation can be effective tools for mitigating the risk of bat-borne diseases. The analysis performed in this paper further demonstrates that PES payments could play an important role towards incentivizing faster agroforestry adoption and reducing pathogen-led human mortality. Further, restoring forests in fragmented areas instead of practicing agroforestry can result in even better outcomes.

Agroforestry and afforestation programs are already being promoted in many parts of the world due to declining productivity and incomes in traditional agriculture. From a policy perspective, targeting fragmented forest areas for agroforestry promotion can yield the additional benefit of increasing rates of bat to human disease transmissions caused by anthropization of natural environments. Agroforestry and afforestation on private farmlands can reduce forest fragmentation and help lower the possibility of bats migrating and roosting in rural or urbanized areas, where the chances of disease transmission increase manifold. Results from this study demonstrate that agroforestry and afforestation can be effective tools for mitigating the risk of bat-borne diseases. The analysis performed in this paper further demonstrates that PES payments could play an important role towards incentivizing faster agroforestry adoption and reducing pathogen-led human mortality. Further, restoring forests in fragmented areas instead of practicing agroforestry can result in even better outcomes.

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