Shooting at the poachers while the rhinos drown: Managing short- and long-term threats to endangered wildlife in conservation reserves

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Shooting at the Poachers while the Rhinos Drown: Managing Short- and Long-Term Threats to Endangered Wildlife in Conservation Reserves

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Abstract

1 Abstract

This paper addresses management challenges associated with conserving endangered wildlife facing multiple threats from illegal poaching, habitat encroachment, and climate and land use change induced flooding. While poaching and encroachment challenges in conservation parks are of immediate nature, climate related risks exist in the long term. The park manager faces a utility function that includes as its arguments local community's incomes, benefits to the larger society from preserving threatened species and the financial costs of monitoring and land use change efforts. Using the case of single-horned rhinos in the Kaziranga national park, India, an optimal mix of monitoring and land use changes is designed in presence of tradeoffs between short- and long-term management efforts. As monitoring only addresses immediate challenges associated with poaching and encroachment, long-term climatic risks remain ignored. Land use management offers risk-protection as well as risk-insurance benefits with respect to climate change induced flooding of the park.

2 Recommendations for Resource Managers

- It is important to incorporate both short- and long-term risks posed to endangered wildlife while investing in conservation efforts. There may exist a tradeoff between mitigating short- and long-run risks due to financial and physical resource constraints. However, ignoring long-term risks to wildlife habitats can jeopardize past conservation efforts.
- Land use management, both within and outside of conservation reserves, enhances resilience to climatic shocks through reducing flooding risks and must be an essential part of wildlife conservation efforts.
- Conservation efforts ignoring local community welfare considerations can become suboptimal as they lead to reduced cooperation and potential conflicts. When wildlife conservation efforts account for local community welfare implications, optimal management plans could result in lower species abundance in the short term. However, increasing the park size through additional land enrollment can mitigate some of this tradeoff.

Keywords: biodiversity conservation; rhino poaching; Kaziranga national park; climate risk to wildlife; land use change; biodiversity flooding risk

1. Introduction

The task of preserving the planet's endangered wildlife is increasingly becoming challenging. Due to population pressure induced land use changes, there remain few natural habitats for such species globally. Protected areas, such as wildlife conservation parks, too face encroachment threats from local populations, particularly in the developing regions of the world. A number of key conservation areas also face the risk of flooding due to changes in land use patterns in their surrounding regions. Consequently, there exists a real possibility that climate change induced events, such as increased incidences of future flooding, could wipe out a large number of such species even if society were to succeed in improving endangered wildlife populations through costly conservation efforts in the short term.

In this paper, we address the crucial question of how to preserve endangered wildlife in conservation parks in the presence of multiple stressors such as illegal poaching, encroachment of their habitat by local communities and increased risk of future flooding from land use changes and climatic events. While poaching and encroachment are immediate threats to a conservation reserve, climate change and land use change related stressors pose long-term threats with the possibility of catastrophic losses to the species. The central issue that is addressed in this paper relates to optimally managing the tradeoffs that arise while allocating resources to mitigate short- and long-term threats. We pick the case of the one-horned rhinos in the Kaziranga National Park (referred to as KNP hereafter) in Assam, India. However, the model and its results have applicability to a wider range of conservation parks across the globe.

Illegal poaching is a significant challenge facing endangered wildlife today. Wildlife smuggling and trade, which is currently worth 10-20 billion USD, threatens the extinction of several species on the planet (UNODC, 2014; WWF, 2016). Illegal trade in wildlife occurs for various reasons. These include culinary and ornamental demands, consumption for their misperceived health and vitality effects, or status effects (WWF, 2012; Lyon and Nautsch, 2013; Hawthorne, 2013). Further, the rarity value of species could also increase their price and demand, a phenomenon that has been termed as the anthropogenic Allee effect (Courchamp et al., 2006; Holden and Mcdonald-Madden, 2017). For all these reasons, illegal poaching of wildlife has been increasing at an alarming rate. For instance, globally more than 25000 elephants were poached in 2011, whereas the rate of rhino poaching in Africa increased by 9000 percent between 2007 and 2014 (Lehmacher, 2016). In 2013, close to 1000 southern white rhinos were illegally killed in South Africa (Di Minin et al., 2014).

Monitoring and regulatory efforts can reduce poaching in wildlife parks, however, they become effective only when park managers resort to drastic steps, such as shooting and killing poachers and intruders in the park. Such extreme measures can become controversial and could end up alienating local populations through causing losses to lives and livelihoods. Shoot-at-sight policies have nevertheless found some support in the literature (Messer, 2010). Park managers face additional challenges such as low wages, diseases, and the risk of getting targeted by smugglers as well as the local populations. Human diseases, such as malaria, affect the productivity of park rangers and increase their costs of operation in several wildlife parks in India that are prone to heavy rainfall (Velho et al., 2011).

In the Kaziranga National Park, land encroachment is a major challenge facing park managers. Illegal encroachment occurs for expanding areas under tea and rubber plantations, for bamboo harvesting and illegal trading in timber (Gogoi, 2015). Illegal operations by mining and stone quarrying firms have further damaged the biodiversity of the KNP (Gogoi, 2015). In 2007, a Ministry of Environment and Forestry report revealed that 7,790 ha of KNP area had been lost to illegal encroachers (MOEF, 2010). Management of the KNP is characterized by frequent conflicts between the park managers and the local populations. Conflicts between local populations and the conservation authorities have been reported in wildlife parks elsewhere as well. In fact, eviction of encroachers from the Krueger national park and securitization of anti-poaching measures have caused alienation of the local populations and made it challenging to obtain their cooperation (Hubschle, 2016). Conservation parks provide timber and non-timber forest products (such as honey, wax, fruits, fodder and fuelwood) to the local communities, which can be a significant source of livelihood for the marginal households (Mackenzie et al., 2012). Human-animal conflicts around such conservation parks add to the burden of local populations through causing losses to crops, livestock as well as human lives (Emerton, 2001; Mackenzie and Ahabyona, 2012).

Land cover change both within and outside of the KNP in Assam further threatens rhino population dynamics in significant ways (Medhi and Saha, 2014). Alluvial grasslands and wetlands, which are a preferred habitat of the rhinos, could change in size from impacts of global warming. Land use changes outside the park can increase the risk of flooding by removing forest cover (Mathur et al., 2007). The Brahmaputra River, which flows through the valley containing the KNP, has the highest flooding potential within the subcontinent (Mathur et al., 2007; ADB, 2009). It is predicted that climate change could increase future discharge in the Brahmaputra river by 50 percent (Manabe et al., 2004; Mathur et al., 2007). Flooding caused by the river deposits large amounts of silts into the alluvial grasslands and wetlands within the park, which could force rhinos to move out into areas where they would be easily poached (Medhi and Saha, 2014). During the flooding season, rhinos are forced to move to the south of the park by crossing the national highway (NH-37). A number of them are killed on NH-37, crushed by oncoming vehicular traffic. Some rhinos drown as well. In 2017, 7 rhinos were reported to have drowned due to flooding of the park (Firstpost, 2017).

Several approaches have been suggested in the literature for managing similar challenges globally. Some models have analyzed the optimal allocation of land usage across farming, wildlife conservation, tourism and livestock (Chaminuka et al., 2014). Fischer et al. (2011), looked at the benefits of making local communities stakeholders in the revenues generated by conservation parks. Das and Hussain (2016) conducted a survey in the KNP area to conclude that ecotourism opportunities were positively benefitting the rural households by generating extra incomes and this was adding to their sense of empowerment. It has also been suggested that in order to prevent wildlife poaching in conservation reserves, the opportunity cost of poaching could be increased through providing better economic opportunities for the local populations (Poudyal et al., 2009). In South Africa, various options have been explored for conserving the southern white rhino populations, including increasing anti-poaching efforts, higher monetary fines and convictions, and legalization of trade in rhino horns (Di Minin et al., 2014). It has been noted that in absence of improvements to the current management practices, the southern white rhinos' wild population would become extinct in the less than 20 years.

Protecting conservation parks and their biodiversity from current and future threats would require long-term investments in land use management, such as buying forest and farm lands and declaring them protected areas. An increase in the size of conservation parks can facilitate the creation of infrastructure (such as embankments, refuge areas and higher grounds) which helps with reducing soil erosion that causes permanent changes in river channels, thereby preventing wildlife losses during flooding events. Given that there exist opportunity costs as well as tradeoffs associated with the various management options, finding the optimal level and timing of their allocation is crucial towards ensuring the long-term sustenance of the wildlife park and its habitants. For instance, dedicating all resources towards anti-poaching efforts may improve wildlife populations in the short term, but it would also increase the risk of future flooding of their habitats if land use changes in the surrounding regions are not adequately managed. Similarly, aggressive anti-poaching efforts could alienate local populations and increase the future costs of preservation efforts. Therefore, policy options that are effective in the short term, may be rendered ineffective against long-term risks.

Design of an optimal wildlife management plan when faced with the abovementioned challenges is an important policy concern. Keeping in mind this concern, the objective of this research is to help a wildlife park manager decide upon the optimal level of efforts towards monitoring and land use changes so that wildlife risks are effectively mitigated. Specifically, the focus of this paper is on the design of an optimal time path of efforts in presence of various inter-temporal risk tradeoffs as well as spatial land use dynamics arising from conflicting interests of the manager and the local populations. We develop a bio-economic model of optimal management of rhino populations in the KNP which incorporates these short- and long-term management challenges. The park manager considers the societal valuation of the rhino population abundance as well as the economic wellbeing of the local community in their utility maximization problem while dedicating resources towards monitoring efforts and land use management over time. Findings from this study provide valuable insights over when higher or lower monitoring efforts may become optimal and how monitoring and regulation could be optimally combined with park area augmentation to manage short-and long-term threats faced by the wildlife.

2. Model outline and assumptions

Consider that a park manager is entrusted with the task of protecting the rhino population and its habitat in the KNP. Immediate threats exist to the rhinos from poaching, as well as the park itself faces encroachment from local communities. The manager can undertake a combination of monitoring and regulatory measures such as increasing the frequency and the extent of inspections within and outside of the park regions, preventing harvesting of forest products by the locals, and confronting illegal intruders within the park. These measures entail both direct financial costs as well as indirect costs such as through loss in productivity for the local communities. In addition, when regulatory measures become stringent, the park manager risks antagonizing and alienating the local populations.

The park manager's utility reflects the larger society's valuation of rhino population abundance as well as the local community's welfare, with the additional assumption that the weights placed on the local community's welfare are relatively lower compared to that on the larger society's valuation. The manager optimizes society's long-term utility when faced with the tradeoff that high monitoring and regulatory measures could reduce farm incomes and adversely impact overall utility. We also consider the possibility that the manager could add new acres to the existing conservation area through purchasing forest lands in the vicinity of the park. This affects land use management outside of the park, as the same land would no longer be available for farming, mining or for tea plantations. Bringing forests under protection mitigates the risks of future flooding in the park, and therefore saves the rhino populations from catastrophic losses.

It is important to mention at the outset that the model presented here abstracts away from the real situation in a number of ways. First, the biological richness of the conservation park is a result of a wide range of species present in the area. However, we consider only rhino population abundance, as it is an iconic species and conservation efforts in the park are largely driven by the threats facing the rhinos. Second, the process of encroachment of conservation parks by the local communities is often governed by factors that are partly political in nature. That is, protecting rhinos would require displacing some communities. Such communities often find political support towards resisting relocation orders. This aspect is not considered in our model. Third, livelihood options of local communities vary significantly. Here we simplify by assuming that local communities rely primarily upon farming and tourism based incomes. In reality, migration is a viable option for many communities irrespective of the stress posed by wildlife conservation efforts. Finally, land use changes in the vicinity of the park, such as deforestation, can affect flooding through a complex geomorphological and hydrological interaction process. Such detailed hydrological modeling is beyond the scope of this paper. With these key limitations in mind, we present the formal model next.

3. Model equations

A logistic growth function is selected for modeling rhino population dynamics within the KNP (Lopes, 2004). Rhino population, $b(t)$, grows according to the equation:

$$(1)\quad \dot{b}(t) = \rho \cdot b(t) \cdot \left(1 - \frac{b(t)}{b_d \cdot x(t)}\right) - p(t),$$

where ρ is the intrinsic growth rate of the rhinos and the variable $p(t)$ represents poaching of rhinos by wildlife criminals. Total area, $x(t)$, of the conservation park determines the maximum carrying capacity, $b_d \cdot x(t)$, of the rhino population, where parameter b_d is the density of rhinos within the habitat. While the size of the park is fixed, its effective area can get reduced through encroachment by the local communities. The effective park area dynamics is given as:

$$(2)\quad \dot{x}(t) = -e(t).$$

where $e(t) \geq 0$ is the rate of encroachment. The illegally encroached area is primarily used for farming (though it could also be used for creating housing shelter and shops, etc.). The incentive for the community to encroach on park lands can be reduced through constant monitoring and regulatory efforts, $\tau(t)$:

$$(3)\quad e(t) = e_{\max} \cdot \left(1 - \frac{\tau(t)^{e_0}}{\tau(t)^{e_0} + e_1}\right),$$

where $\tau(t) \geq 0$ and $e_{\max}$ is the maximum per-period encroachment in the absence of any monitoring, and e_0 and e_1 are parameters that determine the response of the community in terms of reducing encroachment to an increase in the monitoring effort.

A loss in the forest park area is a gain to the local community's farming acres. The corresponding growth in the farming area, $l(t)$, for the local community mirrors the loss in park area as:

$$(4) \quad \dot{l}(t) = e(t).$$

Crop output, $q(t)$, of the local community is given as:

$$(5) \quad q(t) = l^{\alpha} \cdot \left(1 - \frac{\tau(t)^{q_0}}{\tau(t)^{q_0} + q_1}\right),$$

where $\alpha < 1$ reflects the fact that crop output increases at a decreasing rate with an increase in park land encroachment (as land inside the park may not be suitable for farming). q_0 and q_1 are parameters determining the non-linear impact of monitoring and regulatory activities on crop output. $\tau(t)$ represent all activities undertaken by the park manager with the aim to curb poaching and encroachment. In order to avoid further complications, we do not distinguish between monitoring and regulatory efforts that reduce encroachment and those that affect crop yield. For instance, while patrolling the park perimeters looking for poachers, the manager would also deter local populations from accessing their farms closer to the conservation area or prevent them from applying nutrients on farms that could runoff into waterbodies used by rhinos.

Apart from farming, the local community can also earn tourism-based incomes, $m(t)$, as the wildlife within the park attracts substantial tourism. The tourism income, $m(t)$, is assumed a function of the rhino population as:

(6) $$m(t) = m_0 \cdot \log\left(b(t)^{m_1}\right),$$

where parameters $m_0 > 0$ and $m_1 < 1$ determine a non-linear relation between population growth and tourism income, and $b(t)$ is bounded from below by zero. To keep the analysis focused, we simplify the tourism income function by ignoring the impact of other important variables on tourism demand. These variables could be national and international economic growth rates, and climatic events such as increased frequency of extreme rain and flooding, etc. Further, the stock of rhinos serves as a proxy for the overall wildlife richness, and hence tourism demand for the rest of the park's amenities is assumed to go up whenever rhino population improves.

Total income, $i(t)$, of the community is the sum of farming and tourism based incomes:

(7) $$i(t) = \gamma \cdot m(t) + q_p \cdot q(t),$$

where γ is the proportion of tourism revenue coming to the community, as not all tourism activity may employ or benefit the local community. Parameter q_p represents a fixed price of the composite crop grown by the community.

Number of rhinos poached, $p(t)$, is a function of poaching effort, $h(t)$, made by the smugglers, as well as of $\tau(t)$:

(8) $$p(t) = h(t) \cdot \left(1 - \frac{\tau(t)^{p_0}}{\tau(t)^{p_0} + p_1}\right).$$

where and $h(t) \geq 0$, and parameters $p_0 > 0$ and $p_1 > 0$ determine the shape of the relationship between $\tau(t)$ and $p(t)$. The utility function, $u(t)$, of the manager is given as:

$$(9)\quad u(t) = b_{u0} \cdot b(t)^{b_{u1}} + i_{mu0} \cdot i_m(t)^{i_{mu1}} + i_{qu0} \cdot i_q(t)^{i_{qu1}} - \tau_{u0} \cdot \tau(t)^{\tau_{u1}}.$$

Along with monitoring costs, the utility function includes the value of the rhino population abundance measured by parameters b_{u0} and b_{u1}, and tourism and crop incomes weighted by parameters i_{mu0} and i_{mu1}, and i_{qu0} and i_{qu1}, respectively. Parameters $b_{u1} < 1$, $i_{mu1} < 1$, and $i_{qu1} < 1$ reflect the standard assumptions over declining marginal utilities obtained from an increase in the rhino population abundance, crop and tourism incomes, respectively. The financial cost of monitoring and regulation to the park manager is assumed to increase non-linearly in effort, which is measured through parameters τ_{u0} and τ_{u1}, with $\tau_{u1} > 1$ and $\tau_{u0} > 0$.

Poachers are assumed as short-term optimizers, and their objective is to maximize net gains from poaching as:

$$(10)\qquad p_{rhino} \cdot p(t) - h(t)^{c_0},$$

where p_{rhino} is the price of a rhino in the illegal market, and $c_0 > 1$ is a parameter that makes the cost of poaching non-linear in effort. Cost of poaching is assumed to increase non-linearly in effort due to the highly specialized and sophisticated process used by modern poachers. Several models in the literature have assumed non-linear harvesting cost functions (for instance, Burgess et al., 2017). In the context of rhinos in KNP, as the monitoring efforts in the past have evolved to incorporate modern technology, such as radio tagging and the use of satellite information, poachers have been forced to evolve through deploying sophisticated trapping gears and skilled sharp-shooters. Smuggling modern shooting gears into wildlife parks is often a costly and risky process (DNA, 2016).

Along with price of rhino horn and poaching penalty, some studies have also modeled poaching effort as a function of local income levels, income levels in East Asian countries, such as China and Vietnam (which demand rhino horns) and the level of civil unrest in Assam (Lopes, 2004; Poudyal et al., 2009). However, here we simplify by assuming that income driven demand effect from neighboring countries would be reflected through higher rhino prices. Further, econometric estimates do not provide evidence of a significant effect of local wages or domestic income on the poaching level (Lopes, 2004).

First order condition with respect to poaching effort yields:

$$\text{(11)} \qquad \left(\frac{p_{rhino} \cdot \left(1 - \dfrac{\tau(t)^{p_0}}{\tau(t)^{p_0} + p_1} \right)}{c_0} \right)^{\frac{1}{c_0 - 1}} = h(t).$$

The above constraint is incorporated within the optimization objective of the park manager, which is to maximize:

$$\text{(12)} \qquad \int_0^{\infty} \left(b_{u0} \cdot b(t)^{b_{u1}} + i_{mu0} \cdot i_m(t)^{i_{mu1}} + i_{qu0} \cdot i_q(t)^{i_{qu1}} - \tau_{u0} \cdot \tau(t)^{\tau_{u1}} \right) \cdot \exp(-r \cdot t) dt$$

with respect to $\tau(t)$, where r is the rate of time preference. The current value Hamiltonian for the park manager's optimization problem is written as:

$$\text{(13)} \qquad \begin{aligned} & b_{u0} \cdot b(t)^{b_{u1}} + i_{mu0} \cdot i_m(t)^{i_{mu1}} + i_{qu0} \cdot i_q(t)^{i_{qu1}} - \tau_{u0} \cdot \tau(t)^{\tau_{u1}} + \\ & \mu_b \cdot \left(\rho \cdot b(t) \cdot \left(1 - \frac{b(t)}{b_d \cdot x(t)} \right) - \left(\frac{p_{rhino} \cdot \left(1 - \dfrac{\tau(t)^{p_0}}{\tau(t)^{p_0} + p_1} \right)}{c_0} \right)^{\frac{1}{c_0 - 1}} \cdot \left(1 - \frac{\tau(t)^{p_0}}{\tau(t)^{p_0} + p_1} \right) \right) + \\ & \mu_x \cdot \left(-e_{\max} \cdot (1 - \frac{\tau(t)^{e_0}}{\tau(t)^{e_0} + e_1}) \right) + \mu_l \cdot \left(e_{\max} \cdot \left(1 - \frac{\tau(t)^{e_0}}{\tau(t)^{e_0} + e_1} \right) \right). \end{aligned}$$

where μ_b is the shadow price of the stock of rhino population, μ_x is the shadow price of the area of the conservation park and μ_l is the shadow price of farming area. The first order condition with respect to monitoring and regulatory efforts is given as:

$$(14)\qquad -\tau_{u0}\cdot\tau_{u1}\cdot\tau(t)^{\tau_{u1}-1}+\frac{\partial}{\partial\tau(t)}\mu_l\cdot\left(e_{\max}\cdot\left(1-\frac{\tau(t)^{e_0}}{\tau(t)^{e_0}+e_1}\right)\right)$$

$$=\mu_b\cdot\left(\frac{c_0\cdot p_0\cdot p_1\cdot\tau(t)^{p_0-1}\cdot\left(\frac{p_1\cdot p_{rhino}}{c_0\cdot p_1+c_0\cdot\tau(t)^{p_0}}\right)^{\frac{1}{c_0-1}}}{(-1+c_0)\cdot\left(p_1+\tau(t)^{p_0}\right)^2}\right)+\frac{\partial}{\partial\tau(t)}\left(\mu_x\cdot\left(e_{\max}\cdot(1-\frac{\tau(t)^{e_0}}{\tau(t)^{e_0}+e_1})\right)\right)$$

The first order condition requires that the costs of increasing monitoring and regulatory efforts marginally (left hand side of (14)) must be equated to the benefits from the same (terms on the right hand side of (14)).

Along with monitoring and regulation, the manager could also acquire new land to expand the conservation park's area. There are a number of benefits of such an expansion. First, a larger area of the park would increase the maximum carrying capacity for the rhinos. Second, by bringing new acres under conservation reserve area, the risk of future flooding can be mitigated to a certain extent. When forests are cleared for farming or other developmental purposes, the resulting land use change impacts on the water dynamics within the valley during the monsoon season. If the areas adjoining the park are afforested (and protected from harvesting), it would mitigate the impact of future flooding in the region. Third, a larger area of the conservation park would allow for provision of more refuge areas (such as elevated platforms that provide shelter from flooding) for the animals. Therefore, losses to rhino populations during flooding would be lower when the park area is bigger. Finally, the larger is the park area, the lower would be the detrimental impact on wildlife from marginal encroachment. That is, a larger area could provide for a stronger buffer against encroachment and poaching.

The option to include additional land area, $a(t)$, is modeled as:

$$\dot{x}(t) = -e(t) + a(t). \tag{15}$$

As the option to add additional acres is more relevant in a climatic event scenario, let us also model the climatic hazard next. While the park gets annually flooded due to its location in the Brahmaputra valley, climate change and land use changes in the future are projected to further increase the magnitude as well as the frequency of flooding. This increase in flooding magnitude and frequency is expected to arrive in the next 20 to 30 years. While the climatic event is exogenous to the model, the risk of the park getting affected by the resulting severe flooding could be mitigated through land use changes to a certain extent (as discussed in Mathur et al., 2007; ADB, 2009; Manabe et al., 2004). The hazard rate, $\dot{\lambda}(t)$, of an exacerbated future flooding scenario arriving in the conservation park is modeled as:

$$\dot{\lambda}(t) = \lambda_0 \cdot \left(1 - \frac{x(t)^{\lambda_1}}{x(t)^{\lambda_1} + \lambda_2}\right), \tag{16}$$

where λ_0 is the exogenous component of the hazard function. The term $\left(1 - \frac{x(t)^{\lambda_1}}{x(t)^{\lambda_1} + \lambda_2}\right)$ is the endogenous component, which the park manager can control through expanding the area of the conservation park to bring more forest land under conservation. Parameters λ_1 and λ_2 determine a non-linear relationship between an increase in the park area and its impact on $\dot{\lambda}(t)$. The larger the area of the park, the lower would be the hazard rate of future flooding.

In the event that the future climate scenario materializes, the rate of rhino population growth is given as:

$$\dot{b}(t) = \rho \cdot b(t) \cdot \left(1 - \frac{b(t)}{b_d \cdot x(t)}\right) - p(t) - f_0 \cdot \left(1 - \frac{x(t)^{f_1}}{x(t)^{f_1} + f_2}\right), \tag{17}$$

where f_0 is the expected maximum per-period loss to the rhino population due to climate induced exacerbated flooding of their habitat. This loss could occur not only due to drowning but also from opportunistic poaching by rhino horn smugglers who benefit from an increase in the vulnerability of rhinos during their mass migration to higher altitudes.

In the post-climatic event scenario, the park manager optimizes their efforts as previously, however, with the modified rhino population dynamics (as given by (17)). If we refer to the post-climate event optimized value function as $V_{post\_cc}(x,b,l)$, it will be defined as:

$$V_{post\_cc}(x,b,l) = \int_t^\infty \left(b_{u0} \cdot b(t)^{b_{u1}} + i_{mu0} \cdot i_m(t)^{i_{mu1}} + i_{qu0} \cdot i_q(t)^{i_{qu1}} - \tau_{u0} \cdot \tau(t)^{\tau_{u1}} - a_{u0} \cdot a(t)^{a_{u1}}\right) \exp(-r \cdot t)dt, \tag{18}$$

where $a_{u0} \cdot a(t)^{a_{u1}}$ is the non-linear cost of acquiring additional land, with $a(t) \geq 0, \mathrm{a}_{u0} > 0 \,\&\, \mathrm{a}_{u1} > 1$. The overall optimization problem for the policy maker when the event has not materialized yet is given as (see Reed and Heras, 1992 for a formulation of similar optimization problems involving hazard functions):

$$\int_0^\infty \begin{pmatrix} \left(b_{u0} \cdot b(t)^{b_{u1}} + i_{mu0} \cdot i_m(t)^{i_{mu1}} + i_{qu0} \cdot i_q(t)^{i_{qu1}} - \tau_{u0} \cdot \tau(t)^{-\tau_{u1}} - a_{u0} \cdot a^{a_{u1}}\right) \cdot \exp(-rt) \cdot \exp(-\lambda(t)) + \\ V_{post\_cc}(x,b,l) \cdot \exp(-\lambda(t)) \cdot \lambda_0 \cdot \left(1 - \frac{x(t)^{\lambda_1}}{x(t)^{\lambda_1} + \lambda_2}\right) \cdot \exp(-r \cdot t) \end{pmatrix} dt. \tag{19}$$

In the pre-flooding scenario, the park manager selects their level of monitoring and regulatory efforts along with investments in new acres so as to maximize the sum of their pre- and post-flooding values.

The current value Hamiltonian of the above optimization problem is given as:

$$
\begin{aligned}
&\left(b_{u0}\cdot b(t)^{b_{u1}}+i_{mu0}\cdot i_m(t)^{i_{mu1}}+i_{qu0}\cdot i_q(t)^{i_{qu1}}-\tau_{u0}\cdot\tau(t)^{\tau_{u1}}-a_{u0}\cdot a^{a_{u1}}\right)\cdot\exp(-\lambda(t))+\\
&V_{post\_cc}(x,b,l)\cdot\exp(-\lambda(t))\cdot\lambda_0\cdot\left(1-\frac{x(t)^{\lambda_1}}{x(t)^{\lambda_1}+\lambda_2}\right)+\\
(20)\qquad&\mu_{b(t)}\cdot\left(\rho\cdot b(t)\cdot\left(1-\frac{b(t)}{b_d\cdot x(t)}\right)-\left(\frac{p_{rhino}\cdot\left(1-\frac{\tau(t)^{p_0}}{\tau(t)^{p_0}+p_1}\right)}{c_0}\right)^{\frac{1}{c_0-1}}\cdot\left(1-\frac{\tau(t)^{p_0}}{\tau(t)^{p_0}+p_1}\right)\right)+\\
&\mu_{x(t)}\cdot\left(-e_{\max}\cdot(1-\frac{\tau(t)^{e_0}}{\tau(t)^{e_0}+e_1})+a(t)\right)+\mu_{l(t)}\cdot\left(e_{\max}\cdot\left(1-\frac{\tau(t)^{e_0}}{\tau(t)^{e_0}+e_1}\right)\right)+\mu_{\lambda(t)}\cdot\lambda_0\cdot\left(1-\frac{x(t)^{\lambda_1}}{x(t)^{\lambda_1}+\lambda_2}\right)
\end{aligned}
$$

where $\mu_{\lambda(t)}$ is the shadow price of the cumulate hazard function, $\lambda(t)$, which is defined as:

$$(21)\qquad \lambda(t)=\int_0^t\lambda_0\cdot\left(1-\frac{x(z)^{\lambda_1}}{x(z)^{\lambda_1}+\lambda_2}\right)dz\,.$$

It is not possible to obtain further analytical exposition of the above problem, given the non-linear functional forms. Next, we apply the above model to the case of the KNP and derive some insights.

4. Application of the model to the case of KNP

4.1.Parameter calibration

KNP, at about 430 sq km in size, is a relatively small park (Gogoi, 2015). Efforts to add new areas under conservation have been slow and have met with resistance from interest groups such as miners, industry, and local populations. A small amount of area (equal to 40 sq km) was added to the park in 2004 (Dudley and Stolton, 2010). Total size of farm lands in the vicinity is calculated using an estimated 11,666 households from the districts of Golaghat and Nagaon (Bharali and Mazumder, 2012) multiplied by their average landholding per household of roughly 1 ha. This translates into 116.67 sq km of farming area in the vicinity of the park.

Cost of acquiring additional land is estimated using the present value of future returns through rice farming. This amounts (at 3M INR per year) to 33M INR in total present value terms using a market rate of interest of 10 percent. However, initially the manager could acquire forest lands at a much cheaper price and only when more land is needed, the opportunity cost of farming land would be taken into account. Therefore, the cost function for acquiring new land to expand the park is accordingly assumed non-linear, as specified in table 1 in the appendix.

The financial cost of monitoring and regulatory efforts by the park manager is also assumed non-linear. This estimation is based upon the fact that while the actual costs of inspections within and outside of the park may be insignificant as compared to value of the biodiversity that society places on the park, the true costs of monitoring lie in loss of human lives, either of the poachers or the wildlife managers when they come into conflict with each. Such conflicts in the park are reported on a regular basis. Using the statistical value of life (VOSL) estimated in India (Madheswaran, 2007), the above cost formulation implies that the cost to society would be INR 15M per life lost. Similarly, the cost of poaching effort for the smugglers is assumed to be high, and reflects the cost of hiring local helpers and transporting poaching equipment as well as the cost of avoiding detection and confrontation with the park rangers.

An indirect cost of monitoring and regulatory efforts is incurred through reduced crop output. Crop revenue is calculated based upon a conservative estimate of rice output of 2000kg/ha in the districts, which translates at INR 15/kg into 3 million INR per sq. km. Average rice output in Assam was higher at 3400kg/ha in 2014 (Directorate of Economics and Statistics, 2014). However, as the community encroaches on forest land and brings it under cultivation, their average farm income declines due to crop raiding by animals and lack of suitability of the land for cultivation. Also, an increase in the intensity of monitoring and regulatory measures puts a curb on farming practices and reduces farm output. The resulting crop output is calibrated as presented in table 1 in the Appendix.

Rhino population growth rate is taken from Lopes (2014). The density of rhinos in KNP, at 5.81 per sq km, is already one of the highest in the world. Here it is assumed that ideal density is marginally lower at 5 per sq. km., and therefore, there would be some downward adjustment in their population in the long run. For instance, a higher density could result in a higher mortality rate for rhinos due to competition for food and territory. Price of rhinos in the illegal markets is taken to be 60,000 USD (The Guardian, 2017), which is roughly equal to 4M INR. Poachers maximize their poaching incomes through equating their marginal cost of poaching effort to the marginal rewards.

The value to the society from biodiversity assets in the KNP has not been estimated in much detail. One study surveyed about 230 visitors in the park to plot the demand function for park visitation rates (using the travel cost method) and came up with a value of roughly 770 million INR annually (Bharali and Mazumder, 2012). As these estimates are based upon aggregation of the demand functions for the residents in Assam and other States, the value of the park could be higher or lower depending upon whether those that were excluded in the survey had higher or lower willingness to pay for travel to the park.

We adjust the weights in the utility function so that the population abundance of the rhinos in the park acts as a proxy for biodiversity richness, and at the current population of 2500 rhinos, the utility derived by society is roughly half of the estimated value by Bharali and Mazumder (2012). Utility from tourism income of 4 million annually is adjusted downwards by 40 percent to reflect income accruing only to the local community and is further weighted by the park manager to reflect its value with respect to other arguments in the utility function. Agricultural revenue gets a relatively lower weightage in the manager's utility function as compared to rhino population abundance and tourism to reflect the conflicts that exist between local communities' traditional livelihood means and the goal of ensuring the sustainability of the park.

Finally, we consider the parametrization of the hazard function. Climatic models predict that the flooding intensity and damages would be higher in the future due to the impact of warming. Specifically, in the next 20 to 30 years, the region will see a substantially higher flooding rate (Manabe et al., 2004). Climate change related increase in flow could also create permanent channels of the Brahmaputra river that could cut off animals from higher grounds (ADB, 2009). Through increasing the area under conservation and bringing forest lands within the park, both the risk of flooding and the resulting damages could be mitigated. In particular, preservation of forest areas and wetlands in the Brahmaputra region is key to reducing the risk as well as the damages from flooding, as wetlands help absorb flood waters and forests mitigate the impact of flooding. However, the presence of excessive silt in the Brahmaputra river causes it to change course frequently which leads to an expansion of the riverbed area through erosion of the river banks. The larger the riverbed area, the higher is the risk of flooding. Human interventions, such as through sand mining, deforestation and encroachment of wetlands for agriculture have caused a further expansion of the riverbed area, which increased from 3,870 sq km in 1916 to 6,080 sq km in 2006 (Purkayastha, 2017). Therefore, bringing forests and wetlands under protection of the park area would prevent future soil erosion and flooding within the park. Some additional measures, such as construction of embankments and sluices, within the park would also be required.

There are no known estimates of the impact of afforestation in the adjoining areas on preventing flooding in the KNP. The relation between increasing the park area and its impact on hazard rate (given by equation (16)) is calibrated as follows. The base case risk scenario (presented in section 4.2.2 ahead) assumes a hazard rate of 0.2. A hazard rate of 0.2 implies that if the park area were to remain constant in the future (at 430 sq km), the probability of climate related exacerbated flooding scenario manifesting in the next 20 years would be more than 90 percent[1]. If the park area is doubled at 860 sq. km, it would reduce the hazard rate to 0.057. At this hazard rate, the probability that the climate scenario will materialize in the next 20 years is reduced to 66 percent. Similarly, a tripling of the forest area to 1290 sq km will reduce the hazard rate to 0.03. At that rate, the probability of the climate scenario arriving in the next 20 years is about 55 percent. The assumption here is that the marginal benefits of land use change on flooding risk mitigation decline with an increase in the area.

Post-climate value function is calibrated through solving the post-climate optimization problem (in GAMS) for various starting levels of $x(t), b(t)$ and $l(t)$. The resulting utility values are then taken to calibrate a non-linear functional form using the *nl* command in STATA. These four-dimensional post-flooding value functions are presented in table 1 in the appendix. Figure 1 depicts two such value functions. The first value function (V_no_risk) is simply the base case value function without any flooding risks (equation (12)). V_post_cc is the value function in the post-climate scenario (as presented in equation (18)). Finally, the overall model is run using a time horizon of 200 years and a discount rate of 5 percent. For ease of presentation, results are presented for the first 100 years only.

4.2.Results

The scenarios performed in this section are selected with the objective of generating insights related to the optimal level as well as the timing of monitoring efforts and their impacts on rhino populations. In particular, we are interested in knowing under what circumstances the

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[1] The probability of flooding scenario manifesting after time *t*, is given by $\exp(-\lambda(t))$, where $\lambda(t)$ is defined in equation (21). When the park area is kept constant, the hazard rate also remains unchanged, which reduces the expression $\exp(-\lambda(t))$ to $\exp\left(-\lambda_0 \cdot \left(1 - \frac{x(t)^{\lambda_1}}{x(t)^{\lambda_1} + \lambda_2}\right) \cdot t\right)$. Substituting for a park area value of 430 and time of 20, the probability that flooding will occur *after* 20 years becomes: $\exp\left(-0.2 \cdot \left(1 - \frac{430^2}{430^2 + 300000}\right) \cdot 20\right) = 0.0841$. Therefore, the probability of the same occurring *before* 20 years becomes 0.9159.

park manager may find it optimal to increase or decrease monitoring efforts compared to the base line scenario. Specifically, how does a larger park area or a smaller rhino population influence optimal timing of monitoring and regulatory efforts? How does higher weight on farming incomes in the utility function affect monitoring efforts and the long-term rhino populations? Finally, when faced with the risk of future climate induced flooding, whether the manager must invest more into augmenting the park area or undertake higher monitoring efforts?

In section 4.2.1, we present results for various scenarios where the manager does not consider the option to increase the park area. Further, the risk of the climate event is non-existent. Therefore, these scenarios derive time paths of optimal monitoring and regulatory efforts when faced only with poaching and encroachment challenges. Next, in section 4.2.2, we incorporate the climatic risk and also allow the manager to augment the park area. Specifically, we compare the effects of variations in the hazard rate of flooding and costs of acquiring new park acres on optimal monitoring effort dynamics. We also compare the resulting monitoring and regulatory efforts dynamics with the no-risk base case scenario and derive implications for rhino population outcomes.

4.2.1. Scenarios involving no climatic risk and no option to increase park area

In this section we present results from the base case scenario first. Next, we explore the impact on optimal monitoring effort dynamics from variations in the costs of monitoring as well as poaching efforts, variations in the weight placed on farm income in the manager's utility function, and variations to initial rhino populations and park acres.

4.2.1.1.Base case scenario

Optimal monitoring and regulatory efforts under the base case are close to 4 units (figure 2). The total effective area under conservation (as depicted in figure 3) declines despite the constant level of monitoring and regulatory efforts. The level of monitoring effort is not enough to completely discourage encroachment (figure 4), however, it manages to keep the annual level of encroachment constant. As the effective park area (which is the area free of encroachment) serves as the maximum carrying capacity of the rhino population, a decline in the park acres leads to a gradual reduction in the rhino populations in the long term (figure 5). The rhino population is also affected by illegal poaching (figure 6), which is kept under check through monitoring and regulatory efforts. However, the cost of monitoring and regulatory efforts makes it difficult to eliminate poaching or encroachment altogether. Monitoring and regulatory efforts have a direct monetary cost as well as an opportunity cost in terms of forgone farming income for the local community. However, as encroachment leads to an augmentation of the farming lands (loss in park acres directly translates into gain in farming acres), farm income (figure 7) is increasing (under the base case) over time despite the adverse effects of monitoring and regulatory efforts. Further note that farm income has a lower weight in the manager's utility function as compared to the value of the rhino population abundance and tourism incomes. As tourism revenues are directly associated with rhino populations, their annual values will correspond to that of the rhino population.

4.2.1.2.Variations in monitoring and poaching costs, and in the utility weights

Next, consider some scenario variations. Under a scenario where the financial cost of monitoring and regulatory efforts is lower ('$\tau_{u0} = 0.1$'), efforts are much higher compared to the base case. This reduces the level of encroachment significantly, thereby having a positive impact on the long-term park area as well as the rhino population. Whereas, when the cost of poaching is lower (c_0=1.2 compared to the base case value of 2), the entire rhino population is threatened in absence of any monitoring and regulatory efforts. As a consequence, monitoring and regulatory efforts are kept much higher compared to the base case. This keeps in check poaching as well as encroachment and leads to an improvement in effective park acres. The rhino population remains unchanged from the base case (not depicted due to overlap). Higher monitoring, however, adversely impacts on farm incomes compared to the base case.

Another scenario that leads to a very high level of poaching effort arises when the manager assigns a higher weight on farm incomes in the utility function (‘$i_{qu1} = 0.5$’). This scenario is plausible when political pressure from local communities significantly influences wildlife management decisions. A higher weight on farm incomes results in the lowest levels of monitoring and regulatory efforts. This reduces the loss to agricultural incomes resulting from stringent regulations. Lower monitoring levels encourage encroachment and poaching efforts. A gain in farming acres resulting from encroachment further augments agricultural incomes. However, rhino populations suffer significantly from higher poaching and reduced park area.

4.2.1.3.Variations in initial population size and initial park area

Next, we explore how variation in the initial population size and conservation acres influences the trajectory of monitoring and regulatory efforts. A scenario where the starting stock of rhinos is lower at 1250 (half the base case level), monitoring effort in the early years is much lower compared to the base case. This results in a decline in the park area and an increase in farm acres over time. It may appear counter-intuitive to lower monitoring efforts at reduced rhino populations, however, as the density of the rhinos is fifty percent lower compared to the base case, they grow at a much rapid rate. Therefore, their population rapidly improves over time and catches up with the base case population levels in about 60 years.

In the next scenario, the area of the park is increased to 600 sq. km. (compared to the base case area of 430 sq. km.). The optimal levels of monitoring and regulatory efforts decline as the rhino population starts to increase due to a higher carrying capacity. Under this scenario, the park area still declines over time due to lower monitoring and regulatory efforts, however, it remains higher compared to that obtained in previous scenarios. An increase in encroachment results in increasing farm incomes over time. The rhino population is also one of the highest despite an increase in poaching. This scenario highlights the possibility of resilience offered by a larger forest area, as it could absorb larger encroachment and poaching shocks and yet retain a healthy rhino population stock. To consider the resilience offered by a larger park area in presence of poaching, encroachment, as well as natural hazard risks, we run the climate hazard model next.

4.2.2. Risk of climatic event with the option to augment park area

Now, consider the possibility of land use management through acquisition of additional forest acres when there exists a future risk of exacerbated flooding. In the following scenarios, we consider the optimal park management plan when both the risks as well as the extent of damages in the event of exacerbated flooding could be mitigated through enlisting additional areas under conservation. The option to augment the park is valid only in the pre-climate event scenario, however. Once the climate scenario arrives, the manager does not find it economically or technically feasible to increase park area, as permanent changes in the river channels would already have occurred thereby making the land use change option redundant.

Figure 8 presents outcomes for some risk scenarios where the manager invests during the pre-climate regime towards bringing more acres under the conservation park. The risk based scenario compared to the no risk base case scenario (base case in 4.2.1) leads to significant differences in park areas. As increasing the area of the park can postpone the risk of park flooding event as well as reduce the damages from flooding, the manager invests heavily towards increasing the size of the park (figure 9). Therefore, in contrast to the base case under no-risk scenario, the forest area triples to 1200 sq. km in the next 25 years. Also, notice that the level of monitoring and regulatory efforts in the risk scenario is lower and declines over time as compared to the no-risk base case scenario (figure 10). This would mean that both the poaching and the encroachment levels would be higher under the risk scenario (as compared to the no-risk base case scenario). However, the manager more than makes up for the loss in forest acres through purchase of new land while keeping the farm income increasing as well.

Next, we increase the hazard rate from 0.2 to 0.5. At a hazard rate of 0.5, the probability of the climate scenario arriving would be above 90 percent in just 8 years, if the forest area were kept constant at 430 sq. km. When the hazard rate of the climate scenario increases to 0.5, implying that the event is imminent (figure 11 depicts probabilities of survival until time *t*, which are measured through the expression $\exp(-\lambda(t)$), investment in new land declines. Monitoring and regulatory efforts decline as well, due to a lack of time available before arrival of the flooding event. A scenario involving higher cost of acquiring land ($a_{u0} = 0.02$) sees some tradeoffs in terms of increasing monitoring and regulatory efforts but cutting back on additional land purchases (under the risk scenarios). However, when the cost of acquiring land is higher but the climate risk is also increasing, monitoring and regulatory efforts go down due to a discounting effect. Also, assuming that flooding could reduce the farming land area as well, we perform a scenario (‘risk_loss of encroached land_ $a_{u0} = 0.02$’) where the community loses all encroached land. This reduces crop productivity in the post-climate scenario. The manager puts in marginally higher monitoring and regulatory efforts (see figure 10) under this scenario as compared to the scenario ‘risk_ $a_{u0} = 0.02$’. However, there are no perceptible differences observed in additional land purchase between these two scenarios.

If the manager did not face the risk of the climate event, but still had the option to purchase new forest land (that is, adding new land to the park in the base case scenario), the long-term park area is lower compared to the risk scenario. However, it is higher than the base case scenario which did not consider the option of enrollment of new forest land. Given that there are no benefits from flooding risk reduction or damage reduction, this scenario highlights the advantages of combining land use management along with monitoring and regulatory efforts.

5. **Conclusion**

In this paper, we modeled the challenge of conserving endangered wildlife that faces threats from poaching, encroachment of their habitats, and flooding from future climate and land use changes. Optimal monitoring and land use change efforts are derived keeping in mind that such efforts pose significant tradeoffs. For instance, increasing monitoring and regulatory efforts could reduce poaching as well as encroachment, however, it also alienates the local community by reducing their farm incomes.

A number of insights emerge from the model. First, when the manager cannot increase the size of the conservation park but only has the option of increasing the level of monitoring and regulatory efforts to restrict encroachment and poaching, several challenges arise in their conservation efforts. As monitoring and regulatory efforts adversely impact on farm incomes, it is not optimal to raise effort levels high enough so that encroachment or poaching are eliminated. As a result, the optimal level of monitoring and regulatory efforts does not lead to an improvement in the rhino populations. The gradual loss in the effective conservation area due to encroachment exacerbates this problem. In fact, if the manager were to increase the weight on farm income in their utility function, they would need to further lower the monitoring and regulatory efforts, which in term would again lower the rhino populations.

When the manager has the option to increase the park size, it offers both risk-protection and risk-insurance benefits through reducing the probability of flooding and reducing the damages in the event of flooding. The optimal plan under flooding risk entails tripling the size of the park from its current levels. This option would be feasible if it does not lead to a displacement of the local communities but merely brings forest areas in the vicinity of the park under conservation. This strategy prevents future land use changes where the same forest lands could have been converted for farming or mining purposes and would have increased the flooding risks to the park. An increase in the size of the park also allows some laxity in monitoring and regulatory efforts as losses from poaching and encroachment are easily compensated for through a higher growth rate of the rhino population made possible through a change in the carrying capacity of the park. Findings also indicate that acquiring additional land is an optimal response even in the absence of a flooding risk as it allows for a similar trade-off between monitoring effort and park area augmentation.

The real threats posed to endangered species exist both in the short term as well as the long term. Optimal conservation efforts must weigh the trade-offs between short-term population gains and long-term risks to the habitats. From a policy perspective, it makes sense to increase the park size along with monitoring and regulatory efforts, especially when the marginal costs of monitoring and regulations increase steeply. An increase in the conservation area may also improve society’s willingness to pay to preserve the wildlife and its habitat, which would make future conservation tasks easier. These findings are also applicable to conservation areas globally, as poaching and wildlife smuggling is increasingly threatening the extinction of a large number of species. Managing such immediate man-made threats draws resources away from protecting the same species against threats of future climate events. In order to balance the short-term man-made threats against long-term climate risks, a revisiting of current conservation approaches is required.

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Appendix

Table 1: Parameters selected for the numerical example

Equation No.	Equation	Parameter Values
(1)	$\dot{b}(t) = \rho \cdot b(t) \cdot \left(1 - \frac{b(t)}{b_d \cdot x(t)}\right) - p(t)$	ρ =0.05, b_d =5,
(3)	$e(t) = e_{\max} \cdot (1 - \frac{\tau(t)^{e_0}}{\tau(t)^{e_0} + e_1})$	$e_{\max}$ =5, $e_0 = 2$, e_1 =10
(5)	$q(t) = l^{\alpha} \cdot \left(1 - \frac{\tau(t)^{q_0}}{\tau(t)^{q_0} + q_1}\right)$	q_p =3, $\alpha = 0.8$, $q_0 = 2$, $q_1 = 20$
(6)	$m(t) = m_0 \cdot \log(b(t)^{m_1})$	m_0 =1, m_0 =.5
(7)	$i(t) = \gamma \cdot m(t) + q_p \cdot q(t)$	γ =0.6
(9)	$u(t) = b_{u0} \cdot b(t)^{b_{u1}} + i_{mu0} \cdot i_m(t)^{i_{mu1}} + i_{qu0} \cdot i_q(t)^{i_{qu1}}$ $- \tau_{u0} \cdot \tau(t)^{-\tau_{u1}} - a_{u0} \cdot a^{a_{u1}}$	$b_{u0} = 0.1, b_{u1} = 0.75, i_{mu0} = 0.1, i_{mu1} = 0.75,$ $i_{qu0} = 0.1, i_{qu1} = 0.25, \tau_{u0} = 0.5,$ $\tau_{u1} = 1.1, a_{u0} = 0.01, a_{u1} = 2$
(10)	$p_{rhino} \cdot h(t) \cdot \left(1 - \frac{\tau(t)^{p_0}}{\tau(t)^{p_0} + p_1}\right) - h(t)^{c_0}$	$p_{rhino} = 4$, $p_0 = 3$, $p_1 = 100$, $c_0 = 2$
(16)	$\dot{\lambda} = \lambda_0 \cdot \left(1 - \frac{x(t)^{\lambda_1}}{x(t)^{\lambda_1} + \lambda_2}\right)$	$\lambda_0 = 0.2$, $\lambda_1 = 2$, $\lambda_2 = 300000$
(17)	$\dot{b}(t) = \rho \cdot b(t) \cdot \left(1 - \frac{b(t)}{b_d \cdot x(t)}\right) - p(t)$ $- f_0 \cdot \left(1 - \frac{x(t)^{f_1}}{x(t)^{f_1} + f_2}\right)$	$f_0 = 50$, $f_1 = 2$, $f_2 = 10^6$
(12)	V_no_risk	$-83.30084 + 7.635147 \cdot x(t)^{.4006232} \cdot b(t)^{.341107} \cdot l(t)^{.0044774}$
(18)	V_post_cc	$-90.24978 + 1.352286 \cdot x(t)^{..511425} \cdot b(t)^{.45364} \cdot l(t)^{.0051793}$

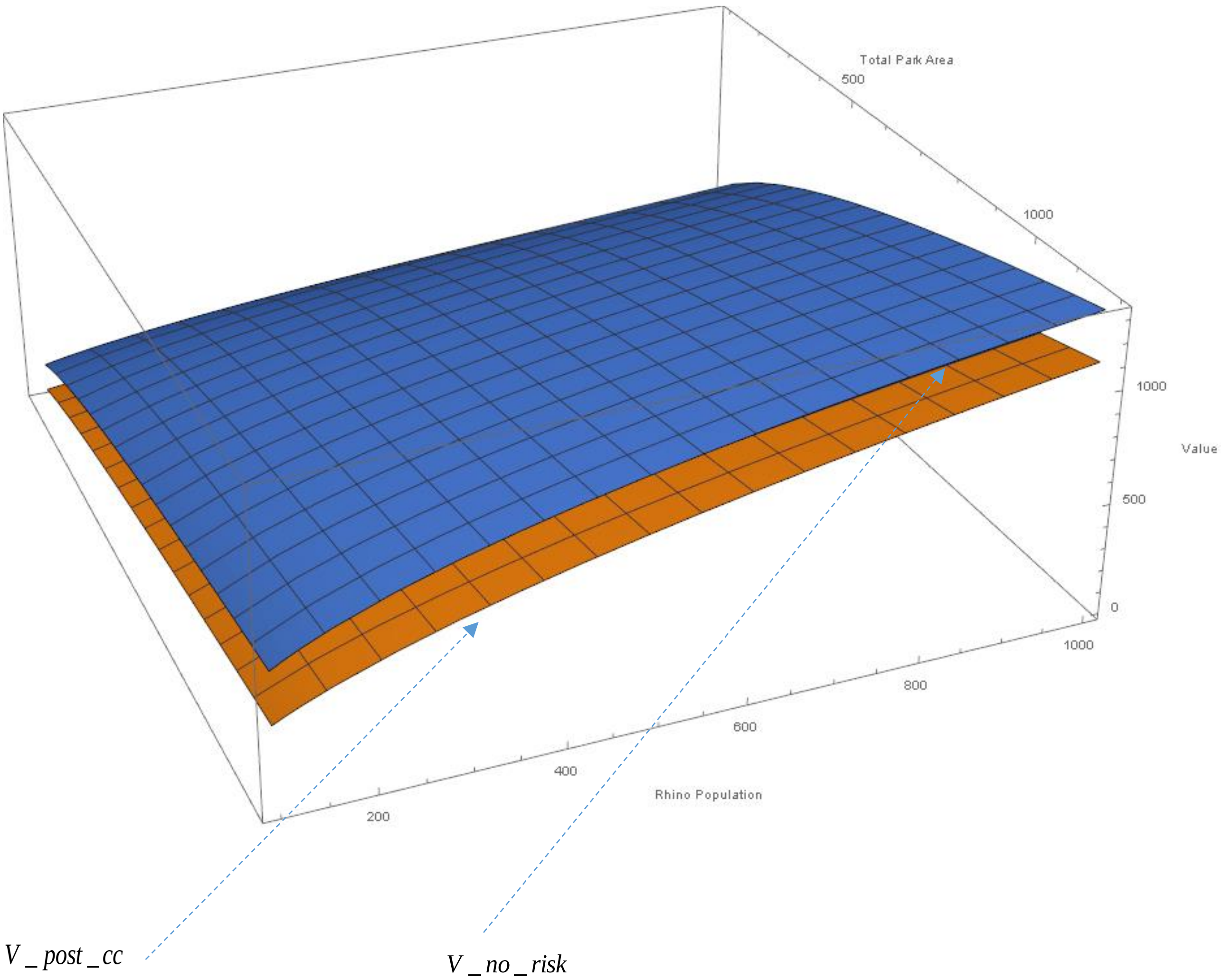

Figure 1: Comparison of no-risk flooding value function with the post-flooding value function

Note: *As the value functions are 4-dimensional, they are being depicted for a fixed farm land area of 100 sq km.*

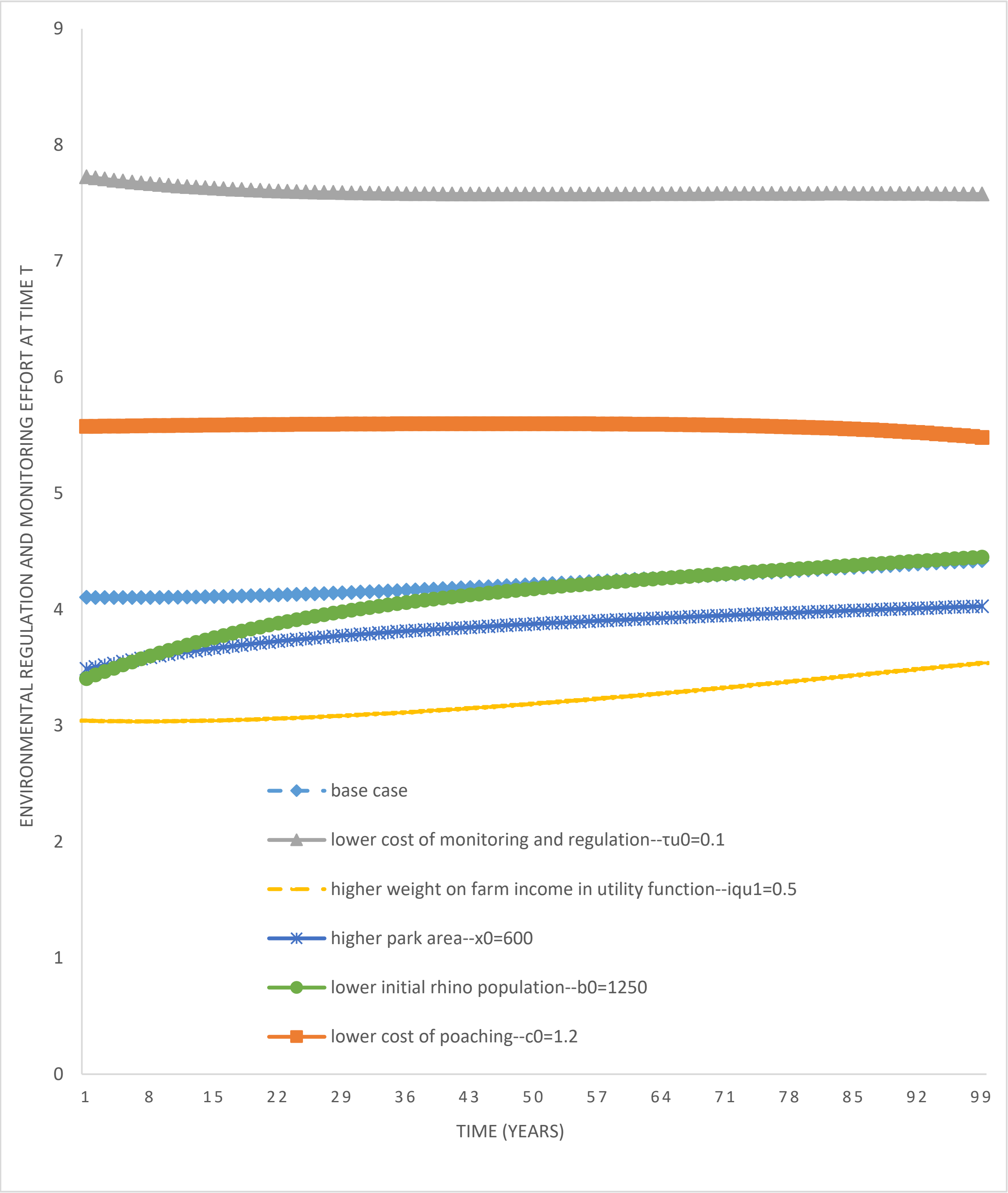

Figure 2: Optimal monitoring and regulatory efforts under various scenarios involving no climate risk

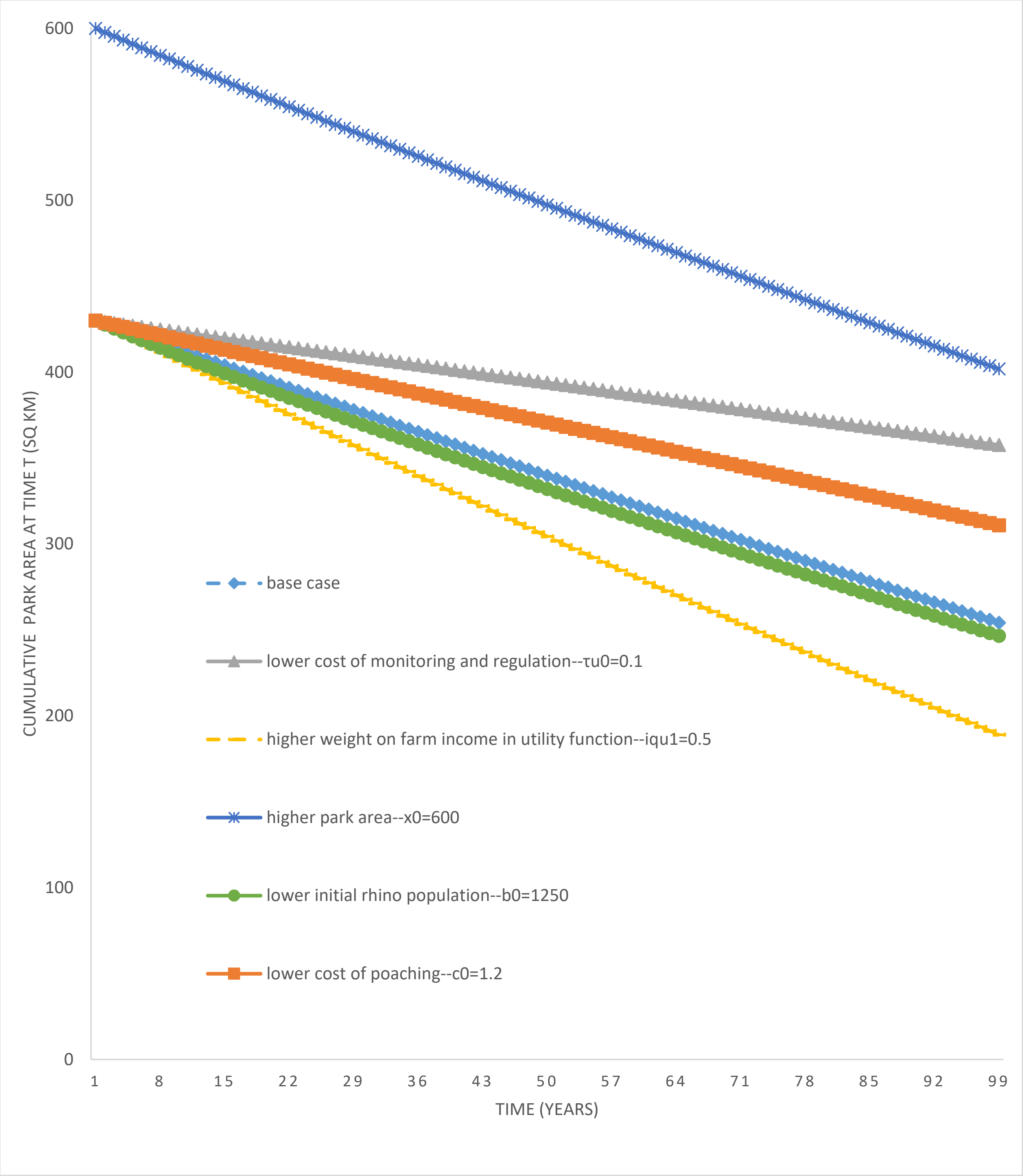

Figure 3: Time path of conservation area decline under various scenarios when no climate risk exists

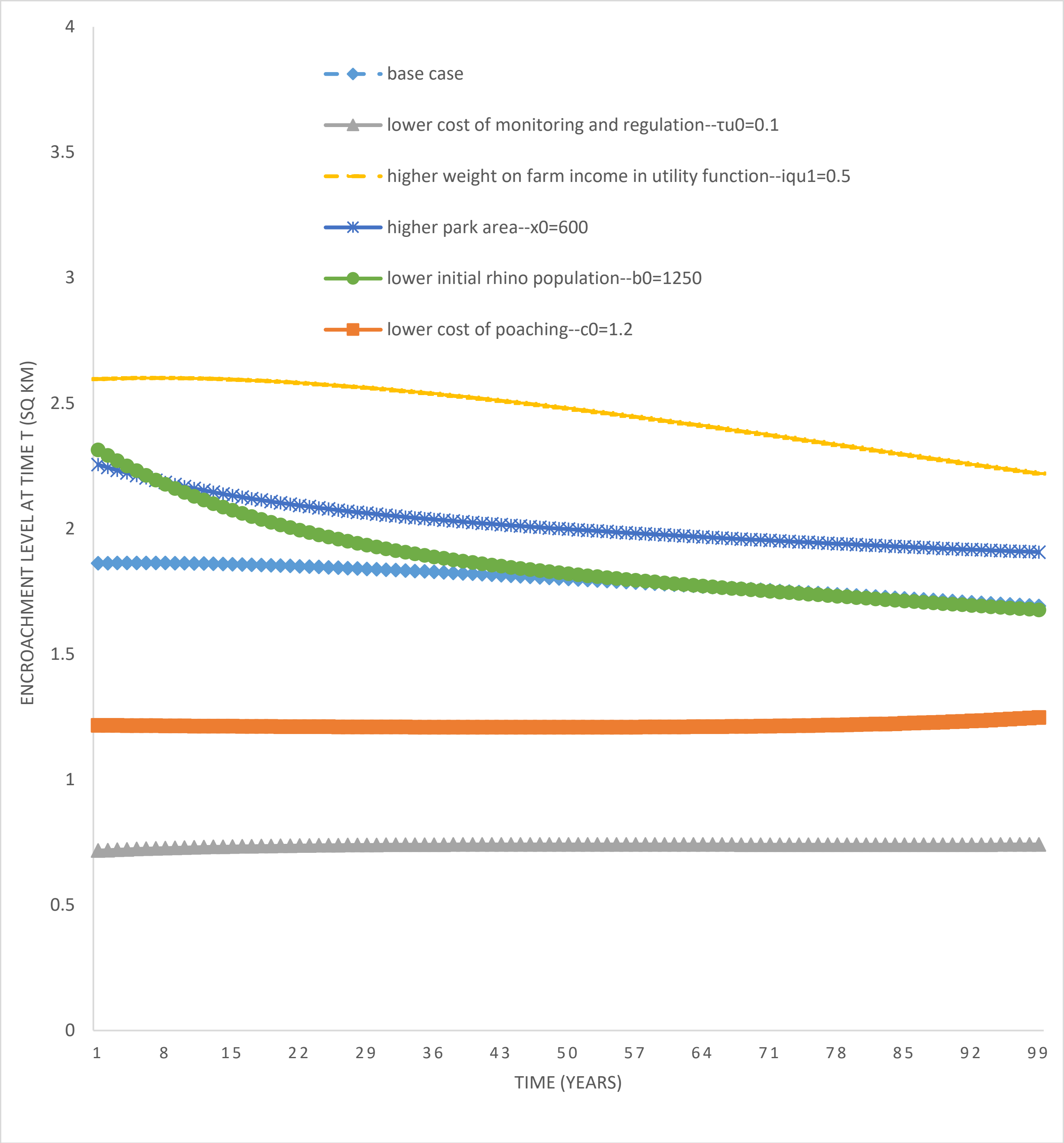

Figure 4: Encroachment of the conservation area under various scenarios involving no climate risk

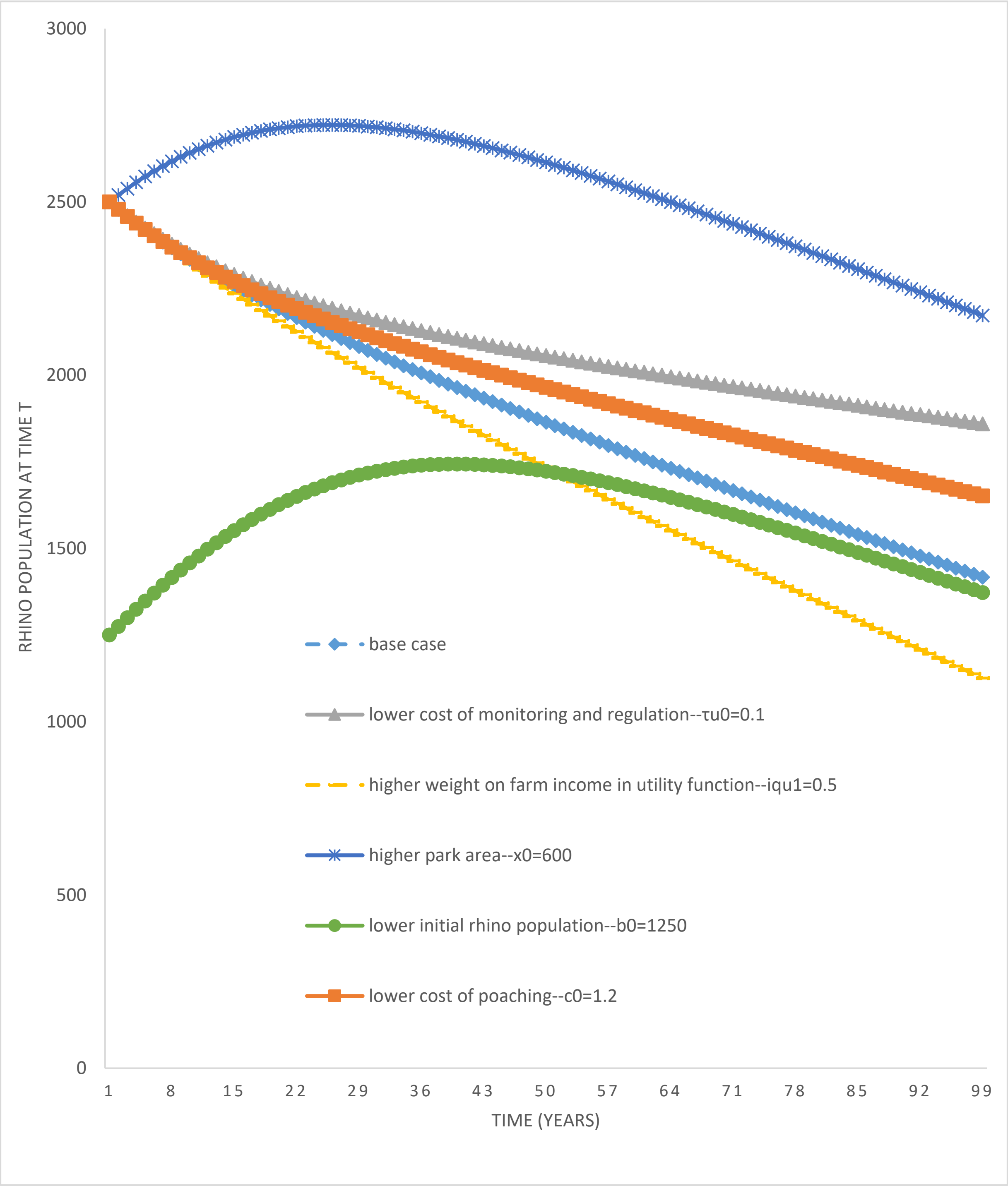

Figure 5: Time path of rhino populations under various scenarios involving no climate risk

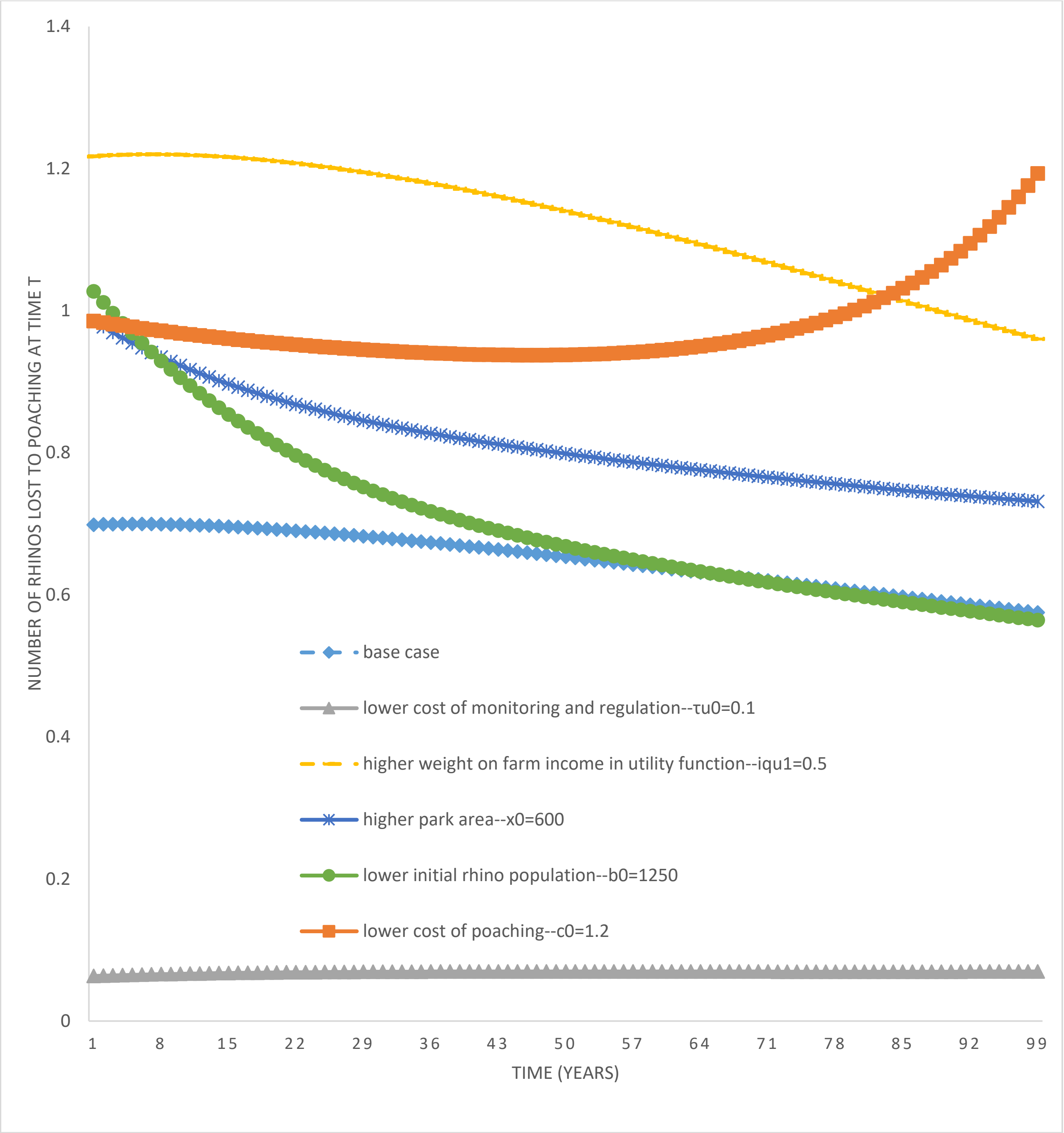

Figure 6: Number of rhinos poached under various scenarios involving no climate risk

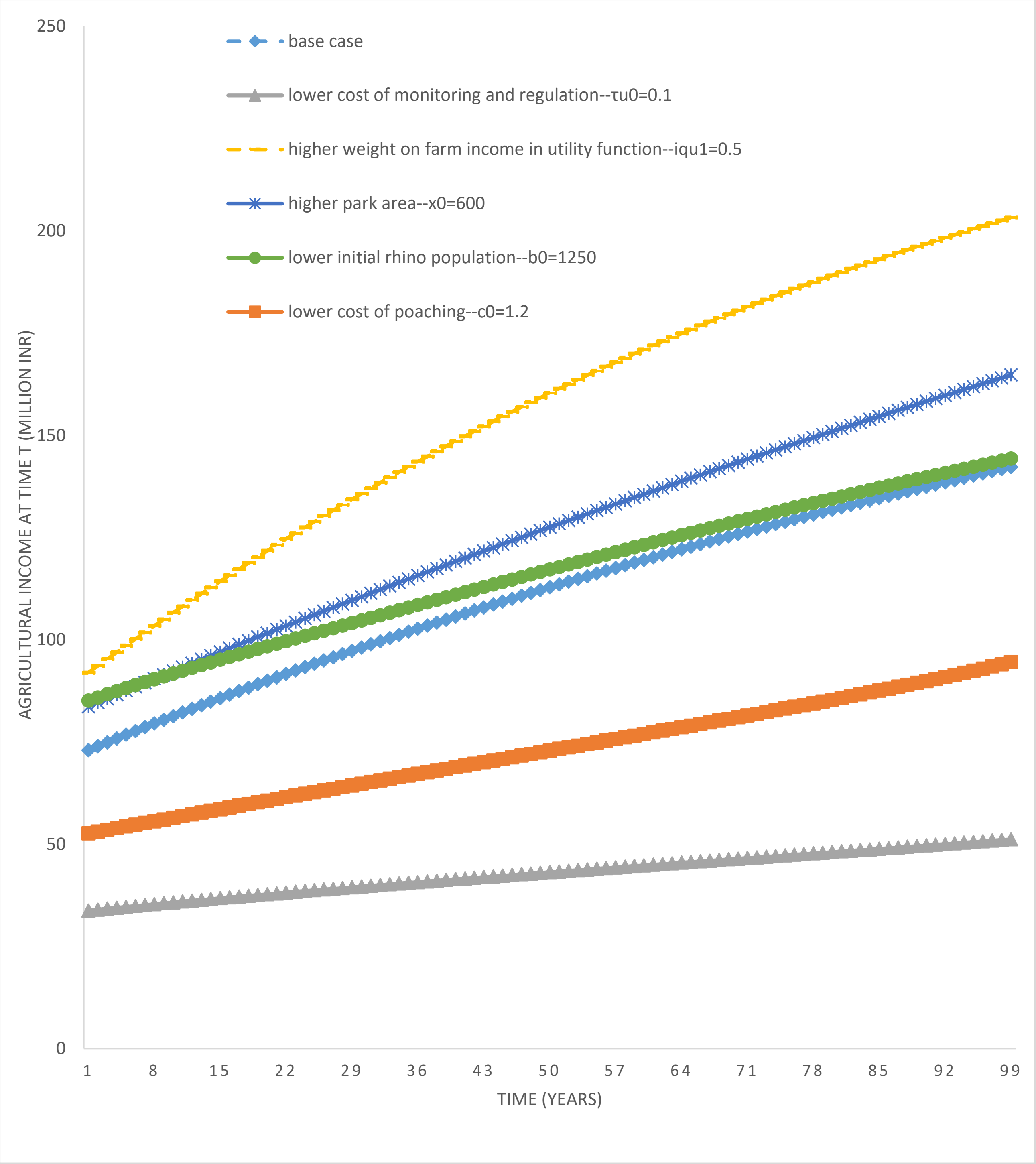

Figure 7: Farm income dynamics under various scenarios involving no climate risk

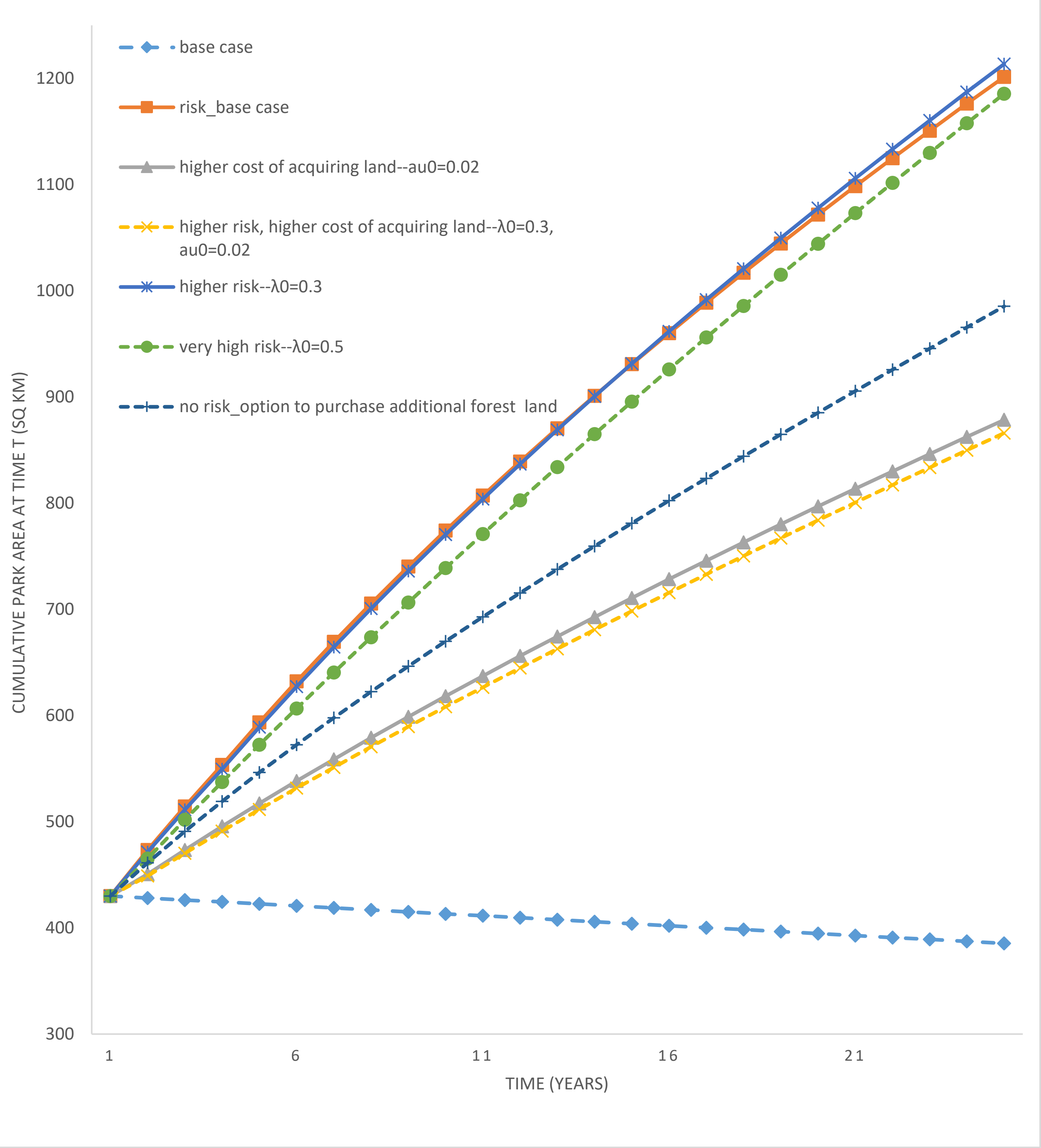

Figure 8: Time path of conservation area under climate risk scenarios

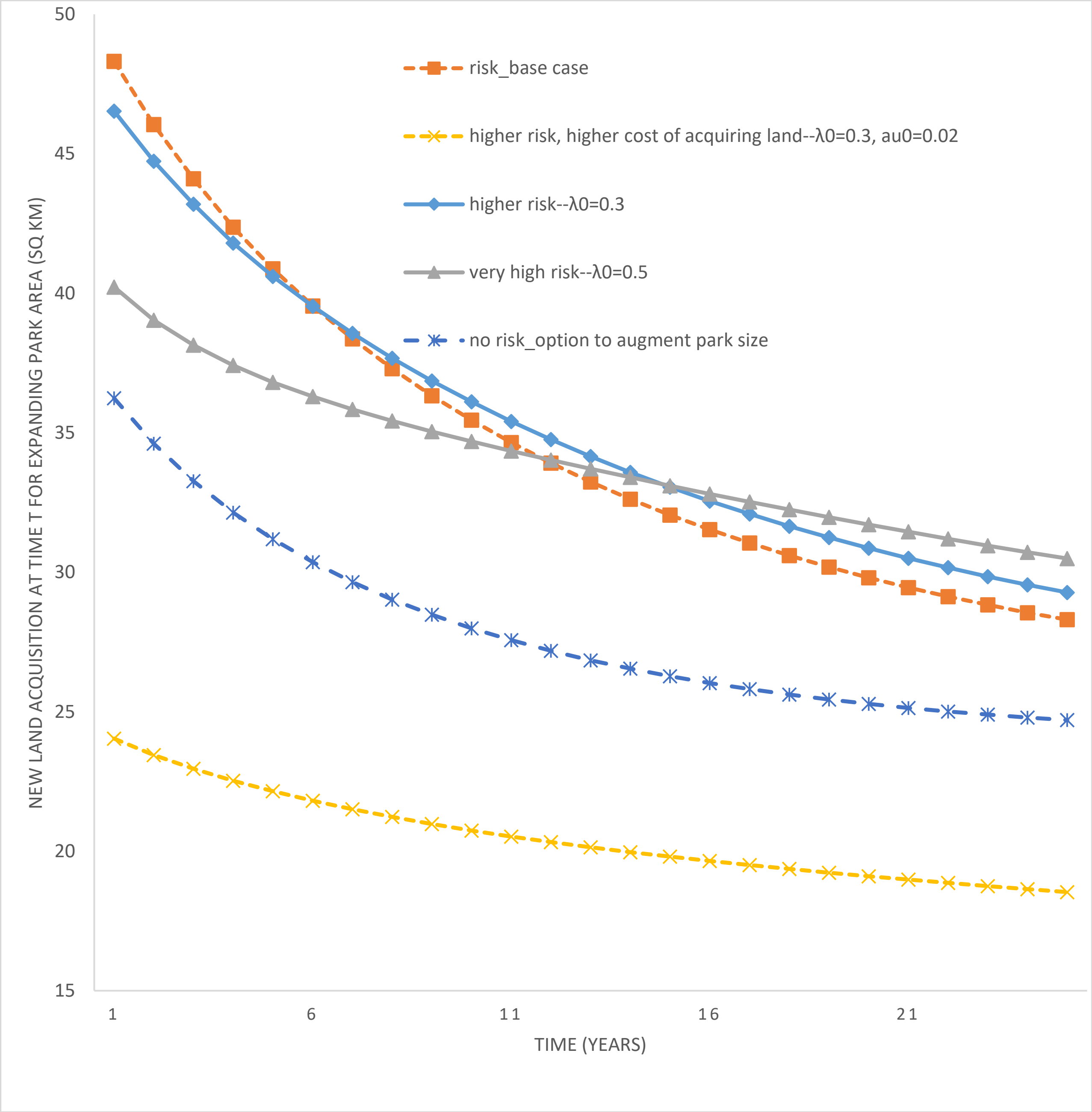

Figure 9: Time path of new land acquisition under climate risk scenarios

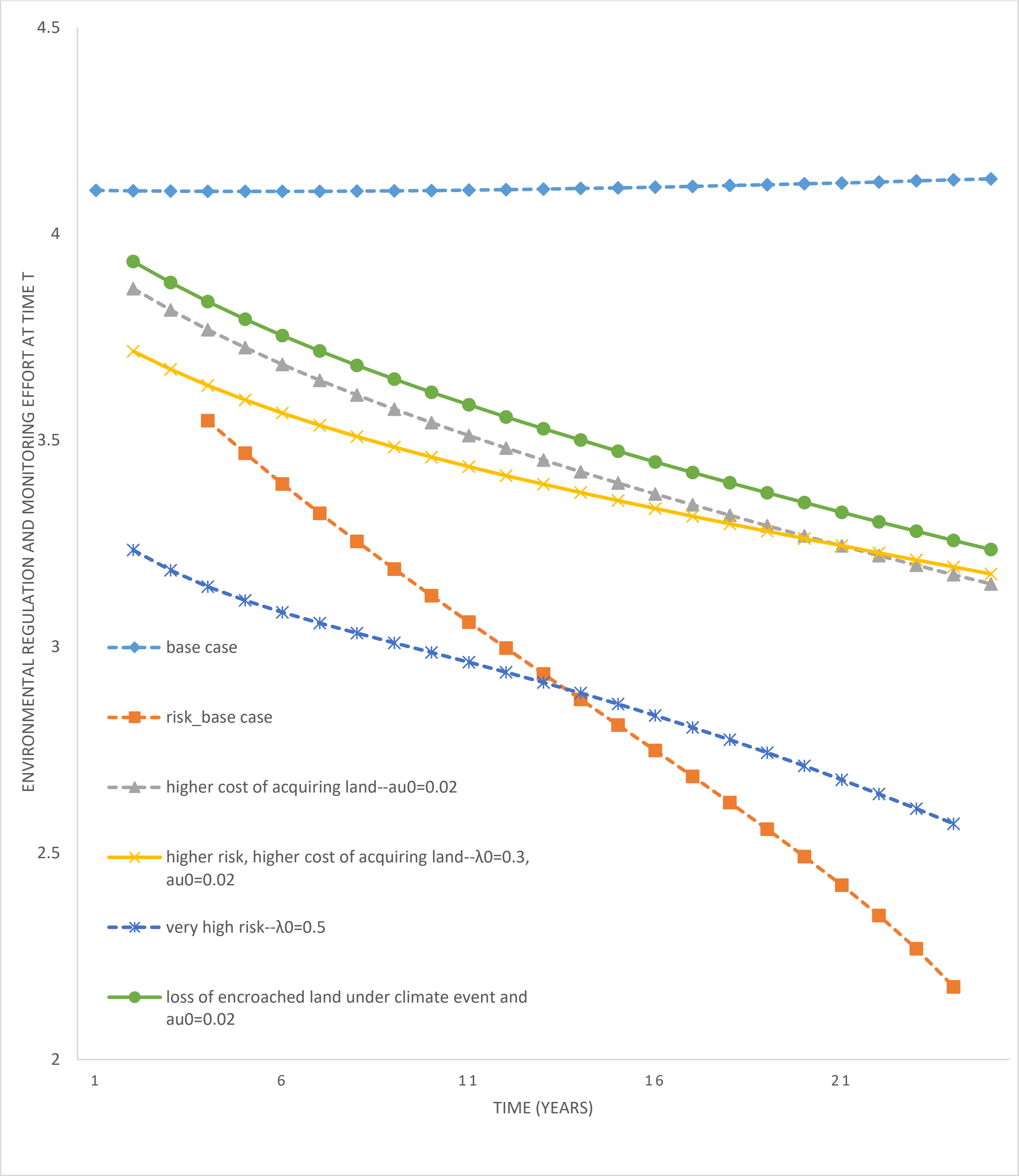

Figure 10: Monitoring effort under climate risk scenarios

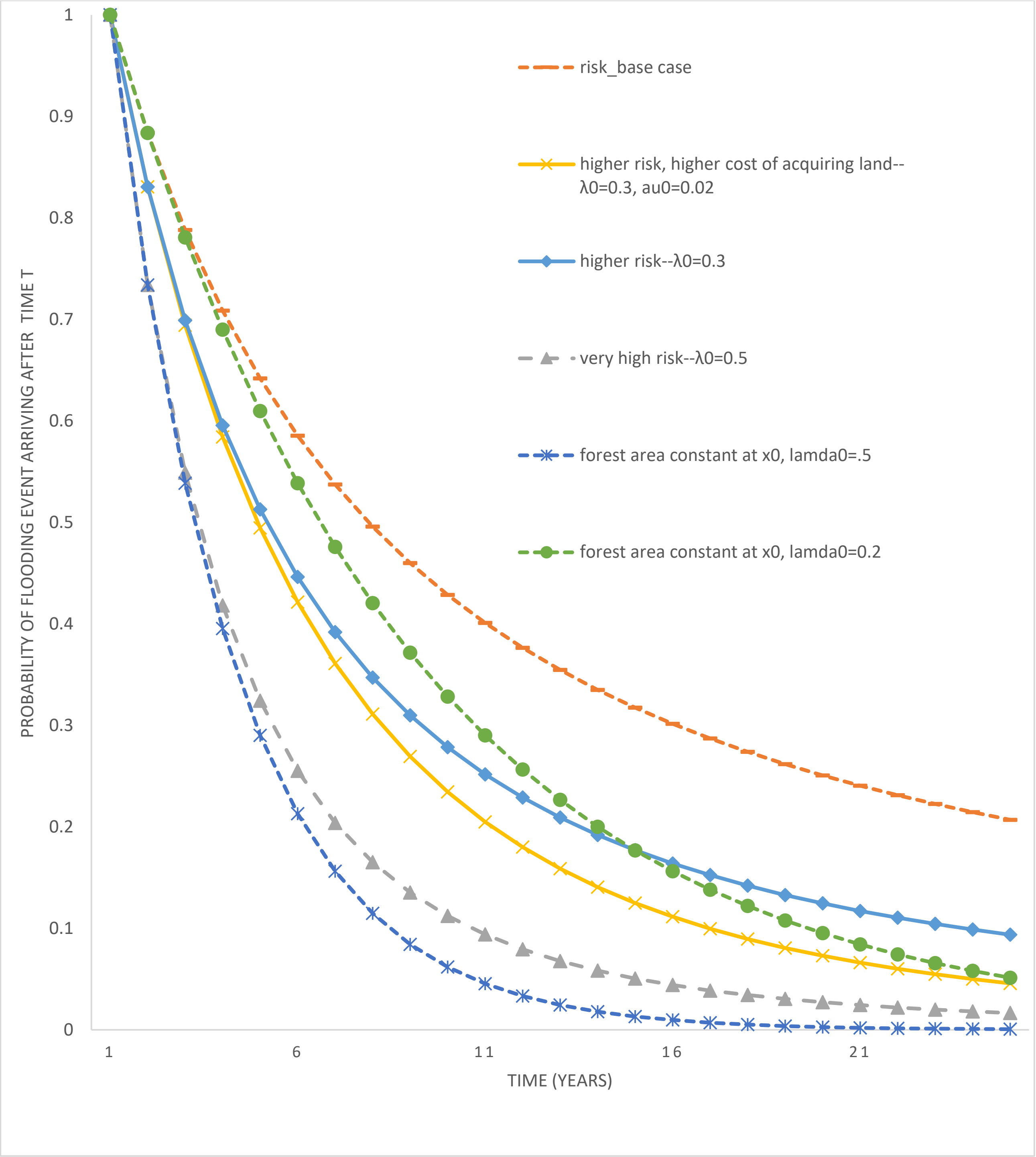

Figure 11: Probability of flooding event arriving *after t* (or not occurring *until* time *t*) under various scenarios