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Synthesis

Developing a system model for articulating the social-ecological impacts of species reintroduction

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ABSTRACT. Reintroducing locally extinct/extirpated species has been considered as an approach for restoring ecosystems. Although such projects share the same goals of rebuilding previously affected ecosystems, the overall impacts that such reintroductions generate on both ecosystems and human society, i.e., on the social-ecological system, are difficult to measure. We propose a system dynamics approach, a platform on which both natural and social scientists could collaborate to identify the social-ecological impacts of species reintroduction as well as factors that affect such decision making. We use cases in Japan to demonstrate the potential applicability of system dynamics in terms of (1) understanding the impacts of a previously reintroduced species, the Oriental Stork (*Ciconia boyciana*), and (2) predicting the impacts of reintroduction of wolves (*Canis lupus*). We present a causal loop diagram of the social and ecological effects of Oriental Stork reintroduction, and we discuss how the relationships between factors could be articulated based on empirical data and ongoing projects in Japan. The model demonstrates how local residents began to appreciate the rich biodiversity, including the Oriental Stork, following its reintroduction, and how public support toward such reintroduction enhanced further projects to reintroduce these species in different parts of Japan. A similar diagram, created to illustrate the social and ecological effects of the potential reintroduction of wolves to Japan, demonstrates how social factors such as environmental education and public attitudes could affect decision making as well as ecological factors such as predator-prey dynamics and overall biodiversity. Further, human-wolf conflicts could negatively affect the overall loop. Creating causal loop diagrams can help managers and stakeholders understand that species reintroduction projects need to be considered via an interdisciplinary approach. The models illustrate that these problems are dynamic and that the factors affecting or affected by such projects change over time, implying the importance of both the spatial and temporal scales in managing reintroduction projects.

Key Words: *causal loop diagram; environmental education; Oriental Stork; social-ecological system; wolf*

INTRODUCTION

Reintroducing locally extinct/extirpated species is considered as one approach for restoring ecosystems, and various projects have been carried out globally, e.g., wolf (*Canis lupus*) reintroduction in the United States (Smith et al. 2003) and beaver (*Castor fiber*) reintroduction in northern England (Campbell-Palmer et al. 2016). Although diverse goals and approaches for ecosystem restoration have been considered, from minor modification to facilitating faster changes via taxon substitution and the acceptance of novel ecosystems (Corlett 2016), there seems to be agreement among researchers and practitioners that reintroducing once-extirpated species can be a valuable way to conserve and restore biodiversity (Jachowski et al. 2016). Although these reintroduction projects share the same goals of rebuilding previously affected ecosystems, the overall impacts that such reintroductions have on both the ecosystem and the human society, i.e., the social-ecological system, are difficult to measure. The social-ecological system framework incorporates subsystems such as resource and governance systems that go beyond disciplinary boundaries such as ecological science and social science (Ostrom 2009). The increasing knowledge regarding reintroduction science indicates that a similar multi-disciplinary approach is required. Ecological research has been conducted to understand how reintroduced species affect the behavior and population of other species, as well as the overall ecosystem. In Yellowstone National Park (hereafter, YNP), after the reintroduction of wolves from Canada in 1995, the behavior of the prey species (elk, *Cervus canadensis*) changed, which in turn caused the underbrush to revive and restored populations of other species such as beaver (Beschta and Ripple 2016). Furthermore, social science research has been conducted, for example, to understand local residents' and visitors' willingness to support the wolf reintroduction in and around YNP (Bath 1989).

However, such reintroduction projects impact both ecological and social systems simultaneously, particularly if the reintroduced species are keystone species that have considerable impacts on the environment. To understand the overall effects of reintroductions, researchers should explore the social-ecological system framework, a model that highlights how people and nature are dynamically interconnected and co-evolving (Hanspach et al. 2014). Species reintroductions demonstrate clearly how ecological and social factors are connected in the real world. For example, social factors can have ecological effects, such as when public opinion (e.g., support for wolf reintroduction—a social factor) affects the decision making of the agency regarding species reintroduction, thus affecting the whole ecosystem (e.g., via the dynamic relationship between the reintroduced predator and its prey species—an ecological factor). Alternatively, ecological factors can have social effects, such as when a rapid increase in a species (such as deer) that causes conflicts with people (an ecological factor) reduces local residents' willingness (a social factor) to accept that species. Therefore, in order to reveal and predict the overall impacts of reintroduction projects, future research needs to identify and investigate the key factors involved, and their relationship with the social-ecological system. Although knowledge from different disciplines is indispensable to identify

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the relationships between ecological and social factors, there has been limited effort to tackle this issue via collaboration between natural and social scientists in the field of reintroduction science (George and Sandhaus 2016).

System dynamics, which aims to identify the dynamic behavior of complex systems, provides a potential platform in which natural and social scientists (and potentially researchers from other academic fields) could collaborate to identify the links between ecological and social factors. The first step in the system dynamics approach is to visualize a system's structure by constructing causal loop diagrams (CLD) showing the feedback effects in a system (Brennan et al. 2019). Reintroduction of species generates complex and diverse effects in the social-ecological system, and requires system-level thinking, which encourages consideration of the interrelationships and dynamics of the whole system. For this reason, we believe that applying the system dynamics approach is well-suited to our case studies. Although the system dynamics and social-ecological system approaches are similar in considering all of the factors of one system, the former has advantages in terms of being able to qualitatively and quantitatively identify relationships between the factors. On the other hand, in a system dynamics model, the researcher must choose which factors to include or exclude.

Here, we present cases from Japan to demonstrate the potential applicability of system dynamics. First, we examine the impacts of a previously reintroduced species, the Oriental Stork (*Ciconia boyciana*). Second, we predict the impacts of a potential reintroduction of wolves in Japan. We developed causal loop diagrams based on previous studies as well as discussion among six authors of this paper on factors to include in models and directions of influences of each factor. In the field of ecosystem restoration, various terms, including "restoration," "conservation translocation," and "rewilding" have been used (Corlett 2016). In this paper, we use "reintroduction" to mean the release of a species back into its natural range from which it had previously been extirpated by humans (Jachowski et al. 2016). In this study, "reintroduction" has similar meaning to "trophic rewilding," as the species we discuss here (the Oriental Stork and wolf) are the top predators in each ecosystem.

LOOP DIAGRAM BASED ON A PRIOR REINTRODUCTION

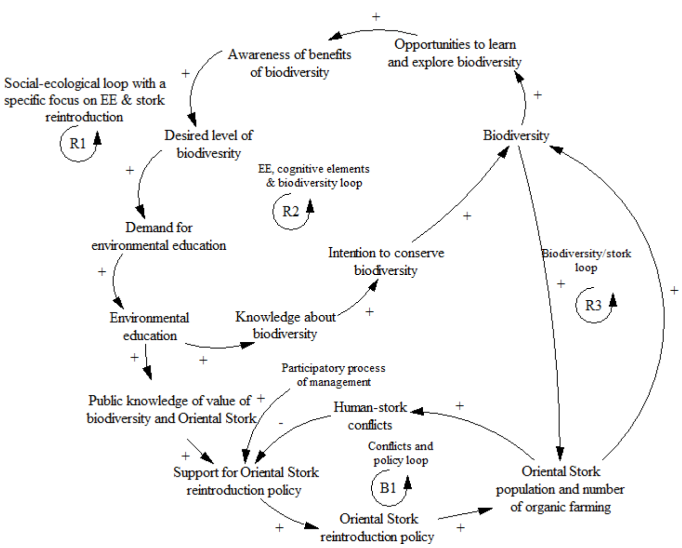
The Oriental Stork is one of the species that went extinct in Japan during the rapid economic growth period (1960s—1980s). For multiple reasons such as hunting, habitat loss (including deforestation), and the decline of its prey in paddy fields (because of the introduction of modern rice-farming methods such as the use of pesticides), the stork population had gradually declined since the 1900s, and the last stork was captured in Toyooka City in Hyogo Prefecture (West Japan) in 1971 (Naito et al. 2011, Yamada et al. 2019). Meanwhile, efforts to increase the number of Oriental Storks in captivity continued, and six storks were translocated from the former Soviet Union for captive breeding in 1990. In 2000, the number of Oriental Storks in captivity had increased to more than 100. Consequently, five storks were reintroduced into the wild area of Toyooka City in 2005; with the subsequent release of additional storks, there are currently more than 300 wild storks in and around Toyooka, as well as in other regions of the country (Hyogo Park of the Oriental White Stork 2024). Oriental Storks can cause conflicts with people as this species frequently walks in paddy fields to feed on aquatic organisms, and their stamping on the rice angers the farmers because the rice is then unsaleable (Kikuchi 2006). Oriental Stork also sometimes nest on utility poles on private property, causing conflict with local residents (Kobe Shimbun 2021). However, although human-stork conflicts occur, they seem to be tolerated by most people, as local residents generally support stork reintroduction (Honda 2008, Takahashi and Honda 2016).

Here, we present a loop diagram for the Oriental Stork reintroduction in Toyooka (Fig. 1). A study conducted before the reintroduction revealed that local residents were already positive about the project, and supported it because they acknowledged that the presence of storks is indicative of a rich habitat and environment (Honda 2008). Another study reported that attitudes toward stork reintroduction differed with the respondent's age, with the younger generation being less supportive (Honda 2008). However, the support of the younger generation toward stork reintroduction increased as a result of learning about the project through the school curriculum and media (Honda 2019, Sakurai et al. 2022). The success of the Oriental Stork reintroduction in Toyooka, and the fact that local residents supported the project, encouraged the local government in other regions to implement similar reintroduction projects, and they were reintroduced in 2015 into Chiba prefecture (eastern Japan) and Fukui prefecture (central Japan; Ezaki and Ohsako 2019). Figure 1 illustrates how environmental education (EE) enhanced the positive attitude of the public toward Oriental Stork reintroduction (R1: Social-ecological loop with a specific focus on EE and stork reintroduction).

Oriental Storks are carnivorous birds; based on their gape size, they can feed on many creatures from small fish to snakes and rodents, and are considered one of the top predators in paddy fields and the surrounding environment. Following their reintroduction, local residents began to appreciate the rich biodiversity (Kikuchi 2017; supporting R2 in Fig. 1: EE, cognitive elements and biodiversity loop). Not only did they recognize the significance of living in a landscape with diverse wildlife, but they took pride in having the Oriental Storks in the region and seeing Oriental Storks in flight and walking in the paddy fields (Evaluation Committee of Oriental White Stork Reintroduction Project 2014, Kikuchi 2017).

In Toyooka, after the reintroduction of Oriental Stork, a city-wide school curriculum, "Furusato Kyoiku" (meaning "education about local areas" in Japanese), was developed in 2017; in this curriculum, all elementary and junior high school students in the city study Oriental Storks (Honda 2019). This program enriched students' understanding about biodiversity and the significance of wildlife reintroduction, and potentially enhanced their willingness to conserve biodiversity and Oriental Storks (Honda 2019). This supports the EE, cognitive elements and biodiversity loop (R2) of Figure 1. The number of Oriental Storks has been increasing (because of both reproduction of storks in the wild and additional reintroduction) since their first reintroduction in 2005 (Ezaki and Ohsako 2019), and Oriental Storks have shown a preference for paddy fields where organic farming has been implemented, and thus for greater biodiversity (Nishimura and Ezaki 2019). This has encouraged farmers who want to conserve

Fig. 1. Causal loop diagram showing relationships between social and ecological factors in terms of environmental education (EE) and Oriental Stork (*Ciconia boyciana*) reintroduction in Toyooka City (R1). This relationship reflects a reinforcing loop involving multiple positive relationships. In a reinforcing loop, which lacks negative relationships (or has an even number of them), changes in one direction are intensified by further changes in that direction. In contrast, the relationship between conflicts and policy reflects a balancing loop; in such loops, which have an odd number of negative relationships, a change in one direction is counterbalanced by one in the opposite direction. This is a simplified model; in reality, the relationships between factors are not necessarily linear and are affected by other factors. Human–stork conflicts can include agricultural damage (e.g., stamping in paddy fields) and property damage (e.g., nesting on poles). The stakeholders can include local residents, farmers, animal-rights associations, agencies, and researchers.



nature (including storks) to engage in organic farming, thereby enriching the biodiversity of the agricultural landscape in the region (Kikuchi 2017). These results support the biodiversity/stork loop reflected in R3 in Figure 1.

Further, the recognition by government ministries (such as the Ministry of the Environment, Ministry of Land, Infrastructure, Transport and Tourism, and Toyooka City) of public support for Oriental Stork reintroduction has enhanced the movement to reintroduce storks in different parts of the country (Evaluation Committee of Oriental White Stork Reintroduction Project 2014). Restoration of stork populations is currently taught in junior high and high school science courses across the country, and the success of reintroduction is repeatedly reported in the media (Sakurai et al. 2022). This increase in environmental education, as well as media reports on stork reintroduction, have increased awareness and potentially support for reintroduction in different regions (Kikuchi 2017, Sakurai et al. 2022). This relationship among social-ecological factors (R1, the social-ecological loop, with a specific focus on EE and stork reintroduction) is supported by the existing data and literature. Interviews with government officials from Toyooka City and from the Ministry of the Environment provide evidence that public support enhances decision making regarding Oriental Stork reintroduction.

LOOP DIAGRAM BASED ON THE POTENTIAL REINTRODUCTION OF WOLVES

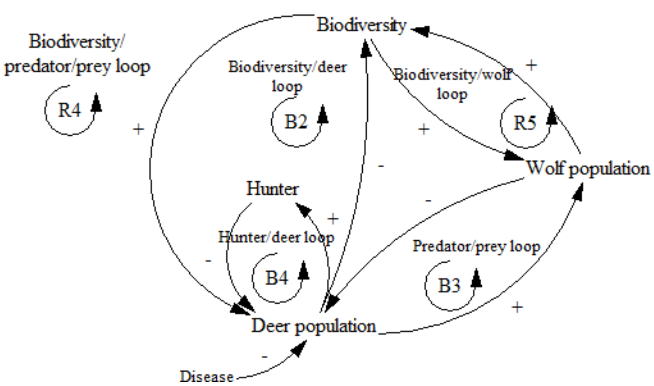
The Oriental Stork reintroduction loop model, which reveals the relationships among ecological and social factors, may be useful in predicting the impacts of a potential species reintroduction, that of wolves into Japan. The role of wolves as a top predator first requires clarification. Not only are predator populations associated with prey populations, they also affect the entire ecosystem (Ripple et al. 2014), including ecosystem nutrient cycling (Schmitz et al. 2010) and herbivore biomass (Letnic and Ripple 2017), via direct and indirect effects. Loss of top predators causes the prey population to increase, which potentially changes the entire ecosystem (Schmitz et al. 2010, Estes et al. 2011). In YNP, since the extirpation of wolves in the 1920s, woody species have declined, primarily owing to heavy browsing pressure by the elk; this in turn destroyed riparian forest, causing the population of beavers (*Castor canadensis*) to decline (Ripple and Beschta 2003). In contrast, following the reintroduction of wolves in the park in 1995, riparian vegetation has been restored, as the elk population has declined and their behavior has changed; this demonstrates the potential effects of a top carnivore in a terrestrial food chain (Beschta and Ripple 2016). Wolf reintroduction has also affected bison (*Bison bison*), coyote (*Canis latrans*), beavers, and songbird assemblages, emphasizing the significance of reintroducing top predators in terms of restoring and increasing biodiversity (Ripple et al. 2014, Beschta and Ripple 2016).

The Japanese wolf (*C. l. hodophilax*), the endemic wolf subspecies on the Honshu, Shikoku, and Kyushu islands, disappeared by 1905. It is now classified as an "extinct species" in Japan. The populations of species hunted by wolves, such as sika deer (*Cervus nippon*) and boar (*Sus scrofa*), have been rapidly increasing in the country, partially because the ecosystem lacks predators that could suppress their populations. Other reasons for the increase in ungulate populations include changes in land-use; for instance, the aging of local residents and depopulation of rural mountainous regions in Japan have increased the number of abandoned fields that become overgrown with brush, ultimately increasing the habitat available for those species (Sakurai 2019). The population density of deer has increased to more than 20 deer/km² in some regions (e.g., Kishimoto et al. 2010). The rise in the wildlife population has also increased human-wildlife conflict, and the current annual cost of agricultural damage caused by terrestrial mammals is estimated to be approximately 13 billion yen (about US$130 million; Ministry of Agriculture, Forestry, and Fisheries 2021).

Although an intermediate density of deer contributes to enhancing local species richness (Suzuki et al. 2013), their overpopulation can alter mountain forest vegetation through overgrazing, resulting in fewer evergreen trees and less diversity of the understory (Takatsuki 2009, Ohashi et al. 2014). Overgrazing owing to deer overpopulation has affected other fauna in the forest ecosystem, e.g., the faunal composition of forest-dwelling birds and small mammals such as *Apodemus* mice has declined because of a reduction in food resources (Seki et al. 2014). The populations of endemic serow (*Capricornis crispus*) have declined, potentially owing to resource competition with sika deer (Koganezawa 1999, Seki and Hayama 2021). Although large herbivores can negatively affect insects, a meta-analysis on the indirect effects of herbivore density on phytophagous insects revealed no clear trends (Takagi and Miyashita 2014).

Based on the situation in Japan and case studies worldwide, we created a simple ecological system loop diagram (Fig. 2). Wolves affect the deer population via predation, while, as its primary prey, the number of deer affects the wolf population (illustrated by relationship B3, the predator/prey loop, Fig. 2). Although wolves also prey on other species such as boar and hares (*Lepus brachyurus*), in this study we focus on the relationship between wolves and deer, because sika deer was historically their staple prey (Matsubayashi et al. 2017). Wolves can reduce the prevalence of infections such as tuberculosis in prey populations (e.g., boars) via predation, thus contributing to maintaining healthy prey populations without reducing their density (Tanner et al. 2019), although the relationships between predators and their prey are more complex than this.

Fig. 2. Causal loop diagram of the relationships between biodiversity level, deer and wolf populations, and hunters. The relationships between biodiversity and deer population, the wolf and deer populations, and hunters and deer populations show balancing loops (B2: Biodiversity/deer loop; B3: Predator/prey loop; B4: Hunter/deer loop). The relationships among biodiversity, deer and wolf populations, and biodiversity and the wolf population show reinforcing loops (R4: Biodiversity/predator/prey loop; R5: Biodiversity/wolf loop). Other factors also affect the dynamics of each factor.



Hunting by humans plays a significant role in controlling deer populations (e.g., Kaji et al. 2010). The growth of deer populations could increase hunters' motivation to hunt them, promoting the recruitment of new hunters (relationship B4, Fig. 2: the hunter/deer loop). In Japan, the overpopulation of deer incentivized government ministries to increase the budget for deer-population management and for providing hunting subsidies to hunters; this in turn increased hunters' motivation and provided incentives for people to obtain hunting licenses (Igota and Suzuki 2008). However, it is important to remember that increase in game species populations does not necessarily lead to an increase in hunters' motivations, as is illustrated by a case in Spain where hunters perceived the need to reduce overpopulation by European rabbits (*Oryctolagus cuniculus*) as an obligation rather than a pleasant activity (Delibes-Mateos et al. 2020). Therefore, we believe that a combination of hunters and wolves will decrease deer populations.

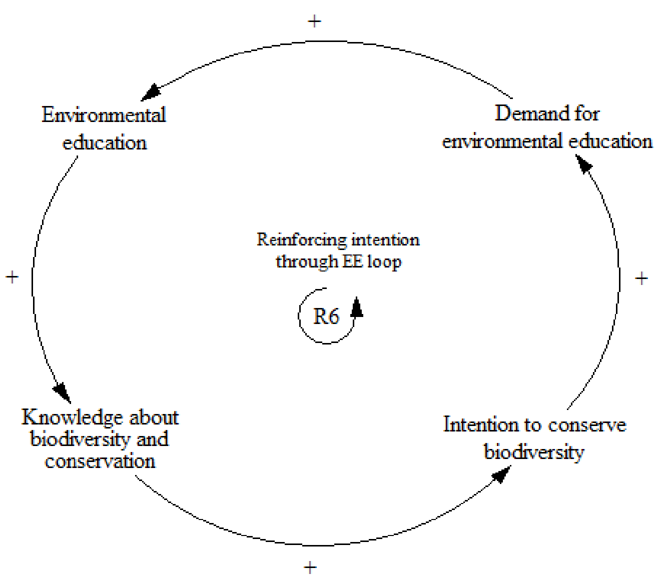
The deer population affects biodiversity both quantitatively and qualitatively, as illustrated by case studies worldwide, with a rapid increase in deer numbers reducing biodiversity. Biodiversity also affects the deer population, because deer thrive in diverse landscapes including forests and grasslands, but not in monoculture plantation forests (Martin et al. 2020). Although biodiversity could affect the wolf population, such a relationship might not be linear. Theoretical and empirical research has shown that greater diversity contributes to greater resilience in the ecosystem community (Tilman 1996, Krebs 2001). In a less biodiverse environment, wolves might depend solely on deer for their prey, hence their population could fluctuate rapidly with the change in the deer population. In many parts of the world, in the absence of natural prey, wolves have started to rely on livestock and other anthropogenic inputs such as garbage (Newsome et al. 2016). In contrast, a highly biodiverse ecosystem could provide wolves other prey besides deer (e.g., boars and hares), making it more likely that the wolf population would stabilize. In that sense, the R5 and B2 loops in Figure 2 should be interpreted as follows: the presence of sufficient biodiversity would stabilize (but not necessarily increase) both the wolf and deer population. The relationships of biodiversity to deer, on the one hand, and to wolves, on the other, differ in that although an increase in the wolf population could increase biodiversity, deer overpopulation could reduce biodiversity. In contrast, deer overpopulation would increase the wolf population by providing additional prey. We discuss this further in the following section. Japan currently lacks a top predator (in this case, wolves); therefore, in the CLD illustrated in Figure 2, only the biodiversity/deer (B2) and hunter/deer (B4) loops currently occur in Japan, illustrating that deer continue to negatively affect biodiversity.

In various parts of the world, ungulate population sizes have declined or been controlled by epizootic diseases; for instance, mange has impacted the Alpine chamois (*Rupicapra rupicapra rupicapra*; Rossi et al. 1995) and tuberculosis has impacted wild boar in Spain (Tanner et al. 2019). Therefore, we have added "Disease" as a potential factor affecting the deer population (Fig. 2). However, in Japan, hunters are considered to be the main factor controlling the deer population, as indicated by historical deer population dynamics: in the 1900s, deer were considered threatened throughout Japan, because of overhunting; as hunting pressure decreased in the 1990s, deer became overpopulated; since the 2000s, the population has been controlled by intense hunting activity (Kaji and Iijima 2017).

From a social-science perspective, we first present a simple CLD illustrating the relationship between environmental education and public intention to conserve biodiversity (Fig. 3) as a benchmark for a combined social-ecological model. Assuming that the decisions of agencies about species reintroduction are affected by public opinion and support for reintroduction (e.g., voting in favor of reintroduction, which can be regarded as pro-environmental behavior), it is necessary to understand how such public opinion and pro-environmental behavior is formed.

People's opinions and perceptions regarding a certain topic are shaped and affected by various factors, including education (Ajzen and Fishbein 1980), the media (Takeshita 2008), past experiences (Ormrod 2008), and information from peers (Decker et al. 2012). Environmental education can increase knowledge about, and foster awareness of, environmental issues, and possibly encourage pro-environmental behavior (Liddicoat and Krasny 2012, Zint 2012). Although knowledge is thought to have limited effects in terms of changing behavior (Ajzen 2001, Kollmuss and Agyeman 2002), the combination of three types of knowledge—systems, action-related, and effectiveness-based—could lead to pro-environmental behavior (Krasny 2020). In this case, people could gain system knowledge by learning about, for example, how the ecosystem functions, in terms of species interactions and predator/prey relationships. People can gain action-related knowledge by discovering, for example, that they can participate in nature observation and restoration activities in their neighborhoods. Finally, effectiveness-based knowledge can be gained by understanding that, for example, voting for ecologically literate candidates and communicating with elected officials (or in this specific case, supporting organizations that promote species reintroduction) are effective ways to promote biodiversity.

Fig. 3. Causal loop diagram illustrating the relationships between environmental education (EE), knowledge (systems, action-related, and effectiveness-based) about biodiversity and conservation, intention to conserve biodiversity, and demand for environmental education. The relationships among these factors are in a reinforcing loop (R6: Reinforcing intention through EE loop). Other factors also affect the dynamics of each factor.



Based on previous studies, a simple CLD regarding the social-science process can be created (Fig. 3). Environmental education can increase public understanding about biodiversity and conservation (Ernst et al. 2009). With the increase in public understanding of biodiversity (in terms of all three types of knowledge about biodiversity conservation), their intention to conserve biodiversity as well as actual behavior could be encouraged (Jacobson 2009, Sakurai et al. 2019). Meanwhile, an increase in public intention to conserve biodiversity could increase demand for environmental education programs, potentially increasing the number of environmental education programs conducted nationwide. As more people engage in conservation-related behavior, this could alter social norms, such as by increasing the social pressure from family, neighbors, and others to engage in pro-environmental behaviors (Hayabuchi 2008). This could in turn cause additional environmental education programs to be implemented to meet this need (Sasaki 2016). Although conservation initiatives and projects are sometimes implemented without specific environmental education programs, we believe that including environmental education programs could make such initiatives more effective and sustainable, as the projects may then have long-term public support (George and Sandhaus 2016). The Oriental Stork reintroduction case demonstrates the potential connections between the frequency of environmental education, public knowledge about biodiversity, public intention to conserve, and the demand for environmental education (Fig. 1).

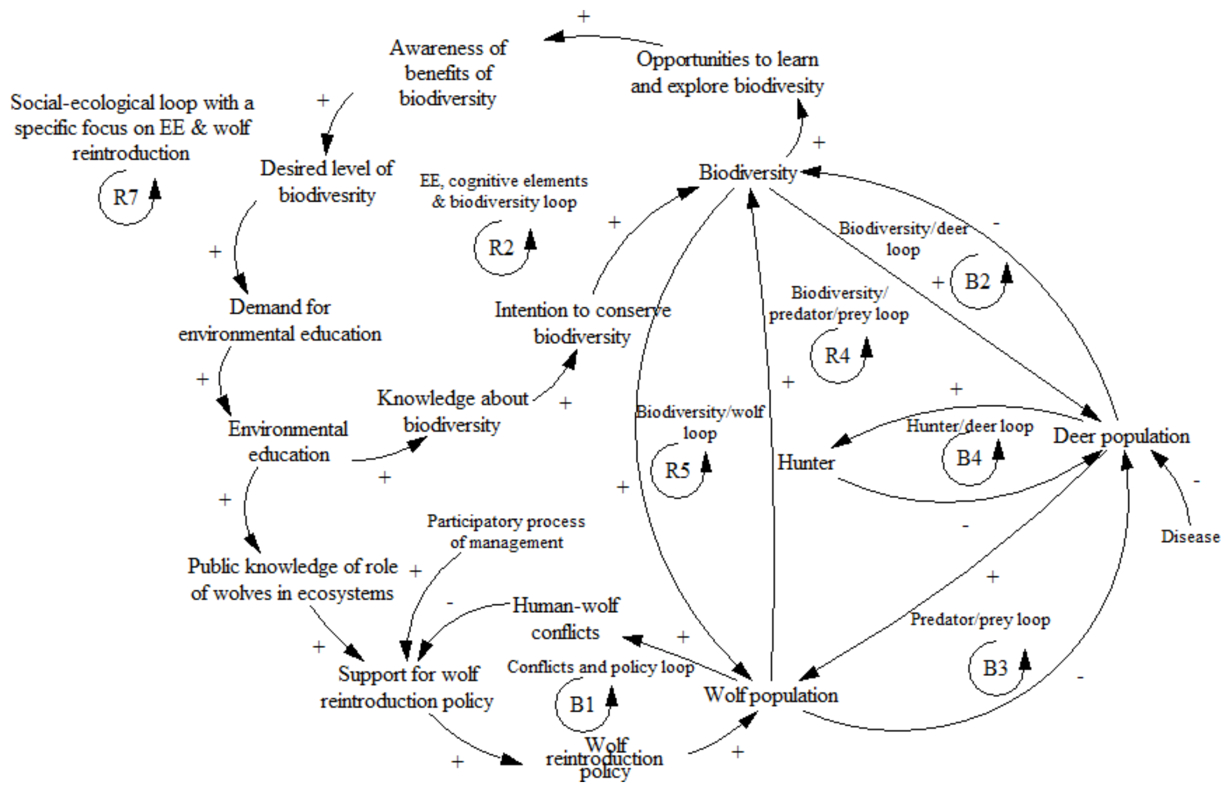
In the real world, ecological and social factors are connected. For example, increased public participation in conservation (potentially via an increase in the number of environmental education programs) could preserve or increase the biodiversity of the surrounding environment. Citizen science projects worldwide have demonstrated how local environment and biodiversity can be conserved through active involvement by citizens (Bonney et al. 2014, Kobori et al. 2016).

Although the reintroduction of once-extirpated top predators can restore self-sustaining ecosystems and enrich their biodiversity, it remains a policy decision whether or not to reintroduce such a species. Such policy decisions are affected by public opinion (especially in democratic countries such as Japan). The model that integrates ecological and social causal loops (Figs. 2 and 3) illustrates how social factors affect ecological factors and vice versa (Fig. 4).

People who understand the ecological roles of wolves are more likely to support wolf reintroduction (Gosling et al. 2019, Sakurai et al. 2020, Sakurai et al. 2023); in many cases, such knowledge is acquired through education (Jacobson 1999, Musiani and Paquet 2004). Knowledge of wolves' roles in the ecosystem (systems knowledge), of the types of activity required to support NGOs that promote wolf reintroduction (activity-based knowledge), and of how supporting such NGOs can influence policy (effectiveness-based knowledge) is likely to foster public support for wolf reintroduction. People with positive attitudes toward reintroduction are more likely to act in support of such policies (e.g., voting for reintroduction; Sakurai et al. 2023). Although we started our discussion here focusing on a simple model considering the general public, stakeholders that are potentially affected by wolf reintroduction, including hunters and ranchers, would have different opinions toward wolves that are not necessarily affected by environmental education. We discuss this in detail in the following section.

In Japan, wolf reintroduction will depend on the amount of public support for the government's policy (Yamanaka and Kaji 2006, Kaji 2017). In the U.S., which has a similar democratic system, Colorado has decided to reintroduce wolves by 2024 (and initial

Fig. 4. Causal loop diagram illustrating the relationships between social and ecological factors in terms of environmental education (EE) and wolf reintroduction (R7). Other factors also affect the dynamics of each factor. Human–wolf conflict can include the loss of pets and livestock, polarization over support for wolf conservation, and urban/rural differences. The stakeholders include local residents, farmers, hunters, animal-rights associations, agencies, and researchers.



reintroductions were completed in December 2023), as a 2020 ballot indicated increased public support for it (NPR News 2020). In Japan, it is not uncommon for the public to influence policy by showing their preferences in a ballot or signature campaign (Murayama 2009). The Japanese public increasingly expects to participate in decision making, and to have their values and beliefs reflected in decisions; acceptance of the ballot procedure as an important process in structuring and implementing policies is growing (Murayama 2009). It is therefore likely that the public will decide on wolf reintroduction in Japan by ballot, as in Colorado.

Lobbying can also play an important role in environmental decision making. In Spain, a formal request by a conservation-related NGO to the government succeeded in having wolves listed in the Spanish Red list of Threatened Species, thus banning recreational hunting as a wolf management option (Ordiz et al. 2022). Environmental issues are among the top lobbying agendas in the U.S. (Baumgartner et al. 2009). For Japan, the potential effects of lobbying on decision making need to be considered.

With this in mind, relationship R7 (the social-ecological loop with a specific focus on EE and wolf reintroduction) in Figure 4 illustrates how environmental education could increase public knowledge of the role of wolves in ecosystems, and how public support for wolf reintroduction policies could affect government decisions. (In the different CLDs presented, the same loop numbers are used when the contents of the loop are same, such as for relationship B2 [the "Biodiversity/deer loop"] in Figs. 2 and 4). If the government decides to reintroduce wolves as a national policy, a new wolf population will be released and established in the country. The presence of wolves would directly and indirectly affect deer behavior and the deer population; once the deer population has relatively stabilized given wolf presence, other species populations are expected to increase, and the overall biodiversity level could increase (as indicated in R4: Biodiversity/predator/prey loop).

An increase in biodiversity could increase opportunities for the public to learn about and experience biodiversity through, for instance, eco-tours or citizen science activities. This, in turn, would foster public awareness of the benefits of a biodiverse environment (as illustrated in R2: EE, cognitive elements and biodiversity loop in Figs. 1 and 4). This is because people begin to understand ecological processes and how biodiversity functions by learning about changes in the country's biodiversity via the media or by visiting such areas. In YNP, the wolf reintroduction program provided visitors with opportunities to learn about the ecological roles of wolves and about whole-ecosystem functioning, irrespective of whether they actually saw wild wolves in the park (Montag et al. 2005). Public attitudes toward wolves are expected to become more positive once they learn about the ecosystem services that wolves provide. Seeing the increase in biodiversity and the value of reintroduced species can shape people's vision of the desired state of biodiversity. For instance, once species have been reintroduced or their populations restored, local residents are more likely to accept those species and recognize their importance in the ecosystem, such as for the Oriental Stork reintroduction in Japan (Honda 2008, Kikuchi 2017, Sakurai et al. 2022) and human-wolf coexistence in Spain (Pettersson et al. 2021).

Wolves can contribute to disease control in their prey populations, in turn reducing transmission from wildlife reservoirs to other animals such as cattle; wolves could thus potentially be recognized as allies, even by those who are expected to oppose wolf reintroduction, such as farmers (Tanner et al. 2019). Species reintroduction could increase the number of environmental education programs implemented, as reflected in the various wolf-watching tours and educational programs offered in YPN related to the wolf reintroduction (Miller 2017).

LIMITATIONS IN CREATING A REALISTIC CLD

Creating diagram-based models helps stakeholders understand the implications of management decisions (van den Belt 2004). Such diagrams enable policy makers to see the "big picture," overcoming the typical tendency toward short-term linear thinking in decision making (van den Belt 2004). However, diagrams are incomplete and cannot fully explain the real world (Bueno 2014). Here, we selected the factors to construct the CLDs, but there are other factors that also affect ecological and social processes. For example, deer populations are affected not only by natural predators, human hunters, and disease, but also by other factors such as the weather. For instance, increasing snow depth interacted with wolf predation to slow the population growth of elk in Alberta, Canada (Hebblewhite et al. 2002). Further, while human-wolf conflicts are included and explained in Figure 4, the complexity and depth of the conflict cannot be fully captured and explained in this model. Adding additional factors to the diagram would provide a better representation of reality, but would increase the model's complexity. However, to be able to understand the dynamics of the system and predict future scenarios, it is more important to identify the relationships among the variables (thus explaining the system's dynamic complexity), rather than accurately verifying the linear cause-and-effect relationships between the factors (van den Belt 2004, Hovmand 2014).

The validity of some of the relationships illustrated in Figure 4 is debatable. For instance, considering relationship R5 (Fig. 4), while wolves could affect the deer population, and deer overpopulation could reduce biodiversity, more research is necessary to clarify whether and how biodiversity levels affect wolf population size. When wild ungulate densities are low, or human-subsidized food sources (such as refuse) are easily accessible, wolves can live near human settlements by feeding on discarded household waste, or by preying on livestock (Newsome et al. 2016). However, this potentially provokes conflicts with humans (Kuijper et al. 2019). It also increases the risk of pathogen infection (Plaza and Lambertucci 2017), potentially increasing the risk of casualties from attacks by rabid wolves (Linnell et al. 2021). Historically, such increases in human-wolf conflict have often led the authorities to eradicate wolves that live near human settlements (Nie 2003). Nonetheless, in many parts of the world, wolf populations have not only been maintained but have increased in spite of human-wolf conflicts such as livestock predation (Newsome et al. 2016). In contrast, high biodiversity encourages the long-term and sustainable survival of a stable wolf population (as simplified by "+ (positive)" in Figs. 2 and 4). Although some studies have revealed how wolves affect the level of biodiversity via cascade effects (Smith and Bangs 2009, Ripple et al. 2014), fewer have examined how the level of biodiversity affects wolf populations. Further studies are necessary to articulate this relationship in greater detail. The factors potentially affecting public attitudes toward wolf reintroduction, as described in the literature, are summarized in Table 1.

The CLD in Figure 4 assumes that wolf reintroduction would have positive outcomes, such as increasing biodiversity and generating public support for even more wolf conservation and reintroduction. However, it could also negatively affect humans if, for example, human-wolf conflicts increased after the project. In many parts of the world, ranchers, livestock farmers, and hunters typically have negative attitudes toward wolf reintroduction or conservation (Bath 1989, Williams et al. 2002). An increase in the wolf population can increase human-wolf conflict and consequently reduce public support for wolf conservation (Eriksson and Herberlein 2003, Pettersson et al. 2021). If this occurs in Japan, conflict such as wolf attacks on pets and livestock could reduce public support for wolf reintroduction and conservation (Fig. 4). Support for the reintroduction of large carnivores depends both on human tolerance toward them and conflict reduction (Forbes et al. 2020). Unlike in the U.S., where wolves have been reintroduced, there is relatively little livestock production in Japan (the U.S. produces about 36 times more beef than Japan annually, while it has 2.6 times more residents; U.S. Meat Export Federation 2021). Therefore, the reintroduction of wolves in Japan could lead to less livestock predation (both in frequency and quantity) than in countries such as the U.S. and European countries.

In Japan, people's perceptions toward wolf reintroduction are affected by factors such as fear of wolves, trust in researchers, and whether or not they believe that reintroduced wolves will become invasive (Sakurai et al. 2020, 2023). In order for a model (such as the CLD in Fig. 4) to be useful and meaningful for stakeholders, it should reflect context-specific information. For example, conflicts related to wildlife reintroduction could be classified as disputes (e.g., disagreements), underlying conflicts (e.g., distrust), and deep-rooted conflicts (e.g., a lack of recognition of cultural values in decision making; Glikman et al. 2022). Therefore, increasing public support for wolf reintroduction requires more than simply environmental education; it also requires the creation of diverse opportunities to enhance governance, including outreach and civic meetings; increasing the public trust in agencies and researchers; promoting the dissemination of fact-based information about wolf-attack frequency; and for decision makers to learn about the local culture and context in the areas where wolf reintroductions are planned (Massarella et al. 2021, Glikman et al. 2022).

Table 1. Factors potentially affecting public attitudes toward wolf reintroduction (WR) and conservation.

Items	Relationships identified by previous studies	Effects on public attitudes toward WR
Knowledge about wolves	More knowledge about wolves leads to more support for WR and wolf conservation (Angeli et al. 1998, Enck and Brown 2002, Gosling et al. 2019, Sakurai et al. 2020). In contrast, hunters with the most accurate knowledge about wolves have the most negative attitudes (Eriksson and Heberlein 2003).	+ and −
Attitudes toward wolves	More positive attitudes toward wolves lead to more support for WR and wolf conservation (Bath 1989, Enck and Brown 2002, Sakurai et al. 2020, 2023).	+
Knowledge about wildlife issues	Increasing public realization that deer populations have grown and cause damage might increase support for WR (Angeli et al. 1998).	+
Beliefs related to the role wolves play in ecosystem	The more critically people think about the ecological role of wolves, the more they support WR (Enck and Brown 2002, Sakurai et al. 2020).	+
Wildlife-related values and beliefs	Greater adoption of mutualism as a value leads to more support for WR and wolf conservation (Hermann et al. 2013, Gosling et al. 2019)	+
Trust in government and other entities	Less trust in politicians leads to less support for WR as a policy (Eriksson 2017) whereas more trust in researchers at universities leads to more support to WR (Sakurai et al. 2020)	+
Risk perception	The perceived risk of wolf attacks reduces support for WR (Enck and Brown 2002, Sakurai et al. 2020).	−
Experiences with wolves	More direct experience with wolves reduces support for WR or wolf conservation (Eriksson and Herberlein 2013). On the other hand, more experience of wolves could increase support for wolf conservation (Petterson et al. 2022).	+ and −
Socio-demographic factors	Livestock farmers oppose WR (Bath 1989) wherease members of environmental groups are more likely to support it (Williams et al. 2002).	+ and −
	Local residents living adjacent to wolf habitats or WR sites are less likely to support it, whereas city residents are more likely to support it (Bath 1989, Bath and Buchanan 1989, Williams et al. 2002, Eriksson and Heberlein 2003, Gosling et al. 2019).	+ and −
	Elder respondents are less likely to support WR (Gosling et al. 2019).	−
	Women are more likely to support WR (Williams et al. 2002)	+
	People with higher incomes are more likely to support WR (Williams et al. 2002)	+
	People with more education are more likely support WR and wolf conservation (Eriksson and Herberlein 2003).	+

Accuracy and correctness are not necessarily the most important objectives when creating a system dynamics model, although such models must be applicable (Bueno 2014). In that sense, stakeholders could include factors and relationships in such models to reflect the types of ecological and social processes that they want to understand and predict. Therefore, models are created based on the outcomes of subjective judgment (Stedman 2016); thus, the reliability and validity of the CLDs should be analyzed and discussed when identifying potential strategies for improving such models (Cornwell 2004, Hovmand 2014).

CHALLENGES AND POSSIBILITIES IN QUANTIFYING THESE RELATIONSHIPS

The system dynamics approach qualitatively and quantitatively predicts the relationships among factors, providing insights into the magnitude of change that would occur in the system (van den Belt 2004). The explanatory power of the model can be determined based on the adequacy of the data used in the analysis. For example, previous studies have quantitatively determined how much knowledge about wolf reintroduction is necessary to change public attitudes toward wolf reintroduction (Enck and Brown 2002). A study in Japan, based on a survey of university students, found that increasing knowledge about wolves (e.g., their roles in the ecosystem and the fact that the reintroduced wolves would be the same species as continental wolves) would increase support for reintroduction by on average 0.6 points on a five-point scale (Sakurai et al. 2020).

A recent survey (Sakurai et al. 2023) revealed diverse public attitudes toward wolf reintroduction: about 40% disagreed with reintroduction while another 40% were unsure about it, and the rest (approximately 20%) agreed with it. In the same study, knowledge that Japanese wolves would be the same species as continental wolves, that they can control deer populations, and that they are necessary for a healthy ecosystem, increased public support for reintroduction by a total of 0.7 points on a five-point scale. Those who agreed with wolf reintroduction had greater intention to engage in behaviors to support it, such as signing a petition to support it. Majority rule is the basis for decision making in many democratic countries, and whether the ratio of citizens who agree to a certain topic increased to more than 50% would be assumed as one social tipping point that could change the policy. Based on previous studies (e.g., Niemiec et al. 2020, Sakurai et al. 2020, 2023), we hypothesized that once a majority of the public obtains scientific information about the identity and role of wolves, they would be more likely to support wolf reintroduction. Further, as the public shifts toward favoring wolf reintroduction, more people would engage in activities to support the reintroduction, and this in turn would encourage or force the government to start considering wolf reintroduction as a national policy.

By including numerical values into the diagram, the proposed model (Fig. 4) could become quantitative. For example, based on current research on public attitudes toward wolf reintroduction in Japan (17% of citizen supported it; Sakurai et al. 2023), we can assume a value of 0.17 for “Support for wolf reintroduction policy,” and assume that this value would change as the opportunities for public participation in wolf-related environmental education would increase. Because there are currently few opportunities where the public can learn about the ecological roles of wolves in Japan, the value for “Environmental education” is assumed to be 0; however, as more information becomes disseminated via the media and community lectures, this value (the number of environmental education events each year) could increase to, for instance, two per year. Such opportunities for environmental education about wolves are expected to increase the "Public knowledge of role of wolves in ecosystem" parameter (currently at 3.27 on a five-point scale; Sakurai et al. 2023), in turn affecting public support for reintroduction.

Similarly, human-wolf conflicts can be quantified using multiple values, including the number of casualties and depredation of pets and livestock. Factors such as the deer population and biodiversity levels have recently been quantified (e.g., the estimated deer population in Japan in 2021 was 2.46 million; Ministry of the Environment 2021). However, more research is necessary to determine the potential sustainable wolf population of Japan and how it would affect the deer population, considering factors such as habitat availability and the rate of fragmentation.

ADDITIONAL FACTORS TO CONSIDER IN DEVELOPING THE SYSTEM MODEL

To better understand the implications of the proposed model and to account for uncertainty regarding the future scenario, both the spatial and temporal scales should be considered. The spatial scale must be considered because wolf reintroduction is aimed at restoring the entire ecosystem; prior reintroduction projects have demonstrated how reintroduced species (such as Oriental Storks in Japan and wolves in YNP) have dispersed into other regions. When considering project feasibility, the Japanese government therefore needs to understand the attitudes and preferences of not only the local residents near the potential reintroduction sites, but also of the broader public. In the case of the stork reintroduction, while we have focused primarily on Toyooka City (Fig. 1), the reintroduced storks have dispersed beyond the boundaries of this city, and now occur in various parts of western Japan. Following stork reintroduction in eastern Japan, storks now occur there, such as in Chiba prefecture (Takahashi and Honda 2016). Public perceptions of storks have become more positive and willingness to accept storks has increased not only in Toyooka but also in other parts of Japan (Takahashi and Honda 2016, Sakurai et al. 2022). Figure 1 thus illustrates not only what happened in Toyooka, but also what is likely to happen at a larger spatial scale in future.

The temporal scale should also be considered when developing a model and predicting relationships between factors. Dissemination of accurate information regarding wolves might occur relatively quickly because a one-time program can increase participants' knowledge and even change their attitudes (e.g., support for natural energy increased after one seminar; Takano et al. 2018). A study in California on the potential reintroduction of grizzly bears revealed that the public generally lacked knowledge of the species and reintroduction, and that wildlife managers thus needed to communicate the ecological and social benefits of reintroduction to the public before introducing management proposals, to prevent the issue from becoming polarizing (Hiroyasu et al. 2019).

At government level, it could take longer to decide to adopt a policy to reintroduce an extirpated species. In the U.S., although the importance and possibility of reintroducing wolves in the YNP had been discussed by researchers and the public since the 1960s (Fritts et al. 1997), it took about 30 years for the government (specifically, The U.S. Fish and Wildlife Service) to actually plan and implement this project (in 1995). In the UK, although the potential to reintroduce wolves has been discussed by researchers (e.g., Wilson 2004, Nilsen et al. 2007) and organizations (Rewilding Britain 2021) for more than 30 years, such projects have not yet become government policy. In Japan, although researchers and NGOs have been discussing the importance and significance of reintroducing wolves for several decades (e.g., Knight 2006, Maruyama et al. 2007), this seems to have had limited influence on the government's decision making, because introducing a species that could cause new problems (such as human-wolf conflicts) is considered a risky project for the government (Kawata 2014).

Once wolves have been reintroduced, the effects on other species rapidly become visible. In YNP, changes in elk behavior and habitat selection were reported half a year after the reintroduction (Ripple and Beschta 2003). Reductions in the deer population were reported a few years after the wolf reintroduction in YNP, although there were multiple potential reasons for this, including the weather (Smith and Bangs 2009). The ecosystem of YNP has changed since the reintroduction, mostly positively, in terms of greater ecosystem resilience owing to the increased biodiversity (Smith and Bangs 2009). Such changes in ecosystems and biodiversity could affect people's understanding and attitudes toward reintroduction projects (e.g., Montag et al. 2005). Most of the millions of visitors to the YNP wish to see wild wolves during their visit (Miller 2017). Environmental education programs and outdoor activities have been established to teach visitors about the importance of wolves in the ecosystem in and around the YNP (National Park Service 2020), potentially influencing the participants' perspectives. In Spain, local businesses and producers have started using wolf-related branding, thus successfully attracting tourists (Pettersson et al. 2021).

The number and frequency of human-wolf conflicts can change over time. Conflicts could increase as the wolf population increases; once measures to prevent damage (e.g., fencing) or farmers' compensation systems have been established, however, such conflicts could be tolerated by those stakeholders (Pettersson et al. 2022). Once the public start to accept wolves as a species that belongs in the landscape, their attitudes toward wolves and reintroduction projects can become positive (Gosling et al. 2019, Pettersson et al. 2022). With ongoing modernization and urbanization, the environmental values of the public have changed from being domination-based to mutualism-based and favoring conservation (Manfredo et al. 2021), and this value-shift is expected to continue. In Japan, people who value mutualism are more likely to support wolf reintroduction (Sakurai et al. 2023).

It could take more than half a century to observe all the effects proposed in our models. In terms of the stork reintroduction in 2005, it took less than 20 years for local residents to recognize the benefits of biodiversity; environmental education activities increased in the region, encouraging biodiversity conservation behavior. The reintroduction occurred about 30 years after the last stork was captured in the region in 1971. The amount of time required for a decision on reintroduction therefore varies depending on the target species, the ecological and social context that led to the extirpation, the level of conflict, and public perceptions toward the species. As has been reported for many species reintroductions around the world, some species are more likely to be reintroduced than others (Seddon et al. 2005). Meanwhile, participatory processes encouraging the involvement of various stakeholders ("Participatory process of management" in Figs. 1 and 4) can make management decisions more effective by ensuring that they have public support. For the stork reintroduction, collaboration among stakeholders—including local residents, the city administration, Hyogo Park of the Oriental White Stork staff and volunteers, local farmers, and natural and social science researchers—ensured ongoing research into storks, demonstrated that storks and human can coexist, and led to the success of the reintroduction project (Kikuchi 2006). In addition, climate change should also be considered. The climate of Japan might change in the next 50 years.

Economic factors should also be considered in such a model. The cost of species reintroduction and management is massive. The reintroduction as well as management of wolves cost more than US$1 million per state (Hoag et al. 2023). However, the ecosystem services generated by wolf reintroduction could outweigh the costs: for instance, the presence of wolves reduced deer-vehicle collisions by 24%, bringing economic benefits 63 times larger than costs of wolf depredation on livestock (Raynor et al. 2021). In Japan, while it cost 5.9 billion yen (about US$59 million) to build and run the Park of the Oriental Stork, the annual benefits of this project have been estimated at about 1 billion yen (about US$10 million) from tourism and about 8 billion yen (about US$80 million) from related projects (Onuma and Yamamoto 2009). Further environmental economics research is necessary to clarify the potential economic value of species reintroductions considering both their resulting ecosystem services and costs.

SUMMARY

In summary, our model predicts that environmental education programs will enhance people's attitudes toward wolf reintroduction; this will influence government's decision making regarding wolf reintroduction; the deer population will be controlled, and total biodiversity will thus increase; this will in turn alter people's attitudes. Causal link diagrams are valuable because they can help managers and stakeholders to realize that the problems are integrated within the system, highlighting the importance of an interdisciplinary approach to understanding the "bigger picture." Further, CLDs help stakeholders to see problems as dynamic, providing insights into how the relationships between factors (and the factors themselves) change over time. For example, it is easy to imagine that wolf and deer populations change over time; however, social factors, such as public perceptions and support for reintroduction, also change over time, and this can be more difficult for stakeholders to grasp. A recent survey in Japan revealed that the younger generation holds more positive attitudes toward wolf reintroduction than the older generation and that public attitudes could shift (Sakurai et al. 2020). The CLD could be further improved by quantitatively verifying the relationships represented in each loop; it could then be used to describe a set of potential future scenarios.

Data Availability:

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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