Environmental and Resource Economics
https://doi.org/10.1007/s10640-024-00874-x

Optimal Ecosystem Change in the Presence of Ecosystem-Mediated Human Health Impacts

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Accepted: 19 April 2024

Abstract

A growing body of empirical evidence suggests that land use change, and the resulting decline in both the area and quality of natural habitats, contributes to an increased incidence of disease in humans. Despite calls to leverage conservation policy to address the burden of disease linked to ecosystem change, the potential benefits are unknown. Efficiently reducing the burden of infectious disease through land use policies and conservation initiatives is challenging because it requires balancing trade-offs that depend on ecological and socioeconomic factors. To assess some of these trade-offs, we developed a dynamic model of optimal land use when ecosystem change affects the overall incidence of infectious disease. We compared the net benefits and paths of optimal policy in which the increased cost of disease resulting from natural habitat loss is included in the optimization with a base case where it is ignored. We found that ignoring the linkage between habitat degradation and infectious disease incidence in the planner's problem reduces the net benefits of land management, such as conservation efforts, and results in significantly higher rates of infection and health costs.

Keywords Environmental externality · Land use change · Habitat degradation · Disease regulation · Vector-borne disease · Deforestation

JEL Codes Q24 · Q56 · Q57 · Q20 · Q15

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1 Introduction

Ecosystem change is a complex issue with both positive and negative consequences for human well-being and the natural environment. On one hand, converting ecosystems for roads, water storage infrastructure, clean energy, resource extraction, and agriculture has advanced poverty alleviation and global food security. These activities contribute to the development of modern infrastructure, connecting populations and enhancing overall quality of life. However, it is crucial to recognize the benefits of land use change while also considering the potential negative impacts on human wellbeing through the loss of ecosystem services and biodiversity.

Conversion of natural habitats also comes at a cost, in the form of lost ecosystem services and reduced biodiversity. As land use changes and natural habitat degradation persist, other costs of converting ecosystems become increasingly apparent, especially for vulnerable populations such as the poor, children, and the elderly (Whitmee et al. 2015). A report by the World Health Organization estimated that changes in environmental factors account for a quarter of the global disease burden, including "ecosystem-mediated health outcomes" such as altering infectious disease risk (Prüss-Üstün, Corvalán, and World Health Organization 2006). Land use change can impact the global disease burden through zoonotic diseases, which are pathogens transmitted between animals and humans. In Africa, Asia, and South America, the creation of water storage and infrastructure has resulted in increases in numerous vector-borne diseases, including Rift Valley fever, malaria, and Japanese encephalitis (Patz et al. 2004). Vector-borne diseases affect more than 3.4 billion people annually and have significant consequences for global health and economic development (World Health Organization 2014), with the United States alone spending US$ 2.9 billion on malaria control programs in 2015 (World Health Organization 2017).

The mechanisms driving changes in disease incidence around ecosystem change are highly dependent on the pathogen and context, but one overarching hypothesis is the "dilution effect," suggesting that higher biodiversity in ecological communities limits the transmission of certain pathogens by regulating pathogen host populations (Keesing et al. 2006). When ecosystems are converted and degraded, the resulting biodiversity loss concentrates the host population. This, in combination with increased human presence on the landscape, increases human contact with pathogen-carrying animals and raises the risk of pathogen transmission (see, for example, Laporta et al. 2013).

Understanding the drivers, mechanisms, and costs of disease incidence and how they relate to land use change and natural habitat degradation is important to develop policies that address human health risk, specifically if complementing conventional disease management programs. Numerous empirical studies have investigated relationships between ecosystem change and disease incidence (MacDonald and Mordecai 2019; Garg 2019; Santos and Almeida 2018; Bauch et al. 2015; Pattanayak and Pfaff 2009; Pongsiri et al. 2009; Vittor et al. 2006; Walsh et al. 1993; Patz et al. 2004), sometimes identifying causality. However, despite calls for a better understanding of how land use policy and resulting ecological changes influence the cost of ecosystem-mediated disease, little has been done to evaluate the potential for managing disease using land use policy or comparing cost savings and health outcomes to conventional disease management practices (Myers et al. 2013; Pattanayak et al. 2017). The void is in part because of the sparse availability of public health data alongside surrounding conservation programs. In the absence of readily available data, simulation modeling can offer insights into the trade-offs of land conversion and generate an understanding of how much land area in an ecosystem ought to be protected to balance ecosystem service production and economic benefits converted landscapes. In addition, conversion is a dynamic process and an important consideration in conservation policy to plan ecosystem change over time to keep the costs and benefits of land conversion in balance. Given the direct (e.g., treatment and prevention expenditures) and some indirect (e.g., educational impacts) costs and benefits, health outcomes have been valued, in some ways, assessing the trade-offs of health outcomes resulting from land use change is more straightforward than managing for other ecosystem service benefits that are complex and more difficult to measure and monetize.

Building on prior literature that models trade-offs of land conversion and conservation (Barbier and Burgess 1997; Hartwick et al. 2001; Bulte and Horan 2003), we develop a theoretical dynamic model in which a land manager optimizes the social net benefits derived from converting natural habitat by determining the time path of land conversion. We employ a simple assumption that ecosystem-mediated zoonotic disease incidence and therefore health cost is a function of the total amount of land converted at any given time. Our model informs the optimal land conversion area, user cost for converted land along the optimal path, and resulting cost of disease from land conversion. We compare results with a base-case model in which the health costs of land conversion are omitted from the social welfare function, as is realistic in the case of most land conversion decisions. To determine how our theoretical findings may play out in practice, we parameterize our model using values that represent the economic, environment, and health realities in the Brazilian Amazon, using data from the state of Amazonas. We choose this region because of its globally recognized value of ecosystem services and unprecedented rates of deforestation. There is compelling evidence that the reemergence of malaria, a mosquito-borne zoonotic disease endemic throughout many tropical regions, is related to land use in this region.

Our work highlights the importance of considering the health costs of ecosystem-mediated disease in land-use decisions. Not only are health costs a significant trade-off of land conversion that should be considered when assessing the net benefits of ecosystem change, but they also play an important role in the dynamic path toward reaching the target conversion area. Depending on the cost of the disease, it may even be optimal to halt land conversion altogether or invest in habitat remediation to restore positive marginal net benefits from converted land. Overall, there can be substantial gains from internalizing health costs in land management, regardless of the magnitude of the cost of the health externality.

2 Model

In our model, a representative land manager makes time-dependent decisions about how much natural habitat to convert, aiming to maximize the discounted social net benefits derived from both converted and unconverted lands within a fixed-area landscape L. The landscape is initially natural habitat $N(t)$ providing societal benefits through ecosystem services. The natural habitat area can be transformed into an alternative land use such as cropland $R(t)$, generating benefits in the form of goods, services, and revenue. When a unit of land area is converted from $N(t)$ to $R(t)$, it ceases to produce ecosystem services. Each unit of land area can only be one of the two types at any point in time so that

$L = N(t) + R(t)$. The proportion of the landscape can be represented by $X(t) = \frac{R(t)}{L}$ and $1 - X(t) = \frac{N(t)}{L}$. Changes in the proportion of converted land over time $\frac{dX(t)}{dt} = \dot{X}(t)$ depend on the chosen level of land conversion activity, $u(t)$, scaled by the available technology θ and the rate of natural habitat succession given by $F(X(t))$. The effectiveness of land conversion activity is taken to exhibit diminishing returns in $X(t)$, meaning that at low levels of $X(t)$ each unit of $u(t)$ is more impactful at creating $X(t)$ .The rate of natural habitat succession is assumed to be higher with less converted land ($X(t) \to 0$) and lower with more converted land ($X(t) \to 1$). These processes are captured by

$$\dot{X}(t) = \theta u(t)\left[1 - X(t)\right] - F(X(t)), \tag{1}$$

where $F(0) = \overline{F}, F(1) = \underline{F}$, with $\overline{F} > \underline{F}$ ensuring that $F(X(t))$ lies between the extreme rates for all X in the interval $(0,1)$.

There are costs associated with converting land from natural habitat (e.g., clearing forest, building roads) and maintaining productive converted land (e.g., weed management, plowing, and fertilizing) represented by $C(u(t), X(t))$. Conversion and maintenance costs are assumed to increase at an increasing rate and are taken to be independent activities such that $\frac{\partial^2 C}{\partial u \partial X}, \frac{\partial^2 C}{\partial X \partial u} = 0$.

Converted land generates benefits according to a concave function $A(X(t))$, where higher levels of converted land produce greater benefits. On the other hand, natural habitat produces ecosystem service benefits measured by $E(1 - X(t))$, where smaller areas of natural habitat imply reduced production of ecosystem services. Notably, smaller areas of natural habitat result in a decrease in ecosystem service production, $\frac{\partial E(\cdot)}{\partial X} > 0$.

Across both converted lands and natural habitat, there exists a wildlife vector species that transmits a zoonotic disease to and between humans, creating direct and indirect health costs. On converted lands, modifications to environmental conditions that favor the pathogen or host (e.g., water retention and delivery infrastructure, warmer ground surface temperatures) increase the abundance of the pathogen per unit land area. Greater human presence through labor-intensive farming activities on the converted landscape results in more frequent contact between humans and the pathogen-transmitting vector, translating to greater disease incidence than in natural habitat. Furthermore, the land conversion activity also increases human contact with the vector species. We assume the provisioning of ecosystem services are separable from the costs of disease incidence.[1] As a result, the costs of disease incidence are a function of converted land and the current-period level of land conversion activity $D(X(t), u(t))$.

The land manager seeks to maximize net benefits derived from both converted land and ecosystem service production on natural habitat. This is achieved by choosing a level of land conversion effort, considering trade-offs associated with both converted land and natural habitat and social health costs associated with land use change. The objective function is given by

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[1] In the absence of guidance from the literature on the direction of interdependencies between ecosystem service provisioning and disease cost we take the most basic case that the benefits from ecosystem service provisioning are separable from the disease costs.

$$\max_{u(t)} V\left(u\left(t\right)\right)=\int_{t=0}^{\infty}\left(A\left(X\left(t\right)\right)+E\left(1-X\left(t\right)\right)-C\left(u\left(t\right),X\left(t\right)\right)\right. \\ \left.-\,D\left(u\left(t\right),X\left(t\right)\right)\right)e^{-\rho t}dt, \tag{2}$$

subject to Eq. 1 and the conditions $0 \leq u\left(t\right), X\left(0\right)=X_0$ where ρ is the discount rate. The optimal rules for $u\left(t\right)$ and $X\left(t\right)$ can be found using Pontryagin's maximum principle.

The associated current value Hamiltonian function, omitting time notation for brevity, is:

$$\mathcal{H}=A\left(X\right)+E\left(1-X\right)-C\left(u,X\right)-D\left(u,X\right)+\mu\left(\theta u\left[1-X\right]-F\left(X\right)\right). \tag{3}$$

Here, μ is the co-state variable associated with the stock of converted land. It measures the relative value of converted land compared to the value of natural habitat, following Hartwick et al. (2001)[2]. The marginal value of converted land can be interpreted as the opportunity cost of land conversion in terms of forgone natural habitat and serves as a key variable providing insight into natural capital values in the model.

To ensure that land conversion activity remains non-negative (assuming habitat restoration would follow a different process and have different costs), we introduce a slackness condition for the control variable. This modifies the current value Hamiltonian as follows:

$$\mathcal{L}=A\left(X\right)+E\left(1-X\right)-C\left(u,X\right)-D\left(u,X\right)+\mu\left(\theta u\left[1-X\right]-F\left(X\right)\right)+\epsilon u. \tag{4}$$

Here, $\epsilon \geq 0$ is a Lagrangian multiplier associated with the non-negativity constraint on land conversion activity. If it is optimal to expand the area of converted land, then $\epsilon = 0$.

The first-order condition from the maximum principle guides choice of the optimal level of land conversion activity and requires

$$\frac{\partial\mathcal{L}}{\partial u}=\mu\theta\left[1-X\right]+\epsilon-\frac{\partial C(\cdot)}{\partial u}-\frac{\partial D(\cdot)}{\partial u}=0;\epsilon u=0,u\left(t\right)\geq 0. \tag{5}$$

On the optimal path if the marginal value of converted land (μ) exceeds the marginal value of preserving natural habitat, then land conversion activity must be positive ($u > 0$). The optimal level of converted land balances is value marginal product, $\mu\theta\left[1-X\right]$, with its marginal costs, $\frac{\partial C(\cdot)}{\partial u}+\frac{\partial D(\cdot)}{\partial u}$. Conversely, if $\mu \leq 0$ then $u=0$ is optimal because at the margin, the value from the converted land is less than the value of natural habitat. From Eq. 5, it is evident that optimal levels of land conversion and land conversion activity are influenced by the consideration of disease costs, which may either be included or excluded in the analysis.

We further analyze the two scenarios: first when land conversion activity is optimal, $u > 0$, and second when it is optimal not to invest in land conversion activity, $u = 0$. The evolution of the marginal value of converted land (μ) is determined by the relative value marginal of land conversion to opportunity costs. The optimal program requires that the adjoint equation for the co-state variable be satisfied along the path of land conversion:

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[2] In this setting μ is not the willingness to pay for an additional unit of converted land as the size of the landscape is fixed.

$$\dot{\mu} = \mu(\rho + \theta u + \frac{\partial F(\cdot)}{\partial X}) - \left[\frac{\partial A(\cdot)}{\partial X} + \frac{\partial E(\cdot)}{\partial X} - \frac{\partial C(\cdot)}{\partial X} - \frac{\partial D(\cdot)}{\partial X}\right] if u > 0 \tag{6}$$

or.

$$\dot{\mu} = \mu\left(\rho + \frac{\partial F(\cdot)}{\partial X}\right) - \left[\frac{\partial A(\cdot)}{\partial X} + \frac{\partial E(\cdot)}{\partial X} - \frac{\partial C(\cdot)}{\partial X} - \frac{\partial D(\cdot)}{\partial X}\right] if u = 0. \tag{7}$$

Equations 6 and 7 incorporate the costs of disease and require that converted land be managed so to ensure its value remains competitive with other opportunities in the economy, earning the market rate of return, ρ (the opportunity cost of holding and using converted land).

With a slight reorganization, Eq. 6 informs how the rate of capital gains (or losses) from holding X, given by the term $\frac{\dot{\mu}}{\mu}$, is equal to the market rate of return ρ net of the sum of the terms on the right-hand-side of (6) or (7). The terms $\theta u + \frac{\partial F(\cdot)}{\partial X}$ in Eq. 6, or $\frac{\partial F(\cdot)}{\partial X}$ in Eq. 7, reflect the marginal impacts of current holdings of converted land on the efficiency of land conversion activity in the future. θu signifies how increased converted area creates a discounted marginal cost due to less effective land conversion activity in future periods and $\frac{\partial F(\cdot)}{\partial X}$ represents the impact of converted land area on the rate of natural habitat regeneration: the more land that is converted, the less forest regeneration occurs, making future land conversion less costly. Depending on relative magnitudes of these marginal impacts, the required rate of capital gains may be increased above or decreased below the market rate of return.

In rearranging (6) so that the left hand side is $\frac{\dot{\mu}}{\mu}$, the term $-\frac{1}{\mu}\left[\frac{\partial A(\cdot)}{\partial X} + \frac{\partial E(\cdot)}{\partial X} - \frac{\partial C(\cdot)}{\partial X} - \frac{\partial D(\cdot)}{\partial X}\right]$ represents the net physical appreciation or depreciation derived from maintaining X as converted land. If the marginal net change in benefits from production on converted land exceed the costs of land conversion activity, the required rate of change in capital gains to balance the equation is reduced. When the health costs are ignored and $u > 0$, the magnitude of the entire right-hand side of the condition will be larger when $\frac{\partial D(\cdot)}{\partial X}$ is omitted and the perceived capital gains from converted land are also large. This implies that on the optimal path the marginal rate of return on land conversion activity is greater than when these costs are included, which follows intuition.

Case 1: $u > 0, \epsilon = 0$

In this case the choice of land conversion activity lies in the balance of the tradeoff to the manager of the value marginal product of land conversion activity $\mu\theta(1 - X)$ with its marginal costs $\frac{\partial C(\cdot)}{\partial u} + \frac{\partial D(\cdot)}{\partial u}$. The marginal value of converted land found in Eq. (3) plays a key role in this tradeoff: $\mu = \frac{1}{\theta[1-X]}\left(\frac{\partial C(\cdot)}{\partial u} + \frac{\partial D(\cdot)}{\partial u}\right)$, and its evolution over time governed by Eq. (6). The solutions to the system are most useful and interesting if presented in terms of μ and X yet are equivalent to the solutions in terms of u and X.

Solving the system in terms of μ and X requires the employment of specific functional forms for the cost and damage functions. The assumed forms are $C(u, X) = \psi u^2 + \gamma X$ and $D(u, X) = \eta X + \varphi[1 - X] + \lambda u^2$ with parameters ψ, γ, η, φ, and λ. Substituting these into Eqs. (1) and (6), the resulting system is:

$$\dot{X} = \frac{\mu\theta^2[1-X]^2}{2[\psi+\lambda]} - F\left(X\right), X\left(0\right) = X_0 \tag{8}$$

$$\dot{\mu} = \mu\left(\rho + \mu\frac{\theta^2\left[1-X\right]}{2[\psi+\lambda]} + \frac{\partial F\left(\cdot\right)}{\partial X}\right) + \varphi - \gamma - \eta - \left(\frac{\partial A\left(\cdot\right)}{\partial X} + \frac{\partial E\left(\cdot\right)}{\partial X}\right) \tag{9}$$

Together, Eqs. (8) and (9) form a dynamical system in $(X\ ,\mu\ )$ space, defining optimal trajectories of land conversion over time. If we consider a land manager's decision akin to a social planner's, we denote the solutions $X^s\left(t\right)$ and $\mu^s\left(t\right)$ to reflect the inclusion of disease costs in the objective function. The locus of time invariant levels of X are given by the $\dot{X}=0$ isocline, denoted $\mu^s|_{\dot{X}=0} = \frac{2(\psi+\lambda)F(X)}{\theta^2[1-X]^2}$. The slope of this isocline is influenced by ecosystem regeneration, the effectiveness of land conversion activity, and marginal costs of conversion and disease incidence. Time invariant levels of the marginal value of converted land ($\mu^s|_{\dot{\mu}^s=0}$ from the $\dot{\mu}^s = 0$ isocline) have solutions:

$$\mu^s|_{\dot{\mu}^s=0} = \frac{\psi+\lambda}{\theta^2[1-X]}\left[\left(\rho + \frac{\partial F\left(\cdot\right)}{\partial X}\right) \pm \sqrt{\left[\rho + \frac{\partial F\left(\cdot\right)}{\partial X}\right]^2 - 4\frac{\theta^2[1-X]}{\psi+\lambda}\left(\varphi - \gamma - \eta - \left(\frac{\partial A\left(\cdot\right)}{\partial X} + \frac{\partial E\left(\cdot\right)}{\partial X}\right)\right)}\right] \tag{10}$$

which requires $[\rho + \frac{\partial F(\cdot)}{\partial X}]^2 - 4\frac{\theta^2[1-X]}{\psi+\lambda}\left(\varphi - \gamma - \eta - \left(\frac{\partial A(\cdot)}{\partial X} + \frac{\partial E(\cdot)}{\partial X}\right)\right) > 0.$

When the net marginal benefits of converting land $\frac{\partial A(\cdot)}{\partial X} + \frac{\partial E(\cdot)}{\partial X}$ are greater than the marginal costs of land conversion activity $(\varphi - \gamma - \eta)$, the overall term is positive.

Case 2: $u = 0, \epsilon \geq 0$

When natural habitat is as or more beneficial than converted land, the marginal value of converted land is negative: $\mu = \frac{\frac{\partial C(\cdot)}{\partial u} + \frac{\partial D(\cdot)}{\partial u} - \epsilon}{\theta[1-X]} < 0$. In this case, increasing the proportion of land converted results in a loss to the overall value of the landscape. Therefore, $u = 0$ and the evolution of μ is governed by Eq. (5), while Eq. (2) becomes $\dot{X} = -F\left(X\right)$. If no land conversion activity has occurred $t = 0$, then none will occur over time and $X = 0$. If some conversion had already occurred at $t = 0$ but no land conversion activity is expended, the size of the converted land stock declines over time due to the habitat regrowth function $F\left(X\right)$. The reduction in the size of the stock of X changes the magnitude of the shadow value of converted land. As more land reverts to natural habitat, the marginal value of converted land will become less negative or potentially positive (Eq. 7). This implies that along the time path land conversion activity may be positive if the co-state variable becomes positive. This scenario could represent the case of a landscape that has been initially over-converted. Allowing the system to return to a natural state can restore some of the ecological benefits to a level in which it is beneficial to invest in land conversion.

If $D\left(u, X\right)$ is not included in the objective function, there will be no marginal cost of land conversion to health in the first-order condition (Eq. 5). The decision regarding land conversion activity hinges on achieving a balance between the value marginal product of converted land and its marginal cost, akin to managing capital growth. However, as the land manager doesn't account for the marginal (health) costs associated with their decisions, they tend to invest in a level of land conversion activity that surpasses the socially optimal conversion rate. This heightened investment in land conversion activity accelerates the rate of land conversion and the steady-state stock of converted land. The omission of the impact of u on the marginal cost of disease incidence results in the level of land conversion activity exceeding the optimal level. As per Eq. 1, this leads to the stock of converted land growing at a faster pace than along the optimal path.

3 Numerical Application

3.1 Motivating Example

We focus on the decision to convert land for large-scale agricultural production in the Amazon rainforest (Amazonia) in South America, a region globally important for ecosystem service production and the supply of commodities and natural products. While Amazonia spans nine countries, nearly 60% of Amazonia resides within Brazil. Since 1970, over 19% of the total area of the Brazilian Amazon has been deforested; the majority of the forest area is first cleared for pasture, and then it transitions into croplands (National Institute of Space Research 2019). While the expansion of agriculture has been critical for the economic development of Brazil, there are widespread concerns about how forest conversion affects the production of ecosystem services and ecological tipping points.

The specific case of land use change and health we consider is changes in malaria incidence in deforested habitats. Since 2009, 99% of the nearly 4 million cases of malaria in Brazil were reported in the Brazilian Amazon (WHO 2019). A combination of socio-economic factors and environmental changes related to deforestation is hypothesized to drive the persistence of endemic malaria in the Brazilian Amazon (de Castro et al. 2006; Packard 2007; Bauch et al. 2015; Santos and Almeida 2018; Terrazas et al. 2015; Olson et al. 2010; MacDonald and Mordecai 2019). Most importantly, human activity in converted areas and harvesting activities within forests are found to increase the incidence of malaria in rural populations (Pattanayak and Pfaff 2009). In new settlements within the Amazon, a pattern of "frontier malaria" has been documented, in which there is an initial malaria epidemic after land clearance begins, followed by a lower but persistent infection incidence (Sawyer 1988; Singer and de Castro 2001; de Castro et al. 2006; da Silva-Nunes et al. 2008). This is represented in our model by allowing for different health costs on converted lands and through land conversion activity.

Deforestation also impacts the disease ecology of malaria. Deforested land retains more surface water and receives more direct sunlight. Water and temperature are two factors that create a favorable breeding habitat for mosquitoes. The creation of irrigation ditches, vehicle ruts, reservoirs, and partial clearing of land provides ample breeding habitat for the primary vector for malaria (Tadei et al. 1998; Vittor et al. 2006). Land conversion and natural habitat degradation also impact mosquito biodiversity and the abundance of species that prey on mosquitoes (Yasuoka and Levins 2007). There is evidence that mosquito species composition and species abundance change along a gradient of land use, with lower biodiversity and a higher prevalence of the vector-transmitting species occurring in converted areas and within 500 m of the forest edge (Hendy et al. 2023), while the abundance of non vector-transmitting species are greater within forest habitat (Young et al. 2021).

Despite national and international investments in controlling malaria, including the World Bank-funded Amazon Basin Malaria Control Program, the Brazilian National Malaria

Control and Prevention Plan, and the Global Technical Strategy for Malaria, the incidence of malaria has reemerged in areas of development across the Brazilian Amazon. Malaria prevalence has long-run socio-economic impacts as well, affecting adult labor productivity (Sachs and Malaney 2002; Cutler et al. 2010) and physical and cognitive development in children (Lucas 2010). Furthermore, the Brazilian Amazon contains some of the poorest states in the country, making the financial cost of a malaria infection a significant economic burden to a household.

In the parameterization described below, we consider the decision-making process of land managers who have make landscape-scale land use decisions. Our case and model represent the incidence of disease due to extensive agricultural operations, where the scale of land conversion by one decision maker has the potential to influence landscape ecosystem service production and disease risk for many. The potential health externalities become especially relevant in cases where industrial farms use hired labor for land clearing and on-farm activities such that the land manager is not exposed to the health risks they create but local populations are. The model and assumptions would need to be modified to analyze other cases of zoonotic disease incidence, such as spillover externalities from hunting or bushmeat consumption that could be the result of small-scale land use or resource extraction decisions.

This numerical example of land conversion in the Brazilian Amazon illustrates the analytical model and compares the optimized net present value and health impacts when the change in disease incidence and costs are ignored and internalized. Simulations compare the solutions to determine the impact on the time path of land conversion activity and social net benefits when health costs are ignored. We then illustrate how policies on the state and control variables can be used to steer non-optimal conversion paths to the optimal solution and illustrate the cost savings of implementing those policies.

3.2 Functional Forms and Parameterization

Functional forms are taken to approximate production decisions for one growing season in the Brazilian Amazon. We assume a concave production function with diminishing returns, $A(X) = \alpha(\ln(1 + X))$ where α is a parameter. The costs of land conversion activity follow $C(u, X) = \psi u^2 + \gamma X$ with parameters ψ and γ. The ecosystem service value is also assumed to follow a concave production function $E(1 - X) = \beta(1 - \ln(1 + X))$. The forest growth function is specified as $F(X) = \frac{0.01}{1+X}$ so that the regrowth rate is dependent on the proportion of natural habitat remaining and greatest when X=0. The cost of malaria is assumed to follow the function $D(u, X) = \eta X + \varphi[1 - X] + \lambda u^2$, allowing for infection risk to differ across converted land, natural habitat, and land conversion activity.

Land use change data were collected from the Brazilian National Institute for Space Research Program for Estimation of Deforestation in the Brazilian Amazon (National Institute of Space Research 2019). In 1970, the total area of land designated as forest was approximately 4,100,000 km^2. This total area is used to nondimensionalize the values in the calibration and transform total area into the proportion of total landscape area. The area of land converted in the year 2000, $\dot{X}_{2000} =$ 18,226 km^2 and the total area of land converted in the year 2000, $X_{2000} = 575{,}903$ km^2 were used to calibrate the model parameters. Per-acre gross value for soybean and corn production in Brazil was estimated at $US 1,200 per km^2 by Meade et al. (2016), which we use to parameterize the converted land benefit function.

Production costs for corn and soybeans were estimated to be \$800 per km^2 by (Meade et al. 2016). Bauch (2004) used surveys of over 500 logging firms operating in the Brazilian Amazon to estimate the cost of legal timber harvest at \$160. No values could be found for lower-cost modes of land clearing. Since the predominant practice for land clearing for pasture is burning, not timber harvest, we assume a slightly lower land clearance cost of \$100 for land conversion activity. Brouwer et al. (2022) conducted a meta-analysis of the literature on the ecosystem services produced by the Brazilian Amazon and estimated the values of carbon regulation, water cycling, and wildlife habitat to be from \$612 to \$403,300 per km^2 per year. We use the low end of their estimates in our parameterization so that ecosystem service values do not vastly outweigh the benefits of land conversion and to focus on the effects of health costs on model results. All monetary values used in the parameterization have been converted to 2020 \$US using the OECD's Purchasing Power Parity. The risk of malaria infection across the types of land uses and activities is assumed to be: natural habitat (0.02 infections/km^2), land conversion activity (0.3 infections/km^2), and converted land (0.1 infections/km^2), based on findings in the literature (Vittor et al. 2006; Santos and Almeida 2018; MacDonald and Mordecai 2019). The direct and indirect cost per infection is assumed to be \$200 (Andrade et al. 2022). The discount rate, ρ, is assumed to be 3% (See Table 1).

4 Results

To demonstrate the effect accounting for linkages between land conversion and disease on optimal land management decisions we compare our parameterized model with a benchmark case that does not include any social cost of disease in the objective function. Time paths of converted land from the simulations are compared with the historic path of land conversion in the Brazilian Amazon (1970 to 2018) in Fig. 1a. The steady state levels of converted land area for both simulations are indicated in Fig. 1a by horizontal lines ($\mathrm{SS_B}$ and $\mathrm{SS_{200}}$). Using the parameters described above, the equilibrium proportion of converted land in the benchmark model is $X_B^{ss} = 0.326$, or 1,336,600 km^2. When disease costs are included in the optimization, the steady state proportion of converted land area is $X_{200}^{ss} = 0.263$, or 1,078,300 km^2. The difference in converted land area between the two simulations is 258,300 km^2. Figure 1b shows how the marginal value of converted land evolves over

Table 1 Parameter descriptions and values used in numerical base case where the total cost of an infection is \$200

Parameter	Description	Value
ρ	Discount rate	0.03
θ	Effectiveness of land conversion activity in transforming habitat	0.1
δ	Ecosystem regeneration	0.01
α	Ag. production function	9510
β	E. service production function	921
ψ	Land conversion activity cost function	4231
γ	Converted lands production function	5980
η	Infection risk on converted land area = 0.1	142
φ	Infection risk on unconverted land = 0.02	2538
λ	Infection risk from land conversion activity = 0.3	8.5×10^{-7}

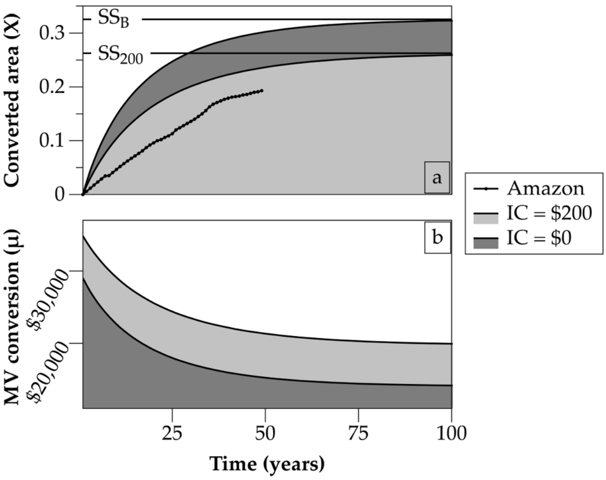

Fig. 1 Time paths of optimal simulated proportion of landscape converted and natural habitat in the Amazon (**a**) and evolution of marginal value of converted land (**b**) for the benchmark model and parameterization with a \$200 infection cost. Steady state proportion of land conversion for both parameterizations are shown with horizontal lines in (**a**). The historic path of land conversion in the Brazilian Amazon is shown for comparison

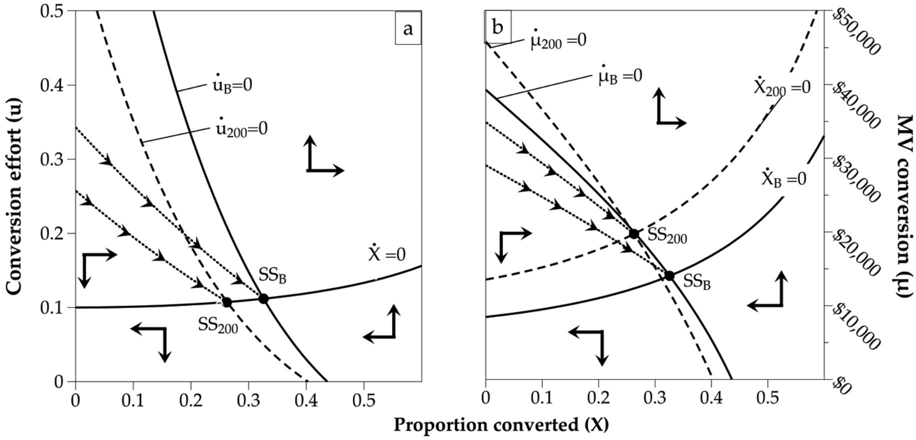

Fig. 2 Phase planes illustrating the optimal level of land conversion activity (left) and marginal value of converted land (right) while following the path to steady state

the time path of land conversion activity and land conversion for both scenarios. In steady state, the marginal value of converted land for the simulations are $\mu_B^{ss} = \$14{,}042$ and $\mu_{200}^{ss} = \$19{,}725$. Along the time path in Fig. 1b, the marginal value of land conversion activity is greatest for small values of X due to the scarcity value associated with converted land highest when a small quantity land has been converted. As the proportion of converted land increases, the marginal value of converting additional land decreases and the benefits of converted land relative to foregone natural habitat become smaller.

The results can also be visualized in phase space. To show the effect of including the changing cost of disease in the optimization, we again compare the optimized model with a benchmark model which has no health costs in the social net benefit function. Figure 2 shows two phase planes, one in (X, u) space (Fig. 2a) and the other in (X, μ) space (Fig. 2b). Both phase planes are partitioned into isosectors, derived using Eq. 1 and time differentiating Eq. 5 and performing substitutions and manipulations to produce $\dot{u} = 0$, for Figs. 2a, 8 and 10 for Fig. 2b.

In both cases, there is a steady state at the origin ($X = 0, u = 0,\ \mu = 0$) and at interior values, SS_B and SS_{200}. Eigenvalues of the linearized system indicate the steady states are saddle path stable, confirmed by the phase arrows in Fig. 2. Considering initial conditions $X_0 < X^{SS}$, the optimal path of conversion to the interior steady states are given by the saddle paths shown in Fig. 2.

The dynamics of both the benchmark and IC = \$200 parameterizations around their steady states are similar. Along the optimal path for both parameterizations in Fig. 2a from initial conditions $X_0 < X^{SS}$, the chosen level of land conversion activity and the marginal value of converted land decrease as the steady state is approached from the left. The intuition follows from considering the phase space of Fig. 2b. Above and to the left of the $\dot{X} = 0$ isocline, the marginal value of converted land exceeds the benefits from natural habitat lost when land is converted, providing incentives for land conversion activity to be positive. Below and to the right of the $\dot{X} = 0$ isocline, assuming some converted land already exists, the opposite incentives result in the choice of no land conversion activity, and result in a decline in the proportion of land converted as the natural habitat regenerates. Above and to the right of the $\dot{\mu} = 0$ isocline, as more land is converted, the ecosystem services are less valuable than agricultural production on converted land, increasing the marginal value of converted land relative to natural habitat. The opposite happens below the $\dot{\mu} = 0$ isocline.

When health costs are included in the welfare function, the $\dot{\mu} = 0$ isocline pivots to become steeper and the $\dot{X} = 0$ isocline shifts upward, as illustrated in Fig. 2b. There is an interesting connection between the marginal value of land conversion and health costs. Accounting for the cost of disease incidence has an instantaneous effect land conversion activity, slowing of the growth of converted land and the overall proportion of land converted in steady state. This means at each point in time, converted land is relatively more scarce and therefore more valuable to producers.

Next we illustrate how if a land manager were to begin accounting for health impacts of ecosystem change on the social welfare at some point along the land conversion horizon, the chosen conversion path can be steered onto the optimal path. Figure 3 illustrates two scenarios in which non-optimal land use decisions (the benchmark trajectory) could transition onto the socially optimal path in X and μ phase space. In Fig. 3a, the conversion trajectory begins at $X = 0$ with the land manager ignoring the health costs and continues along the benchmark optimal path for the first 30 years of the simulation. When the health costs are included to the land managers' decision in year 31, land conversion activity is reduced, meaning that the rate of change in the size of the stock of converted land decreases. This immediate decrease causes the marginal value of converted land to increase, because converted land becomes scarcer and more valuable. Adjusting the land use decisions to reflect the marginal damage functions will steer the chosen level of land conversion activity and the path of conversion to the optimal steady state.

Figure 3b illustrates an extreme possibility of high disease damages (\$1,000 per infection), where following the benchmark trajectory has led to over-conversion of landscape compared to the socially optimal path. In this case, to converge to the optimal equilibrium, land conversion activity stops so that natural habitat regenerates, reducing the stock of converted land. The marginal value of converted land jumps significantly when land conversion activity ceases. The rationale for this is that curbing land conversion creates scarcity in agri-

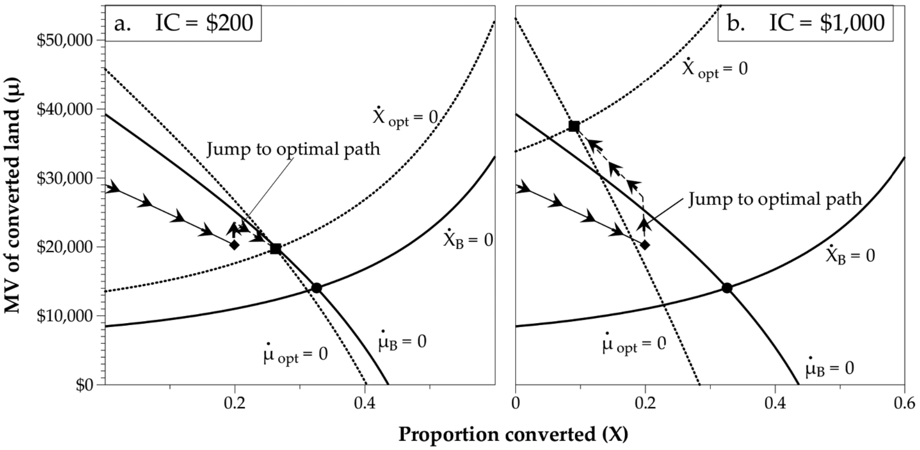

Fig. 3 Impact on the marginal value of converted land when considering health costs are introduced to the welfare function along the trajectory of land conversion for two cost per infection scenarios- $200 and $1,000 per infection

cultural land, increasing its value. Since the level of land conversion activity remains zero, ecosystem regrowth is the only term in Eq. 1, so some of the landscape returns to natural habitat. As the proportion of land area that remains in agriculture becomes smaller, the value of that land increases.

Adding costs to production decisions affects the net marginal benefits of production. Are the welfare impacts of land conversion activity and on converted land significant? Are there any welfare gains from implementing policies to correct the path and area of land conversion? Fig. 4 summarizes the total net benefits and magnitude of health costs from disease incidence for the optimized and non-optimized (benchmark) scenarios. We also perform these calculations for the scenario illustrated by Fig. 3a, where a non-optimal path is followed for 30 time steps and then a policy is implemented to steer conversion onto the optimal trajectory. In each of these calculations we use a cost of $200 per infection.

When the health costs of ecosystem change are considered in the objective function (optimized model) the net benefits created by following the optimal land conversion trajectory are $39,452/km^2 and the total discounted social cost of disease incidence is $3,162/km^2. In the benchmark (non-optimized) scenario, the net benefits from the chosen conversion path are $33,534/km^2 and the discounted cost of disease incidence is $4,331/km^2. Finally, to determine the benefits from jumping onto the optimal path, we calculate the net benefits and cost of disease for the scenario in which the benchmark trajectory is followed for 30 years. After 30 years a policy is implemented that allows for decision makers to account for health costs in land conversion decisions, steering the system to an optimal trajectory. In Fig. 4 this is the ‘bench to optimized’ scenario. In this scenario, we calculate the net benefits from land management to be $33,695/km^2 and the social cost of disease is $3,932/km^2. This result indicates that there are benefits to implementing policy toward the optimal path. While accounting for ecosystem change-health linkages along the entire trajectory results in the greatest welfare and lowest cost of disease, there are welfare gains to implementing a policy at any point in time. In conclusion, the sooner policy can be imple-

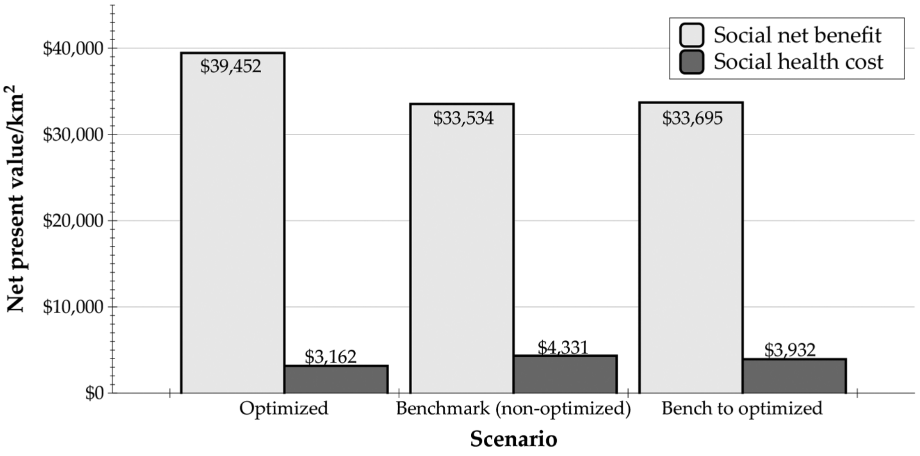

Fig. 4 Net present value and social cost of disease (per km^2) from land use decisions across three model simulations- 'optimized' in which the social cost of disease has been included in the objective function, 'non-optimized' where social costs of disease exist but are not included in the objective function, and 'jump to optimized' where the non-optimized path is followed for 30 years and a jump to the optimal path occurs when a policy is implemented

Table 2 Parameter changes performed in the sensitivity analysis

Description	New parameter values
Optimized model, IC = $200	None
High agriculture value relative to e. service	$\alpha = 11{,}412$
High discount rate	$\rho = 0.1$
High ecosystem regeneration rate	$\delta = 0.05$
Low agriculture value relative to e. service value	$\beta = 1{,}439$
Low probability (0.1) of infection from land conversion activity	$\lambda = 4{,}231$
Low probability (0.05) of infection on converted land	$\eta = 356$
Infection cost = $50	$\lambda = 635, \eta = 36,$ $\varphi = 8.5x10^{-7}$
Infection cost = $1,000	$\lambda = 12{,}694, \eta = 712,$ $\varphi = 1.7x10^{-5}$

mented to accurately weigh the trade-offs of land use decisions, the greater dividends there will be to social welfare.

5 Sensitivity Analysis

We test additional scenarios to analyze the sensitivity of our results to the parameters used in the model. The additional parameterizations and changes to results are summarized in Table 2. All results are compared to the model parameterized with a per-case infection cost of $200, and these results are illustrated by horizontal lines on each of the three plots.

Figure 5 summarizes the net present value of land use and cost of disease incidence (both per-km^2) for three cost per infection (IC) parameterizations, IC = \$50, IC = \$200, and IC = \$1,000. For each of these parameterizations, the results for the optimized, benchmark, and 'bench to optimal' policies are shown. As above, in the optimal model the social health costs are included in the objective function and this simulation produces both the highest possible social net benefits and lowest social health costs. The benchmark (health externality not included in objective function) results in the lowest social net benefits and highest social health costs. The 'bench to optimal' simulations produce higher net social benefits and lower social health costs than each benchmark scenario. However, the magnitude of benefits is dependent on the parameterization. The greater the assumed infection cost, the greater the gains from implementing the policy to internalize the created externalities.

All sensitivity results are summarized in Fig. 6. The horizontal lines in each subfigure in Fig. 6 indicate the values (net benefits, cost of disease, steady state area of land conversion, and steady state marginal value of converted land) for the optimized IC = \$200 simulation. Increasing the value of agricultural production (Fig. 6, Hi ag) increases the optimal area of land to convert in steady state. Because ecosystem service production still has significant value, it remains optimal to maintain more than half the landscape as natural habitat. In addition, the steady state marginal value of converted land and net benefits of land use are both high because the value of converted land has increased. Therefore, while the cost of disease is high relative to many of the other parameterizations, the net present value from converted land is also high.

Seemingly counter to intuition, a larger discount rate reduces the steady-state area of land converted (Fig. 6, Hi discount)[3]. This is because, unlike the standard renewable resource problem, the shadow value of converted land reflects the marginal benefit of conversion not the marginal user cost. Analytically, this result can be seen in Eq. 5, where the discount rate

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[3] We thank an anonymous reviewer for highlighting this counterintuitive result.

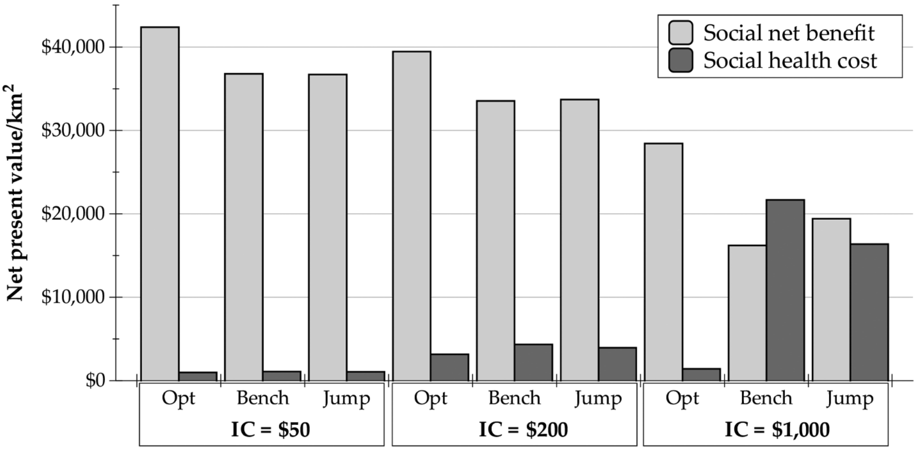

Fig. 5 Net present value of converted land and cost of disease on converted land for three infection cost parameterizations \$50/infection, \$200/infection, and \$1,000/infection

is implicitly represented through the marginal benefit of converted land, μ. Using Eq. 6 to assess how the discount rate impacts μ, the steady-state shadow value is decreasing in the discount rate, meaning higher discount rates lead to lower steady-state shadow values and lower marginal benefits from conversion and therefore less conversion. The lower steady-state converted area in turn reduces incidence of disease and cost of disease. Increasing the rate of natural habitat regeneration (Fig. 6, Hi regen) means that for land to remain converted, land conversion activity needs to increase to maintain converted land. In addition, because a high level of land conversion activity is needed to maintain converted land, which is expensive and results in higher disease cost, the marginal value of converted land is low in this parameterization. Reduced benefits from agricultural production (Fig. 6, Lo ag) on converted land relative to ecosystem services decreases the optimal area of land conversion.

Reducing disease incidence from land conversion activity (Fig. 6, Lo IC effort) increases the steady state area of land conversion, which reduces the steady state marginal value of converted land. In this parameterization, land conversion activity can increase without incurring a greater disease burden, so the net present value of land conversion increases and the social cost of disease decreases. Lower infection incidence on converted land (Fig. 6, Lo IC area) slightly increases the steady state area of land conversion. As most of the disease incidence in this parameterization comes from the control variable, conversion activity, there is only a small reduction to the social cost of disease.

6 Discussion and Conclusions

There is growing recognition that the loss of natural habitat and ecosystem change affects human welfare not only through the loss of ecosystem services, such as carbon sequestration, but also through impacts to human health. While the monetary benefits from converting natural habitats can be easily measured, the true costs of land use change are muddied by missing or absent markets for lost ecosystem services. The complex nature of disease dynamics makes it difficult to identify the mechanisms that drive changes in health outcomes, and often disease transmission is not something that is monitored surrounding conservation efforts. However, the consensus in the literature is that for some infectious dis-

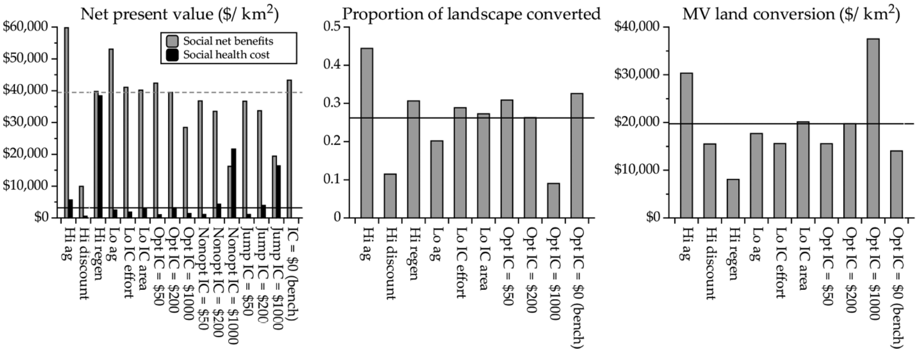

Fig. 6 Net benefits and disease costs, steady state proportion of total land converted (X) and marginal value of land converted (μ) for sensitivity parameterizations. The horizontal lines on each of the plots indicate the values for the optimized simulation where IC = $200 for comparison

eases, ecosystem change does increase their prevalence. If we have a general understanding of the magnitude of the relationship between ecosystem change and health, and the costs of disease are known, models can analyze the net benefits to human health from conservation and policies managing the conversion of natural habitats.

Understanding the costs of habitat degradation from land conversion is especially important in the context of biodiverse and environmentally valuable tropical systems across South America, Africa, and Asia. Current incentive-based policies that have attempted to curb land use change are largely in the form of payment for ecosystem services (PES) programs. While PES programs have had some success, we often lack a full understanding of the value of ecosystem service production and the ability to translate services into monetary values. It is plausible that future PES programs could incentivize natural habitat management to positively affect health outcomes. However, the potential health effects of land use change are diverse in type, ecology, drivers, and costs. The specific health externalities created by landscape-level decision-makers (e.g., endemic disease, air/water quality, effects of climate change) differ from those created by small-scale landowners/managers, and this must be factored into the policies themselves. Further understanding of disease ecology, local socioeconomic settings, and mechanisms is needed to develop effective policies — from national land management policies to PES programs — to manage disease incidence.

The purpose of our work was to develop a general dynamic framework to assess the trade-offs of land conversion decisions, accounting for the fact that degraded habitats and the time that people spend in them affect disease incidence. Using our modeling framework, we illustrate how ignoring health costs of land conversion results in sub-optimal land management decisions. We also illustrate how ignoring the economic-disease linkages reduces the marginal value of converted land relative to natural habitat. Larger costs of disease incidence and lower overall values for converted lands compound reductions in the overall per-square-kilometer value of land in our simulations, parameterized for the Brazilian Amazon. Our results change with variations in model assumptions, but the finding that ignoring disease costs results in significant losses to net benefits is robust to changes in most model parameters. Our results suggest that implementing policies that target land managers increases the net benefits from the landscape and reduces the regional cost of disease.

There are several important caveats to our modeling strategy and findings. First, we have set up a case that represents a large landscape and a disease damage function that is specific to vector-borne diseases accompanying large-scale land conversion. The policies to mitigate externalities created in this case must be developed using location-specific empirical evidence for drivers of change in disease incidence. Further research into how habitat degradation and economic decisions simultaneously affect infection risk is needed to accurately estimate damage functions at a smaller regional scale. Second, we have assumed no uncertainty in any of the values included in our model. There may be a good reason to assess how uncertainty in market conditions, ecological tipping points, or disease risk impacts our results in future work. Finally, our modeling framework treats space as implicit. Rather than optimizing the total area of land conversion, a spatially explicit model could assess optimal patterns of conversion to reduce ecosystem service loss and disease risk by factoring in the significance of forest edge habitat and fragmentation in the loss of ecosystem services.

Conceptualizing environmental goods and services as natural capital is appealing because it allows for the direct evaluation of the trade-offs of specific management actions. Translating changes in production ecosystem services to social welfare impacts continues to be a challenge due to missing or absent markets. However, disease costs create a unique opportunity for valuing an ecosystem service and the development of policy because there is a direct connection between the lost service and market values. While disease control has, to date, been an understudied ecosystem service we see opportunities for informing the management of natural landscapes.

Acknowledgements This work was supported by NSF Grant 1414374 as part of the joint NSF-NIH-USDA Ecology and Evolution of Infectious Diseases program and the UK Biotechnology and Biological Sciences Research Council Grant BB/M008894/1. PD is supported by a grant to EcoHealth Alliance from Johnson & Johnson.

Funding The study is supported by the Department of Anaesthesia at Danderyd Hospital and the Institute of Clinical Sciences, Karolinska Institutet at Danderyd Hospital, no further funding.

Declarations

Conflict of Interest The authors have no conflicts of interest to disclose.

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