Agricultural and urban land use policies to manage human–wildlife conflicts

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Abstract. Human–wildlife conflicts occur in residential areas, causing human injuries and outbreaks of zoonotic diseases. Governments have implemented policies, such as extermination, and construction of animal deterrent fences. When wildlife has a high biological value, we face a trade-off between the benefits of wildlife conservation and human safety. This study proposes a new policy of growing crops preferred by wildlife, rather than crops for human consumption, in part of the farmland, thereby attracting wildlife to the converted field and preventing them from entering residential areas. Using an ecosystem-urban economics model, we compare multiple policies including the conversion policy in terms of social welfare, and show that, regardless of the wildlife value, the crop conversion policy can be the most efficient, and fences with land use regulation is the second most efficient policy. On the other hand, the commonly-used policy of extermination is not so effective because exterminating wildlife with a high biological value significantly reduces social welfare.

JEL classification: R11; R14; Q28
Keywords: Human–wildlife conflict; land use regulation; extermination; animal deterrent fence; ecosystem conservation; urban economics model

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1. Introduction

Human–wildlife conflicts often occur in urban residential areas, causing human injuries, damage to the crop, and outbreaks of zoonotic diseases. Urban carnivores causing such conflicts are bears, coyotes, large felines, etc. As countermeasures, city governments have erected animal deterrent fences and exterminated harmful animals. Zoning is an alternative policy because it can separate animal activity zones from human activity zones. Some animals have high values for biodiversity, and most large animals are often necessary to maintain a healthy ecosystem. Thus, we face a strong trade-off between their ecological benefits and human safety. So, we need to discuss the efficiency of feasible policies. However, this discussion is rather complex due to the need to take account of the spatial distribution of humans and wildlife.

Figure 1 shows the locations of bear attacks on humans resulting in injuries in Japan, as described in the Ministry of the Environment's Manual for Responding to Bear Appearances (2021). According to this figure, the number of bear attacks in residential areas has increased every year. In 2020, the share of bear attacks in residential areas and farmland has reached 37.6%, exceeding 34.8% in mountain forests.[1] Bears enter residential areas and scavenge for garbage to feed on during a poor season for their usual food source in the forest. This is why the total number of bear attacks fluctuates over time.

Similar situations appear worldwide for wolves, bears, boars, foxes, coyotes, leopards, tigers, snakes, bloodsucking mosquitos, and mites (Woodroffe et al., 2005; White and Gehrt, 2009; Gates, 2016; Peteriani et al., 2016; Krafte Holland et al., 2018; Abrahms, 2021). Distefano (2005) summarizes the situations of human–wildlife conflicts in many countries and provides an overview of countermeasures against them. Typical countermeasures are construction of animal deterrent fences and extermination. Zoning policies may be useful

[1] In the residential area of Sapporo, Hokkaido, there was a series of bear-involved damages, resulting in twelve deaths and 2,163 bear sightings in 2021. In addition, these bears invaded the airport, causing the airport to be temporarily blocked and a total of eight flights to be canceled.

because they can separate the territories of animal activity from that of human activity to some extent. However, there has been little analysis of optimal land use policies for the human–wildlife conflict because no models account for the spatial dimension that is a crucial aspect of conflicts. As Poessel et al. (2013) show that the severity of conflicts varies across cities, the severity depends on the location and the numbers of people and animals in the area.

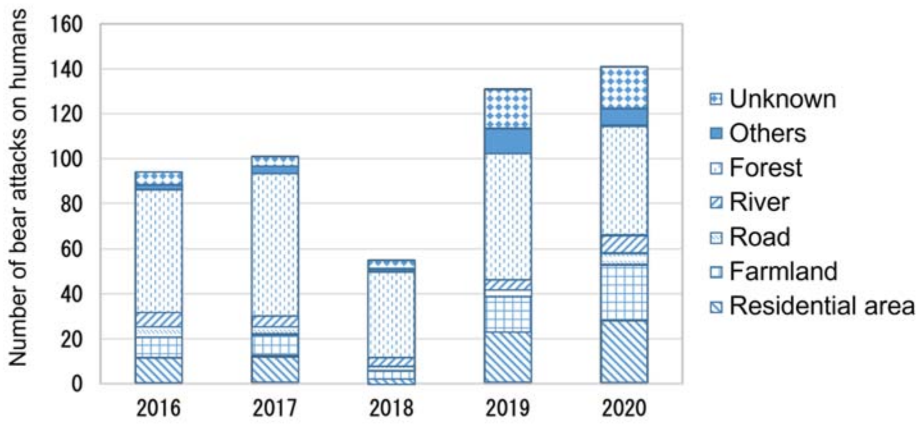

Figure 1. Number of bear attacks on humans by location

Some economists have already recognized ecosystem services as important inputs to economic activity, and developed ecosystem-economy combined models (e.g., Tschirhart, 2000; Eppink et al., 2004; Eichner and Pethig, 2006; Finnoff and Tschirhart, 2008; Eichner and Pethig, 2009). However, none of the previous papers have considered the spatial aspect of human–wildlife interactions, possibly because space has been largely ignored in economics. Only urban economics takes account of continuous space, and has researched optimal land use policies, considering traffic congestion, greenhouse gas emissions, and natural ecosystems (e.g., Brueckner, 2000; Buyukeren and Hiramatsu, 2016; Kono et al., 2012, Pines and Kono, 2012; Rhee et al., 2014; Kono and Kawaguchi, 2016; Borck, 2016; Kono and Joshi, 2017, 2019; Borck and Brueckner, 2018). Yoshida and Kono (2022) propose a new model that combines an animal behavior model with an urban economic model to identify the relationship between animal activity areas and human population density. Yoshida and Kono (2020) optimize urban boundary regulation and forest density control in the same model.

Extending the urban-ecosystem model of Yoshida and Kono (2020, 2022) to account for the presence of agricultural land, the current paper quantitatively evaluates the efficient levels of multiple countermeasures against urban carnivores. We target urban bears as representative urban carnivores. In our model, the target area is composed of residential areas, agricultural areas, and forests. The residential areas are inhabited by workers of composite goods-producing firms, and agricultural land is inhabited by farmers. Our model endogenously takes account of damage caused by bears in each location, labor mobility between agriculture and manufacturing industries, and animal populations. The forest area supplies a food source for the animals, but it has a poor season every few years. During this poor season, the animals attempt to enter the city in search of food.

We numerically simulate the efficiency of five policy instruments: i) extermination; ii) animal deterrent fences with equilibrium land use; iii) land use regulation allocating the areas of land for residential, agricultural, and forest use; iv) animal deterrent fences with land use regulation; v) crop conversion with land use regulation.

For i) extermination policy, we determine how many animals to exterminate to maximize social welfare under equilibrium land use. In ii) animal deterrent fences are installed between the agricultural area and the forest. We assume that no bears will enter residential areas under the fencing policy. Land use regulations, which are included in iii)-v), optimally adjust the sizes of residential, agricultural, and forest areas. In iii), only land use regulations are implemented. In iv) the fences with land use regulations, we optimally adjust the sizes of the forest, residential area, and farmland and place fences between the agricultural area and the forest. v) Crop conversion with land use regulation is a policy of growing crops preferred by wildlife, rather than crops for human consumption, in part of the farmland, thereby attracting wildlife to the converted field and preventing them from entering residential areas. Since bears do not pay for the crops, the government compensates for the farmers' loss of income. The government finances the compensation by a lump-sum tax collected from people.

We clarify which policy can obtain the maximum welfare improvement, and how much welfare improvement the policy instruments can achieve, compared to the first-best welfare. The first-best here refers to the ideal situation where social welfare is maximized by controlling all agencies' behaviors including animal behaviors (i.e., animal time density at each location). In addition, we also perform some sensitive analyses regarding parameters representing the value of bears and forests.

The main results are as follows. Regardless of the parameters, crop conversion is the most efficient. This policy can reduce human-bear conflicts in residential areas because it can direct bears to a specific area of farmland. Bears have alternative food sources there even during a poor nut season, which makes the bear population rise. The fence with land use regulation is the second most efficient. This policy does not allow bears to enter residential areas at all, which reduces the bear population. To prevent such a decline in bear population, we should increase the forest area. As a result, the fence with optimal land use regulation can eliminate conflicts in residential areas, and the number of bears and trees can increase. However, the reduction in the residential area results in higher land rents. This is why the fence with land use regulation can lower social welfare more than the crop conversion. The imposition of only land use regulation cannot completely prevent bears from entering residential areas. Accordingly, welfare gains are slight. When the number of exterminations is high, the bear population decreases significantly. When the value of bears is high, social welfare becomes lower. On the other hand, low numbers of exterminations result in little or no reduction in damage caused by bears. Therefore, the welfare gain of extermination is not large. As a result, the crop conversion policy is likely to be the most desirable among policy candidates.

We can also find that the crop conversion policy has the potential to achieve more than 90% of the first-best welfare regardless of the parameters. If the fence can prevent bears from entering the city entirely, the fencing policy with land use regulation can achieve more than 80% of the first-best welfare regardless of the parameters.

The rest of the paper is organized as follows. Section 2 introduces the model. Section 3 shows the detail of the five policy instruments. Section 4 demonstrates the efficiency of these policy instruments through numerical simulations. The final section concludes the paper.

2. The Model

2.1 Residential area, agricultural area, and forest

The model mostly follows the urban-ecosystem model of Yoshida and Kono (2020, 2022). Consider a closed monocentric city surrounded by a natural habitat covered by forests. There are $2\overline{N}_h \in \mathbb{R}_+$ identical households in the city, and land is equally owned by city residents.[2] For simplicity, city population equals the number of households.

The city is linear with a width of one unit, and $x \in [-Z^A, Z^A]$ denotes a locational distance from the city center. The city is symmetric, and the right-hand side (RHS, hereafter) has $\overline{N}_h$ population. N_h^R people reside in the residential zone and commute to the central business district (CBD) for producing composite goods, and N_h^A people reside in the agricultural zone for farming. For simplicity, people do not enter the forest.[3]

The land is divided into the following four zones: (i) CBD ($x = 0$), (ii) a residential zone ($x \in [0,\ Z^R]$), (iii) an agricultural zone ($x \in [Z^R,\ Z^A]$), and (iv) a forest zone ($x \in [Z^A, Z^F]$), where $Z^R \in \mathbb{R}_{++}$ is the residential boundary, and $Z^A \in \mathbb{R}_{++}$ is the agricultural zone boundary, $Z^F \in \mathbb{R}_{++}$ is an exogenous boundary of the forest. Superscripts R, A, and F indicate the residential zone, the agricultural zone, and forest throughout the paper. Following a real

[2] This is a typical urban economics model defined as the closed-city model under public landownership by Fujita (1989). Total profit of the land returns to all households evenly.

[3] It is because the first-order effect of humans on ecosystems might be due to construction and paving. Households entering natural habitats for hiking could be important for examining the environment, but we ignore this aspect for simplicity.

land use pattern, the geographical pattern is assumed as depicted in Figure 2. It shows only the RHS of the land, assuming that the left and the right are symmetric.

The RHS of the forest zone has $\bar{i}$ species whose populations are denoted by $\mathbf{N} = \{N_1, \ldots, N_{\bar{i}}\} \in \mathbb{R}_+^{\bar{i}}$. For simplicity, all animals or organisms belonging to the same species are assumed to be identical. To represent a simple predator-prey interaction of urban carnivores, the current paper supposes only two species (i.e., $\bar{i} = 2$). We target urban bears as representative urban carnivores. Bears (i = 2) feed on nuts produced by trees (i = 1), and trees take up nutrients from the soil.

Bears consume nuts to obtain nutrients to generate their offspring. Suppose that there is an exogenous probability of a good nuts season, denoted as p. In a poor season, bears enter the residential area up to $X \in [0, Z^R]$ in search of garbage and home garden crops. X is endogenously determined.

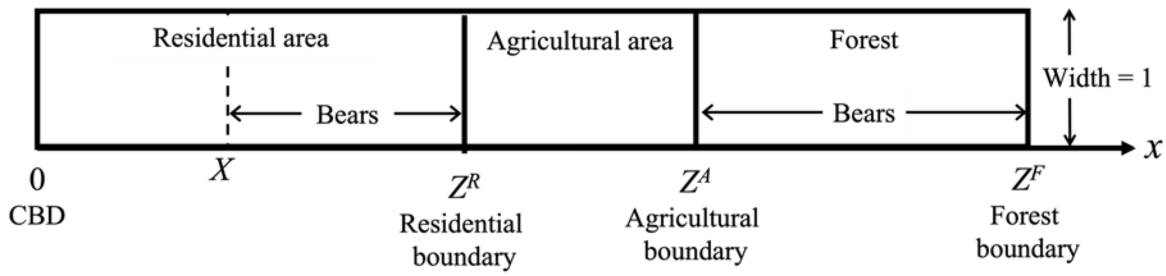

Figure 2. The model city adjacent to a natural habitat

2.2 Firm

A firm producing composite goods has a linear production function where labor is the only variable input. The aggregated production function is assumed to be represented by $F_c(N_h^R) = \omega N_h^R$, where F_c and ω are the total output and production efficiency coefficient of this industry, respectively. The profit is $\pi_c = \omega N_h^R - w N_h^R$, where w is the wage rate. The profit maximization condition in a competitive market is

$$w = \omega. \tag{1}$$

The developer pays the landowner a land rent $R(x)$ to build a condominium. The developer decides the height of the condominium $h(x)$. The developer's profit is $\pi_d = r^R(x)h(x) - C(h(x)) - R(x)$, where $r^R(x)$ is the unit rent of the condominium, and $C(h(x))$ is the cost function of the condominium depending on $h(x)$. The profit maximization condition in a competitive market is

$$r^R(x) - C'(h(x)) = 0. \tag{2}$$

From the zero-profit condition,

$$R(x) = r^R(x)h(x) - C(h(x)). \tag{3}$$

2.3 Household behavior

All the people in the city are assumed to derive utility from the consumption of agricultural products $a^j(x)$, residential lot size $f^j(x)$, and composite goods $c^j(x)$. In a poor nut season, bears search the residential zone for food, and households feel afraid of encountering bears and being attacked by them, which decreases their utility.[4] On the other hand, the household's utility increases with the quality of ecosystem services. The quality measured in terms of utility is determined by the population of bears and trees according to the function $E(N_1, N_2)$. We assume that the partial derivative of the function with respect to the population is positive, but the marginal benefit of each component is diminishing. This utility, expressed as function E, explains the positive externality for humans, which includes the existence value of bears and trees as well as the service from the natural environments (e.g., purified water). The population of bears and the number of trees can be changed by policies.

For simplicity, residential lot size $f^j(x)$ does not depend on the location and is normalized as 1 (i.e., $f^j(x) = \overline{f}^j = 1$ for all j). Therefore, from the land supply condition in

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[4] Even if an adult never feels unsafe, their utility decreases as long as carnivores stay in the city because he/she feels a risk of their children or pets being attacked. In other words, such disutility includes psychological concerns about the encroachment of carnivores.

the residential zone, the human population density at each location is expressed as the height of condominiums $h(x)$.

The expected utility function of either the urban residents (*j* = *R*) or farmers (*j* = *A*) is

$$v^j(x) = U(a^j(x)) + c^j(x) - [p \cdot 0 + (1-p) \cdot g(m_h(x))] + E(N_1, N_2), \tag{4}$$

where $m_h(x)$ is the number of bears that urban residents may encounter, which implies the risk of being injured by bears, and $g_1(m_h(x))$ is the disutility derived from a fear of encountering bears in poor nut seasons. The marginal utility with respect to the agricultural goods is positive but the marginal utility is diminishing. Since households are homogeneous, the utility will be common across locations because households can migrate for free,

$$v^j(x) = V, \ \forall x \in [0, \ Z^A]. \tag{5}$$

2.3.1 Urban residents' behaviors

The household spends money on commuting, housing, and consumption of composite goods. The income constraint is given by

$$w + \Omega - \Psi = c^R(x) + p_a a^R(x) + r^R(x)\overline{f}^R + \tau^R(x), \tag{6}$$

where Ω is the per-resident revenue from land ownership, p_a is the price of agricultural goods, $r^R(x)$ is the unit rent of the condominium at location *x*, $\tau^R(x)$ is the commuting cost depending on the distance from the CBD, and Ψ is a per-resident tax to cover the cost of implementing some policies such as extermination and animal deterrent fences.[5]

Developers rent to a household that pays the highest rent for the condominium. $r^R(x)$ equals the maximum rent bid by a household, as a result of competition among households. Since households are homogeneous, their utility level is constant regardless of locations in equilibrium. Therefore, the equilibrium rent is equal to the rent, taking equilibrium utility level

[5] The Japanese government imposes a tax to cover the resources for forest maintenance.

V as given. Mathematically, such bid-rent behavior is formalized as follows:

$$r^R(x) = \max_{c^R(x),\, a^R(x)} w + \Omega - \Psi - \tau^R(x) - c^R(x) - p_a a^R(x)$$
$$\text{s.t. } V = U(a^R(x)) + c^R(x) - g(m_h(x)) + E(N_1, N_2)\,. \tag{7}$$

The first order condition with respect to $a^R(x)$ is $U'(a^R(x)) = p_a$. This indicates that $a^R(x)$ does not depend on the location. The bid-max land rent of the urban resident is given by

$$r^R(x) = r^R\left(\Omega - \Psi - V - E(N_1, N_2) + g(m_h(x)), p_a\right). \tag{8}$$

2.3.2 Farmer's behavior

The production function of a farmer is $F_a(L(x))$, where $L(x)$ is the area of farmland owned by a farmer. For simplicity, we assume that each farmer owns one unit area of farmland; $L(x) = \overline{L}$. Since we assume that the lot size of a farmer's housing is constant across agricultural areas (i.e., $f^A(x) = \overline{f}^A$), the population density of farmers $n^A(x)$ is constant regardless of the location; $n^A(x) = 1/(\overline{f}^A + \overline{L}) = \overline{n}^A$.

The farmer consumes part of the agricultural goods produced by him/herself, $a^A(x)$. The farmer earns income by shipping the remaining agricultural goods $\overline{F}_a - a^A(x)$ to the market in the CBD. The income constraint of the farmer is

$$(p_a - \tau^A(x))(\overline{F}_a - a^A(x)) + \Omega - \Psi = c^A(x) + r^A(x)(\overline{f}^A + \overline{L})\,, \tag{9}$$

where $\tau^A(x)$ is the transportation cost for shipping the agricultural goods to the CBD.

The equilibrium utility level of the farmer is V, which is the same as that of residents because people can freely choose their occupation, farmer or worker in the CBD. Bid-rent behavior is formalized as follows:

$$r^R(x) = \max_{c^R(x),\, a^R(x)} \frac{(p_a - \tau^A(x))(\overline{F}_a - a^A(x)) + \Omega - \Psi - c^A(x)}{\overline{f}^A + \overline{L}} \tag{10}$$

$$\text{s.t. } V = U(a^A(x)) + c^A(x) + E(N_1, N_2).$$

The first order condition with respect to $a^A(x)$ is $U'(a^A(x)) = p_a - \tau^A(x)$. Thus, the agricultural consumption of the farmer depends on the location. The bid-max land rent of the farmer is given by

$$r^A(x) = r^A\left(\Omega - \Psi - V - E(N_1, N_2), p_a\right). \tag{11}$$

2.4 Urban carnivore's model

We apply the Yoshida and Kono (2022) model to urban bears' behavior. The individual bear behaves so as to maximize its net offspring (e.g., Eichner and Pethig, 2006, 2009), which is essential for the continued existence of a species. To produce the offspring, a bear usually feeds on nuts produced by trees and consumes human-related food, such as garbage and home garden crops obtained in the residential area during a poor season. At the same time, it tries to avoid encountering humans as much as possible. We formalize this situation, using the following traditional Lotka-Volterra-type equation:

$$b = \alpha Q - \beta M - \gamma, \tag{12}$$

where b is a bear's net offspring, $Q \in \mathbb{R}_+$ is the bear's intake of food, $M \in \mathbb{R}_+$ is the number of encounters with humans which may result in the bear's death, $\alpha > 0$ is a bear's reproduction efficiency per unit of food, $\beta > 0$ is a bear's reproduction loss per encounter with humans due to extermination, and $\gamma > 0$ is an exogenous parameter representing the loss of a bear's offspring due to natural death.

There is a $1-p$ probability of a poor nut season, and only then do bears enter the residential area. The bear's expected net offspring b is as follows:

$$b = p\alpha\bar{Q}^{F_1} + (1-p)\left[\alpha(Q^F + Q^R) - \beta M\right] - \gamma, \tag{13}$$

where $\bar{Q}^{F_1}$ is the bear's constant intake of nuts in a good season, Q^F is the bear's intake of nuts in a poor season, Q^R is the bear's intake of human-related food acquired in the residential zone during a poor season.

Urban bears spend time foraging for nuts in the forest and human-related food in the residential area and consume them when they find them. The bear's expected intake of food at location x depends on the time density of the bear and the density of food. An individual bear's time density within zone j is denoted as $t^j(x)$, which indicates the total length of time that the bear spends at location x within zone j for eating in one year.

The amount of nuts the bear consumes during a poor nut season is expressed by integrating the expected intake of nuts at location x over the range of the forest. The expected intake of nuts at location x is obtained by multiplying the time density in the forest by the density of nuts $t^j(x)n_1(x)$, where $n_1(x)$ is the density of nuts at location x during a poor season. For simplicity, we do not focus on the time density in the forest. We assume $\overline{n}_1(x)=\overline{n}_1$, which indicates the time density in the forest is constant across the forest. The amount of nuts the bear consumes during a poor season is

$$Q^F = \overline{n}_1 \int_{Z^A}^{Z^F} t^F(x)dx. \tag{14}$$

The amount of human-related food the bear consumes in the residential zone is expressed by integrating the expected intake of food at location x over the bear's search range in the residential zone:

$$Q^R = \int_X^{Z^R} t^R(x)\rho(t^R(x))h(x)dx, \tag{15}$$

where $h(x)$ is human population density and $\rho(t^R(x))$ expresses the availability of human-related food.[6]

Similarly, M is expressed by integrating $t^R(x)$ multiplied by the density of humans at location x over the search range in the residential zone:

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[6] We assume that $\rho_i(\cdot) > 0$ in $t_i^j(x) \in [0,\ 1]$ to avoid a case in which individual i's intake of food is negative and that $\rho'_i(\cdot) < 0$, and $\rho''_i(\cdot) < 0$, implying the situation where the more food individual i eats, the more difficult it is to find new food at the same location. A carnivore eats garbage at one location. Then, if the carnivore eats all the available food waste in the garbage, it should move and find another source of garbage. In this way, function $\rho_i(\cdot)$ is exogenously given and is used for the situation where animals have food which is stationary.

$$M = \int_X^{Z^R} t^R(x)\delta(x)h(x)dx\,, \tag{16}$$

where $\delta(x)$ is a parameter that explains a human's chance of encountering bears.[7] The time constraint for the bear in a poor season is

$$\bar{T} = \int_X^{Z^R} t^R(x)dx + \int_{Z^A}^{Z^F} t^F(x)dx\,, \tag{17}$$

where $\bar{T}$ is the time available for feeding, excluding time spent sleeping, breeding, and so on.[8]

An individual bear maximizes the expected net offspring (13) by controlling Q^F, Q^R, M, $t^j(x)$, and X subject to (14)–(17), taking human population density as given. The Lagrangian function for the maximization problem and its first order conditions are found in Appendix A. The equilibrium condition with respect to $t^R(x)$ is

$$\alpha\rho(t^R(x))h(x) + \alpha t^R(x)\rho'(t^R(x))h(x) - \beta\delta(x)h(x) - \alpha\bar{n}_1 = 0\,. \tag{18}$$

Equation (18) indicates that the bear determines how much longer it will stay at each location in the residential areas, taking human population density as given. This equation intuitively reflects that when a bear stays longer at one location, it could obtain more food (the first term), but it could decrease marginal returns of food (the second term) and face more risk of encountering humans and being killed by them (the third term) and lose the chance to obtain food at the forest area (the fourth term).

2.5 Market clearing conditions and definition

The number of bears that a household may encounter at location $x \in [X, Z^R]$, $m_h(x)$, is equal

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[7] The value of the parameter increases with x (i.e., $\delta'(x) < 0$). It implies that the closer to the CBD they are, the more chance they have of meeting humans.

[8] We assume that the migration trajectory for wild animals is unobservable, so the total time $\bar{T}$ is the time used for eating food except for the migration between locations and the other activities such as sleep, reproductive activities, and parental care.

to a bear's time density multiplied by the number of bears,

$$m_h(x) = t^R(x)N_2 . \tag{19}$$

The total number of trees depends on the size of the forest:

$$N_1 = N_1(Z^A) . \tag{20}$$

The total number of nuts is determined by the number of trees N_1. The production function of nuts is $F^1(N_1)$ in a good season and $F^2(N_1)$ in a poor season. We assume that the sign of the first-order derivative of the production function with respect to N_1 is positive, and the second derivative is negative regardless of whether the season is good or poor.

The population of bears is determined by the Lotka-Volterra equation. Since b is an individual bear's expected net offspring, the dynamics of population change are described by multiplying the bear's expected net offspring by the population of bears:

$$\frac{dN_2}{dT} = N_2 b = N_2 \left\{ p\alpha \bar{Q}^{F_1} + (1-p)\left[\alpha(Q^F + Q^R) - \beta M \right] - \gamma \right\} - K , \tag{21}$$

where T is time and K indicates the number of bears the government kills under the extermination policy. Since the total amount of nuts available for foraging equals the total consumption of nuts for all bears, we can obtain $F^1(N_1) = N_2 Q^{F_1}$ and $F^2(N_1) = N_2 Q^F$. Using these relationships, we can rewrite (21) as

$$\frac{dN_2}{dT} = \alpha\left[pF^1(N_1) + (1-p)F^2(N_1) \right] + N_2\left\{ (1-p)\left[\alpha Q^R - \beta M \right] - \gamma \right\} - K . \tag{22}$$

The expected population of bears N_2 is derived from (22) with $dN_2/dT = 0$:

$$N_2 = \frac{\alpha\left[pF^1(N_1) + (1-p)F^2(N_1) \right] - K}{\gamma - (1-p)(\alpha Q^R - \beta M)} . \tag{23}$$

The total city population $\bar{N}_h$ equals the total population of all households,

$$\bar{N}_h = N_h^R + N_h^A . \tag{24}$$

The total population of urban residents and farmers equals the total number of households in the residential and agricultural zones:

$$N_h^R = \int_0^{Z^R} h(x)dx \text{, and} \tag{25}$$

$$N_h^A = \int_{Z^R}^{Z^A} \bar{n}^A dx = \bar{n}^A (Z^A - Z^R) . \tag{26}$$

The market clearing conditions with respect to the composite goods and agricultural goods are, respectively,

$$F_c(N_h^R) = \int_0^{Z^R} c^R(x)h(x)dx + \int_{Z^R}^{Z^A} c^A(x)\bar{n}^A dx \text{, and} \tag{27}$$

$$\int_{Z^R}^{Z^A} F_a(\bar{L})\bar{n}^A dx = \int_0^{Z^R} a^R(x)h(x)dx + \int_{Z^R}^{Z^A} a^A(x)\bar{n}^A dx . \tag{28}$$

At equilibrium, the residential boundary is determined where the land rent of the residential zone equals the land rent of the farmland:

$$R(Z^R) = r^A(Z^R) . \tag{29}$$

At equilibrium, the city boundary is determined where the land rent of the farmland equals the cost of farmland development, that is, the cost of land conversion from forest to farmland:

$$r^A(Z^A) = r^F . \tag{30}$$

Since land is equally owned by city residents, Ω should be equal to or less than per-capita land rent revenue.[9]

$$\bar{N}_h \Omega \le \int_0^{Z^R} [R(x) - r^F]dx + \int_{Z^R}^{Z^A} [r^A(x) - r^F]dx . \tag{31}$$

The system consists of 19 equations ((1)–(3), (14)–(20), and (23)–(31)) and has 14 unknown variables $\{w, p_a, V, \Omega, Q^F, Q^R, M, Z^R, Z^A, X, N_1, N_2, N_h^R, N_h^A\}$ and 4 unknown functions $\{t^F(x), t^R(x), h(x), R(x)\}$. By Walras's law, one of those equations is omitted.

[9] Inequality implies that residents can waive the land revenue. However, as long as per-capita land revenue has a positive utility, equality holds in (7). This inequality is useful to derive the sign of the Lagrange multiplier for this constraint, simply using the Kuhn-Tucker condition. The same treatment with the same objective is shown in Kono and Kawaguchi (2016), Kono and Joshi (2017), and Kono and Joshi (2019).

3. Five policies for human–wildlife conflicts

We use the model to calculate the efficiency of the following five policies: i) extermination; ii) animal deterrent fences under the equilibrium land use, iii) animal deterrent fences with land use regulation, iv) land use regulation that designates the boundaries between the residential zone, the agricultural zone, and the forest zone, and v) crop conversion with land use regulation. The government implements each policy to maximize social welfare. Social welfare W is composed of the total utility of households:

$$W = \bar{N}_h V . \tag{32}$$

The five policies are explained as follows. The i) extermination policy determines how many bears we should exterminate to maximize social welfare. The land use for residents, agricultural crops, and the forest is determined at market equilibrium. The cost of extermination is financed by the lump-sum tax for households, Ψ.

The ii) fencing policy places fences between the agricultural zone and the forest zone to prevent bears from entering cities. Real fences cannot prevent bears from entering the city completely, because some areas cannot be physically fenced (e.g., rivers and valleys). But the current paper assumes ideal fences with which no bears enter the city for simple discussion. The bear population under this policy can either increase or decrease for the following two reasons. First, this policy prevents bears from consuming human-related food during a poor nut season, which decreases the number of bears. However, if the size of forests increases at equilibrium, this makes bears consume more nuts during a good harvest, which increases the number of bears.

Policies iii)-v) involve land use regulation, which optimally designates the size of the residential and agricultural zones and the forest zone. As the forest size decreases, the number of bears decreases. This reduces not only damage by bears but also the quality of ecosystem services. Considering this trade-off, we should optimize the land use regulation. Policy iii) implements land use regulation only. Policy iv) adds land use regulation to Policy ii). By combining the land use regulation and the fencing policy, the government optimally adjusts the sizes of the forest, residential area, and agricultural area, and places a fence between the agricultural area and the forest.

The v) crop conversion policy, which is proposed in the current study, is to convert crops currently grown on farmland to some food preferred by bears during poor nut seasons. This policy directs bears to farmland and prevents them from entering residential areas. There are four requirements for converting crops. 1) Crops to be converted are highly nutritious to maintain the population of the animals. 2) The animals prefer the crop over food they can collect in residential areas. 3) The animals prefer the main food they usually collect in a good season more than the crops to be converted. Thus, the animals do not appear on the farmland during a good season for their main food. 4) The new crops should be suitable for the target land.

Taking bears as a case study, we can propose corn as a crop that satisfies the above requirements. Corn has fewer calories per unit than nuts, and are probably more nutritious than food bears can find and eat in residential areas. During poor nut seasons, it is difficult for bears to find nuts in the forest, and they expand their foraging areas. Eventually, they find and eat corn in the farmland, preventing bears from entering the residential area.

Under this policy, to maintain their population, we do not exterminate bears in the agricultural zone. So, the bear's expected net offspring function is

$$b = p\alpha\bar{Q}^{F_1} + (1-p)\alpha(Q^F + Q^A) - \gamma . \tag{33}$$

The amount of corn bears consume is expressed as

$$Q^A = \int_{X^A}^{Z^A} t^A(x)\rho(t^A(x))\bar{\eta}(x)dx , \tag{34}$$

where $t^A(x)$ is the time density in the agricultural zone, $\bar{\eta}(x)$ is the exogenous density of produced corn, $\rho(t^A(x))$ expresses the availability of corn, and $X^A \in [Z^R, Z^A]$ is the boundary of the farmland for corn. This policy determines the area for producing corn within the agricultural zone, i.e., $X^A \in [Z^R, Z^A]$. We also optimally determine the areas of residential, agricultural, and forest zones.

A bear maximizes the expected net offspring function (33) by controlling Q^F, Q^A, $t^A(x)$, and $t^F(x)$ subject to (14), (16), (34), and the time constraint ($\overline{T} = \int_{X^A}^{Z^A} t^A(x)dx + \int_{Z^A}^{Z^F} t^F(x)dx$). The first-order condition with respect to $t^A(x)$ is

$$\alpha\rho(t^A(x))\eta(x) + \alpha t^A(x)\rho'(t^A(x))\eta(x) - \alpha\overline{n}_1 = 0. \tag{35}$$

The interpretation of this equation is mostly the same as (18). The different point is that (35) does not have the third term in (18), because, under this policy, we do not exterminate bears.

Since farmers cannot earn income under the crop conversion policy, the government compensates farmers for the loss due to the conversion. The government finances the compensation by a lump-sum tax collected from people in the residential zone. In addition, households cannot consume agricultural goods under this policy. Thus, the government imports agricultural goods using the revenue earned from selling the rest of the corn to the other cities:

$$(\int_{X^A}^{Z^A} \overline{\eta}(x)dx - Q^A N_2)p_c = (a_c^R N_h^R + a_c^A N_h^A)p_a, \tag{36}$$

where p_c is the exogenous price of corn. The households residing in zone j consume a_c^j during poor nut seasons. The right-hand side of (36) is the revenue from the export of corn, and the left-hand side is the purchases of imported agricultural goods.

In summary, we formally define the above policies as follows:

Definition 1 (Five policy instruments for human–wildlife conflicts).

i) Extermination under an equilibrium land use:

$$\max_K W \quad \text{s.t. (1)–(3), (14)–(20), (24)–(31).}$$

ii) Animal deterrent fences under an equilibrium land use:

$$\max W \quad \text{s.t. (1)–(3), (14)–(20), (23)–(31), } t^R(x) = 0\text{, and } K = 0.$$

iii) Land use regulation:

$$\max_{Z^R, Z^A} W \quad \text{s.t. (1)–(3), (14)–(20), (23)–(31), } \Psi = 0\text{, and } K = 0.$$

iv) Animal deterrent fences with land use regulation:

$$\max_{Z^R, Z^A} W \quad \text{s.t. (1)–(3), (14)–(20), (23)–(31), } t^R(x) = 0\text{, and } K = 0.$$

v) Crop conversion with land use regulation:

$$\max_{Z^R, Z^A, X^A} W \quad \text{s.t. (1)–(3), (14)–(20), (23)–(31), (34)–(36), } t^R(x) = 0\text{, and } K = 0.$$

Many cities have already implemented policies i) and ii). Some cities are contemplating Policy iii). Policies iv) and v) are new policies that no city implements to the best of our knowledge.

4. Numerical simulations

This section calculates welfare improvements to clarify the most desirable policy among the five policies with some reasonable parameters. For sensitive analyses, we consider two cases in terms of parameters representing the value of bears and forests: i) when the value of the forest is high; ii) when the value of the forest is low (i.e., when the value of bears is relatively high).

In addition, we investigate what proportion of the first-best welfare each policy achieves. We define the first-best as the ideal situation where the government controls all endogenous variables, including even animal behavior (i.e., bear's time density: $t^R(x)$, $t^A(x)$), under the circumstance where bears can consume corn during poor nut seasons.[10] We formally define the first-best as follows.

[10] In the first-best optimum, the government controls the time density of bears ($t^R(x)$ and $t^A(x)$). So, we do not use the equilibrium conditions with respect to the time density: (18) and (35).

Definition 2 (First-best optimum).

$$\max_{Z^R, Z^A, X^A, t^R(x), t^A(x)} W$$

s.t. (1)–(3), (14)–(17), (19), (20), (24)–(31), (34), (36), $\Psi = 0$, and $K = 0$.

Needless to say, perfectly controlling bears' behavior is unrealistic. This first-best situation is calculated for our reference.

4.1 Parameter setting

We set parameters fitting for the human-bear conflicts occurring in Minami ward, Sapporo, Hokkaido, Japan. The city government has published a map of bear sightings and human injuries caused by bears.

The total length of a city with the forest zone is 20 km. The width is 1 km. The total number of households is $\bar{N}_h = 150$ (thousands of households).[11] We divide the residential and agricultural zones into 1 km and 0.5 km discrete areas, respectively. At market equilibrium, the urban boundary Z^R and the agricultural boundary Z^A are located at 15 km and 15.5km away from the CBD, respectively. We set that a poor harvest occurs twice every three years, which indicates the probability of a good season is $p = 1/3$.

We specify the quality of ecosystem services depending on the number of bears and trees as $E(N_1, N_2) = \theta_1 N_1 + \theta_2 \ln(N_2) + \theta_3$, where θ_1 , θ_2, and θ_3 indicate parameters representing how much people value the ecosystem service from the targeted species. We specify the utility function as $v^j(x) = c^j(x) + b \ln a^j(x) - pkm_h(x) + \theta_1 N_1 + \theta_2 \ln(N_2) + \theta_3$, where b and k are positive parameters. k represents the humans' fear of encroaching bears. θ_1, θ_2, θ_3, and k vary according to the human–ecosystem interaction and kinds of species. Here, these preference parameters are set as $\theta_1 = 0.001$, $\theta_2 = -14$, $\theta_3 = 250$, and $k = 4000$. For sensitivity analyses, we

[11] Any total number of households will work, as long as it is positive. For example, Eichner and Pethig (2006) used 100 as the total number of households.

set (θ_1, θ_3) = (0.0001, 250), (0.01, 250), and (0.001, 200).

As in Kono and Kawaguchi (2015), the income per household per year is set at US$40,000. The parameter in the utility function b is set at 1, which implies that 0.0025 percent of the income of US$40,000 is spent on the consumption of agricultural goods. We set the number of trips to the CBD as 225 round trips per year per person, the average speed as 30 km/hour, and travel cost including travel time as US$30/hour. Further, we set the cost of housing land development r_F as US$20,000. We set the area of farmland per household L as 0.28 km^2, which is calculated by dividing the total area of farmland by the number of farmers in Minami ward. We set the lot housing size $\overline{f}$ as 100 m^2. We set the price of agricultural goods as US$10/kg.

Next, we set the ecosystem parameters in the Lotka-Volterra equation (13): α, β, and γ. We specify some functions in the ecosystem models such as the bear's availability of food in the residential area and the production function of nuts: $\delta(x)$, $\rho(t^R(x))$, $F^1(N_1)$, and $F^2(N_1)$. In a zoo, a bear consumes 376.5 kcal and produces 1–3 cubs depending on its calorie intake. We assume that a bear consumes 70 % of 376.5kcal intake to have two cubs in nature. So, we set $\alpha = 2 / (376.5 \times 0.7)$. Next, we set the parameters for the human's chance to encounter and exterminate bears (β and $\delta(x)$) so that humans kill about ten bears in the residential area at the equilibrium: $\beta = 1$, $\delta(x = 9) = 5.2923$, $\delta(x = 10) = 5.2918$, $\delta(x = 11) = 5.29178$, $\delta(x = 12) = 5.29175$, $\delta(x = 13) = 5.29173$, $\delta(x = 14) = 5.2917$, $\delta(x = 15) = 5.2916$, $\delta(x = 16) = 5.29156$, and $\delta(x = 17) = 5.29153$. Other parameters are set so that the number of urban bears is assumed to be 15. We set the availability of nuts as $\rho(t^R(x)) = -\exp(0.5t^R(x)) + 698.4$ and the number of natural deaths as $\gamma = 2.4$, and the production function of nuts is specified as $F^1(N_1) = 100N_1^{0.5}$ for a good season and $F^1(N_1) = 0.01N_1^{0.5}$ for a poor season.

4.2 Welfare improvements

Table 2 shows the results of simulations. We obtain social welfare, the residential boundary, the agricultural zone boundary, the number of bears, two externalities (human injuries and the quality of the ecosystem), and the difference in social welfare from laissez-faire equilibrium.

[Table 2 here]

We first focus on the situation where (θ_1, θ_3) = (0.001, 250). Of the six policies, social welfare is the largest in v) crop conversion. In v), the social welfare is larger than the equilibrium by US$1,476 per household. This policy achieves 99 % of the first-best welfare gain. On the other hand, social welfare is the smallest in i) extermination because the value of bears is high, and the decrease in human injuries is small. Even though we exterminate bears, the area of bears' activity does not change. That is why the human-bear conflict will not disappear. On the other hand, crop conversion can deter bears from entering residential areas without reducing the bear population.

Social welfare is the second largest in iv) the fence with land use regulation regardless of parameters, which is US$1,322 per household larger than the equilibrium. There are two reasons. First, human-bear conflicts disappear with the fence. Second, the land use regulation increases the area of forests, and thus the bear population rises even though bears cannot consume human-related food in the residential area.

The fence without land use regulation can improve social welfare by US$1,258.5 per household, which is 85% of the first-best welfare gain because the decrease in the bear population is small. Under this policy, bears cannot consume nuts in the forest during a poor season. In addition, they cannot enter the residential areas and face no risk of being killed by humans.

We have two notes about the fencing policy. First, when urban bears depend on the food found in the residential area to survive, the bear population may decrease considerably in the fencing policy without land use regulations. We may obtain smaller welfare gains. Second, under ($\theta 1$, $\theta 3$) = (0.001, 200), the land use pattern in the fencing policy with land use regulation is the same as the equilibrium land use pattern. From this point, the animal deterrent fence is an effective policy to solve the conflict regardless of land use regulations. However, as Kido et al. (2011) show, we should note that bears enter the urban areas through riverbanks and roads where we cannot install a fence, indicating that we cannot prevent bears from entering cities completely. Therefore, we need some policy instruments that keep animals away from cities.

In iii) land use regulation, social welfare is US$88 per household larger than the equilibrium, and we can obtain 6% of the first-best welfare gain. The size of the city is 3 km smaller than the equilibrium because the values of bears and trees are high, and thus we should have a larger area of forests to increase the number of bears and trees. However, we cannot reduce the human-bear conflicts so much by land use regulation only. We should combine it with the fencing policy, crop conversion policy, or place-based extermination in the residential areas to reduce the bear's time density. Yoshida and Kono (2020) demonstrate land use regulation with place-based extermination. To do this optimally, we have to increase the area of forests to avoid too much of a reduction in the carnivore population.

Next, we focus on sensitivity analyses to understand the relationship between the value of ecosystems and optimal policies. Under (θ_1, θ_3) = (0.01, 250) and (0.0001, 250), the optimal location of the agricultural zone boundary Z^A in iii) land use regulation is smaller than the equilibrium (i.e., we should shrink the city size). Under (θ_1, θ_3) = (0.01, 250), the optimal location of the agricultural zone boundary Z^A in iii) land use regulation is 11.5 km. Under (θ_1, θ_3) = (0.01, 250), it is 12.5 km. Under (θ_1, θ_3) = (0.0001, 250), it is 13.5 km. This result is intuitive because the forest area should be larger as the value of trees becomes higher.

Finally, we focus on the situation where the value of bears is lower, i.e., (θ_1, θ_3) = (0.001, 200). The optimal location of the agricultural zone boundary Z^A in iii) land use regulation is 16.5 km, which is 1 km larger than the equilibrium. This result implies that we should have a smaller forest to reduce the bear population. In policies iv) and v), the optimal land use pattern is the same as the equilibrium. This result indicates that we should reduce the remaining externalities in other ways, such as crop conversion and animal deterrent fences.

4.2 Effect of each policy on the human–bear conflict

This section shows the numerical values of human population density $h(x)$ and bear density $t^R(x)\times N_2$ to understand the effect of each policy on the human–bear conflict in the residential areas. The number of human-bear conflicts increases as the amount of time when humans and bears stay in the same place increases. Thus, this study defines the potential level of the human-bear conflict as $h(x)\times t^R(x)\times N_2$. Figure 3 plots this variable at each location under the five policies with $(\theta_1, \theta_3) = (0.001, 250)$. Solid lines, dashed lines, and dotted lines, respectively, indicate the human population density, the bear density, and the potential level of the conflicts.

In equilibrium, the human population density (i.e., solid lines) decreases with the distance from the CBD. The slope depends only on the commuting cost in the area without bears. It drastically drops with bears. The bear density (i.e., dashed lines) increases with the distance from the CBD because the risk of encountering humans decreases. The potential level of conflict is largest at x = 10, and it decreases with the distance from the CBD. The total time spent in the residential area (i.e., the integral of $t^R(x)\times N_2$ within the residential area) is almost the same as the time spent in the forest.

Next, we focus on the effect of each policy on the human–bear conflict. As described in the introduction, we consider the situation where, since the animal has high ecological value, we would like to reduce human injuries and preserve bears as much as possible. Therefore, the optimal number of exterminations is nearly zero, and there is no effect on the bear density.

Under iii) land use regulation, because of the smaller size of the residential zone, the human population density increases in the residential zone without bears. The total number of conflicts (i.e., the integral of $h(x)\times t^R(x)\times N_2$ within the residential area) is smaller than the equilibrium because the size of the forest increases, and bears stay longer in the forest.

When we place fences between the agricultural zone and the forest under policies ii) and iv), the bear density becomes higher in the forest than in equilibrium because bears cannot enter the city. Under iv) the fence with land use regulation, the area of the forest increases.

Finally, under v) crop conversion, the density of bears is small in the agricultural zone because the calorific value of corn is sufficiently high, and bears do not have to stay longer to forage corn. Because the bears are provided with corn, the number of bears is higher than that under iv) the fencing with land use regulation. In the first-best, three variables are almost the same as that under v) crop conversion (thus, we do not show the graph in the current paper). The difference is that, with only a tiny faction of the bears' time being spent in the residential areas, the bear population is able to grow more.

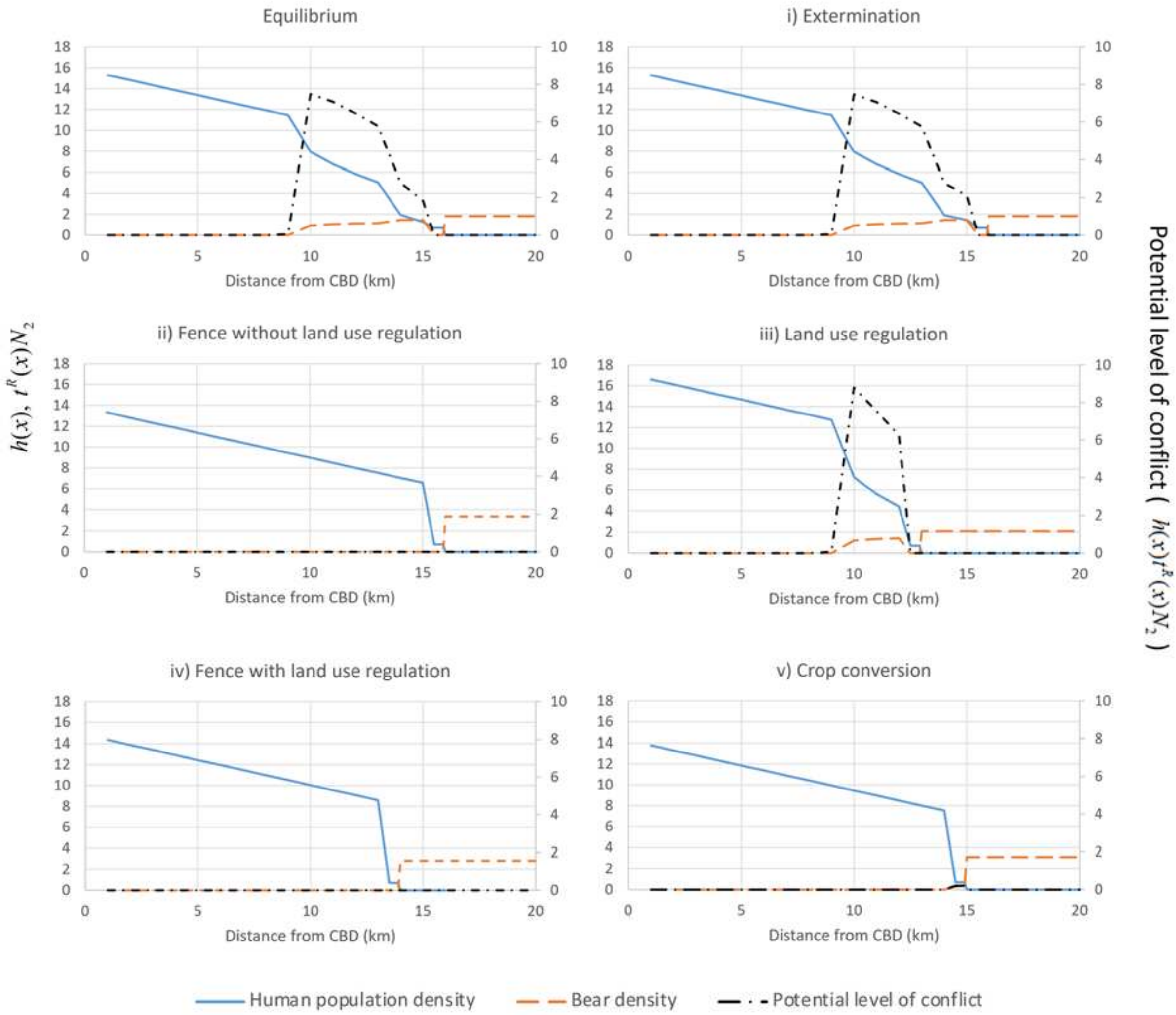

Figure 3. Effect of each policy on the potential level of human-bear conflict

Note: The vertical axis on the left is the human population density and bear density, and the vertical axis on the right is the potential level of conflict. The horizontal axis is the distance from the CBD.

5. Conclusions

Human-wildlife conflict has increased, causing damage to crops, human injuries, and outbreaks of zoonotic diseases. Extending the urban-ecosystem model of Yoshida and Kono (2020, 2022), the current paper quantitatively evaluates the efficient levels of multiple countermeasures against urban carnivores. Our numerical simulations have shown two crucial policy implications. First, crop conversion with land use regulation is the most efficient policy. This policy uses crops preferred by animals to direct them to an area outside the residential area. That is why the level of interaction between people and wildlife is low, which maintains the wildlife population even during poor food seasons in forests.

Land use regulations alone are not efficient because the incentive for wildlife to leave residential areas is weak. Therefore, we need to combine it with another policy that discourages wildlife from entering residential areas. Land use regulation with animal deterrent fences is the second most efficient method, regardless of the parameters. It reduces the population of wild animals because animals cannot enter residential areas during poor food seasons in the forest. Land use regulation increases the forest area to offset the reduction, which allows wildlife to take more food during good food seasons in the forest. That is why we can secure wildlife populations and reduce conflicts. However, since fences cannot be placed on rivers or roads in reality and cannot entirely prevent wildlife from entering the city, the welfare effect of animal deterrent fencing is less than what we have shown. So, crop conversion would be one effective option.

Climate change exacerbates resource scarcity, forcing people and wildlife to share increasingly crowded spaces (Abrahms, 2021). Human–wildlife conflict will increase in cities with climate change. A future task is to design effective policies against human–wildlife conflicts in a world with changing climates.

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Table 1. Numerical results

Policy		Laissez-faire	i) Extermination policy	ii) Fence only	iii) Land use regulation	iv) Fence with land use regulation	v) Crop conversion
$(\theta_1, \theta_3) = (0.001, 250)$							-
Social welfare (rank)	Yen/household	32142	32151 (5th)	33401 (3rd)	32231 (4th)	33464 (2nd)	33618 (1st)
Welfare gain	%	-	0.6	85.2	6.0	89.6	99.8
Residential boundary	Km	15	15	15	12	13	14
Agricultural zone boundary	Km	15.5	15.5	15.5	12.5	13.5	14.5
Boundary of crop conversion areas	Km	-	-	-	-	-	14
Bear population	herd	15.34	15.33	15.33	19.8	18.43	17.39
Human injury	Yen	34977	17391	0	21256	0	367
Quality of ecosystem services	Yen	3284	2383	3284	4182	3908	3696
$(\theta_1, \theta_3) = (0.01, 250)$							
Social welfare (rank)	Yen/household	32461	32470 (5th)	33720 (3rd)	32763 (4th)	33925 (2nd)	34017 (1st)
Welfare gain	%	-	0.54	80.9	19.4	94.1	99.8
Residential boundary	Km	15	15	15	11	13	13
Agricultural zone boundary	Km	15.5	15.5	15.5	11.5	13.5	13.5
Boundary of crop conversion areas	Km	-	-	-	-	-	13
Bear population	herd	15.34	15.33	15.33	21.1	18.4	18.9
Human injury	Yen	34977	34689	0	14902	0	434
Quality of ecosystem services	Yen	3603	3602	3603	5040	4368	4461

Table 1. Numerical results (continued)

Policy		Laissez-faire	i) Extermination policy	ii) Fence only	iii) Land use regulation	iv) Fence with land use regulation	v) Crop conversion
$(\theta_1, \theta_3) = (0.0001, 250)$							-
Social welfare (rank)	Yen/household	32111	32119 (5th)	33369 (3rd)	32231 (4th)	33418 (2nd)	33579 (1st)
Welfare gain	%	-	0.6	85.6	8.2	89	99.8
Residential boundary	Km	15	15	15	13	13	14
Agricultural zone boundary	Km	15.5	15.5	15.5	13.5	13.5	14.5
Boundary of crop conversion areas	Km	-	-	-	-	-	14
Bear population	Herd	15.34	15.33	15.34	18.44	18.43	17.39
Human injury	Yen	34977	34689	0	26020	0	367
Quality of ecosystem services	Yen	3252	3251	3252	3862	3720	3657
$(\theta_1, \theta_3) = (0.001, 200)$							
Social welfare (rank)	Yen/household	31375	31384 (5th)	32543 (2nd)	31443 (4th)	32543 (2nd)	32792 (1st)
Welfare gain	%	-	0.6	82.4	4.7	82.4	99.8
Residential boundary	Km	15	15	15	16	15	15
Agricultural zone boundary	Km	15.5	15.5	15.5	16.5	15.5	15.5
Boundary of crop conversion areas	Km	-	-	-	-	-	15
Bear population	herd	15.34	15.33	15.33	13.53	15.33	15.73
Human injury	Yen	34977	34689	0	34305	0	300
Quality of ecosystem services	Yen	2517	2516	2575	2240	2575	2575

Appendix A. First order conditions for the animal behavior

First, we set the Lagrangian function expressing the animal's behavior in the laissez-faire equilibrium:

$$\begin{aligned} L &= p\alpha\overline{Q}^{F_1} + (1-p)\left[\alpha(Q^F + Q^R) - \beta M\right] - \gamma \\ &-\phi^F[Q^F - \overline{n}_1\int_{Z^A}^{Z^F} t^F(x)dx] - \phi^R[Q^R - \int_X^{Z^R} t^R(x)\rho(t^R(x))h(x)dx] \\ &-\varphi[M - \int_X^{Z^R} t^R(x)\delta(x)h(x)dx] + \lambda[\overline{T} - \int_X^{Z^R} t^R(x)dx - \int_{Z^A}^{Z^F} t^F(x)dx]. \end{aligned} \tag{A.1}$$

Differentiating (A.1) with respective variables, we obtain (A.2)–(A.7):

$$\frac{\partial L}{\partial Q^F} = 0 : (1-p)\alpha - \phi^F = 0, \tag{A.2}$$

$$\frac{\partial L}{\partial Q^R} = 0 : (1-p)\alpha - \phi^R = 0, \tag{A.3}$$

$$\frac{\partial L}{\partial M} = 0 : -(1-p)\beta - \varphi = 0 \quad , \tag{A.4}$$

$$\frac{\partial L}{\partial t^R(x)} = 0 : \phi^R h(x)[\rho(t^R(x)) + t^R(x)\rho'(t^R(x))] + \varphi\delta(x)h(x) - \lambda = 0 \quad , \tag{A.5}$$

$$\frac{\partial L}{\partial t^F(x)} = 0 : \phi^F \overline{n}_1 - \lambda = 0, \tag{A.6}$$

$$\frac{\partial L}{\partial X} = -\phi^F t^R(X)\rho(X)h(X) - \varphi t^R(X)\delta(X)h(X) + \lambda t^R(X) = 0, \tag{A.7}$$

where we use the boundary condition $t^R(X) = 0$. The first order conditions with respect to shadow prices are suppressed because they are obvious.

From the above conditions, we can obtain the equilibrium conditions with respect to $t^R(x)$ at any $x \in [X, Z^R]$ and to $t^F(x)$ at any $x \in [Z^A, Z^F]$, taking $h(x)$ as given:

$$(1-p)\alpha\rho(t^R(x))h(x) + (1-p)\alpha t^R(x)\rho'(t^R(x))h(x) - (1-p)\beta\delta(x)h(x) - \lambda = 0 \quad , \tag{A.8}$$

$$(1-p)\alpha\overline{n}_1 - \lambda = 0 \quad . \tag{A.9}$$

Substituting (A.9) into (A.8) yields

$$\alpha\rho(t^R(x))h(x) + \alpha t^R(x)\rho'(t^R(x))h(x) - \beta\delta(x)h(x) - \alpha\overline{n}_1 = 0. \tag{A.10}$$

Next, we obtain the first order condition with respect to $t^A(x)$ under the crop conversion policy. As above, we set the Lagrangian function expressing the animal's behavior

$$L = p\alpha\overline{Q}^{F_1} + (1-p)\left[\alpha(Q^F + Q^A)\right] - \gamma$$
$$-\phi^F[Q^F - \overline{n}_1\int_{Z^A}^{Z^F} t^F(x)dx] - \phi^A[Q^A - \int_{X^A}^{Z^A} t^A(x)\rho(t^A(x))\overline{\eta}(x)dx] \tag{A.11}$$
$$+\lambda[\overline{T} - \int_{X^A}^{Z^A} t^A(x)dx - \int_{Z^A}^{Z^F} t^F(x)dx].$$

Differentiating (A.11) with respective variables, we obtain (A.12)–(A.16):

$$\frac{\partial L}{\partial Q^F} = 0 : (1-p)\alpha - \phi^F = 0\,, \tag{A.12}$$

$$\frac{\partial L}{\partial Q^A} = 0 : (1-p)\alpha - \phi^A = 0\,, \tag{A.13}$$

$$\frac{\partial L}{\partial t^A(x)} = 0 : \phi^A\overline{\eta}(x)[\rho(t^A(x)) + t^A(x)\rho'(t^A(x))] - \lambda = 0 \quad , \tag{A.15}$$

$$\frac{\partial L}{\partial t^F(x)} = 0 : \phi^F\overline{n}_1 - \lambda = 0\,. \tag{A.16}$$

The first order conditions with respect to shadow prices are suppressed because they are obvious.

From the above conditions, we can obtain the equilibrium conditions with respect to $t^R(x)$ at any $x \in [X, Z^R]$ and to $t^F(x)$ at any $x \in [Z^A, Z^F]$, taking $h(x)$ as given:

$$(1-p)\alpha\rho(t^A(x))\eta(x) + (1-p)\alpha t^A(x)\rho'(t^A(x))\eta(x) - \lambda = 0\,, \tag{A.17}$$

$$(1-p)\alpha\overline{n}_1 - \lambda = 0\,. \tag{A.18}$$

Substituting (A.18) into (A.17) yields

$$\alpha\rho(t^A(x))\eta(x) + \alpha t^A(x)\rho'(t^A(x))\eta(x) - \alpha\overline{n}_1 = 0\,. \tag{A.19}$$