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The Return of Eurasian Beavers: Mitigating Potential Conflicts Through Adaptive Management

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Table of Contents

SUMMARY

The Eurasian Beaver is returning, after being hunted down to the brink of extinction for its fur, meat and castoreum glands from medieval times all through the 19th century. It is now recolonizing much of its previous range through conservation protocols, reintroduction efforts and natural recolonization of water units all over Europe. As for many other wild species, its comeback is still threatened by extensive human growth and urbanization, as well as climate change leading to diminished water reserves which are part of its natural and obligate habitat. Management strategies applicable to pre-existing populations, as well as for reintroduction protocols, are essential to ensure their permanence and sustainability.

As a keystone species, beaver presence has the potential to create a positive cascading effect for the regeneration of wetland habitats and all its plant and animal residents. Furthermore, extensive scientific literature indicates how beavers' water storage, through dam constructions, may help filter streams, replenish groundwater supplies and stop wildfire from spreading uncontrollably.

Their presence nevertheless poses some risks, both in rural and urban contexts. When their dams collapse or spill over due to seasonal changes and sudden rainfall increase, damages can be extensive and costly. Inhabiting waterways, they may also become vectors for disease propagation and pose a potential zoonosis threat. This dissertation discusses in depth the benefits and risks related to beaver presence and provides an overview of management strategies to promote their conservation and mitigate human-beaver conflicts, keeping in mind animal welfare and ethics principles and best practices.

INTRODUCTION

Beaver ecology has been rigorously articulated by F. Rosell and Campbell-Palmer in '*Beavers: Ecology, Behaviour, Conservation and Management' (OUP Oxford Edition of 2022).* In order to base existing and potential beaver management and risk – reduction strategies, the maximization of beaver - induced benefits and their role as keystone species on reliable facts and documented evidence, this dissertation contains citations from the aforementioned '*Beavers Ecology Toma'*, as well as a few other pertinent publications. As this work utilizes mostly Rosell and Campbell-Palmer's assembly of scientific beaver data as main reference, where not otherwise stated, measurements and other figures are all of the same origin: (Rosell and Campbell-Palmer, 2022). This citation will be added to the end of each section to avoid being redundant.

An in-depth understanding of this species is a key to maximise potential beavers' benefits and avoid or minimise potential conflicts or negative impacts. The topic of this dissertation was chosen due to its significant relevance in shaping current and future climate change adaptation strategies. With water depletion and desertification being two non-negligible global environmental trends, these rodents have the potential to contribute to climate resilience strategies and should be considered as a financially viable tool of the wider menu of nature – based solutions to climate change. For this to happen, direct conflict between humans and beavers must be avoided.

A Few Words on Castor spp.

Today's beavers are the only remaining member of the once diverse and abundant family of Castoridae < 40 million years ago. Their evolutionary specializations, which earns them the definition of ecological or landscape "engineers", evolved from a terrestrial ancestor, who already possessed excellent burrowing capacities, but was not yet dependant on wetlands; the *Paleocastor*. Its heritage consisted of giant Castoroides, as well as smaller burrowing Dipoides for up to 30 different genres roughly 1.9 million years ago.

The modern beaver is the second largest Rodentia order's member still existing today, after the south American capybara. Climate modifications throughout millennia, together with prehistorical anthropogenic pressures have affected beaver distribution over millions of years and in doing so also affected its evolution. They have now evolved to be obligate semi-aquatic habitants of riparian zones and wetland ecosystems. Without access to enough water, this modern species doesn't fair well, needing water for safety, submerging lodge entrances, as well as for dietary needs with aquatic vegetation composing up to 80% of their diet depending on seasonality and mineral requirements.

Beavers are crepuscular and nocturnal mammals with well-developed primary and secondary olfactory systems. They can detect primary food sources such as aspen a few hundred meters away. They also possess a range of specialized features making them well adapted to a semi-aquatic lifestyle. Their articulated tail, allowing for maximal maneuverability in water but heavy on land; valvular flaps in the ear and automatically shut the nostrils when in contact with water; and a third eyelid or 'nictitating' membrane improves underwater vision; powerful - webbed hind feet; and a double layered fur that allows for warm trapped air to sit in-between – keeping the skin dry.

Beavers require either soil, woody debris or even suitable crevices to construct their homes, which vary in number, architecture and design according to habitat allowance and family composition. The "burrow" model" was chosen in 95% of France's Rhone valley beavers where banks where steep enough, whilst in Northwest Russia by only 50%, with the other half choosing the "lodge" model consisting of sticks and woody debris (but nearly any material can be accommodated into the design including rubbish) piled up to usually around 1-2m high and 2-4m wide, this pile will be chewed-through; starting from the under-water entrance and going up to an initial feeding chamber at water-level (where food is eaten and fur can drip off excess water). A further tunnel is chewed through leading up and above water level to the sleeping chamber (also where the kits are born and remain until 2 months old). This type of housing suits colder climates and low banks better and can be built on shores or in the middle of standing water bodies providing the water is deep and calm enough. On a steep sandy bank with deep enough water and tree cover, a burrow may be more cost efficient. Simpler burrows are used by displaced or dispersing beavers needing quick refuges for example until winter is over and ice melting allows to travel further. Day rests or "lairs"; visible as indents in the bank or hollows in the ground a few metres inland, sometimes with a substrate roof cover provide safe resting spots and temporary shelters for beavers moving through their territory. Deeper burrows usually occur under large trees, so that the roots serve as a solid frame with less risk of collapse.

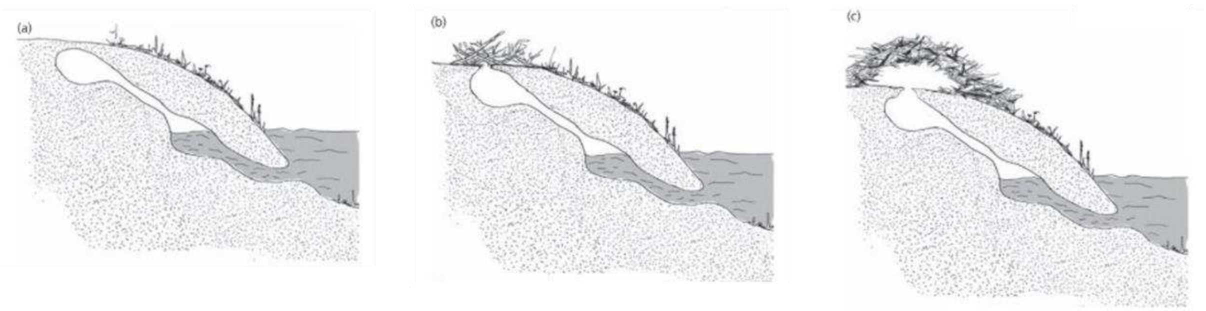

Figure 1. A burrow (a), a bank lodge (b), and stick lodge (4c). (Illustration of R. Campbell-Palmer, 2022)

Both sexes are 'socially monogamous and opportunistically promiscuous' and can both be dominant over the other within the actively reproducing couple. There are no gender specific behaviour variations except for the short period following kit birth. Offspring can stay with parents for a number of years. This has been demonstrated as increasing future fitness by learning and actively helping in family duties whilst increasing in body size and learnt skills, improving survival chances at dispersal. Until dispersal or death of a parent, they are subordinates and do not reproduce themselves. If a mate is found, they will move out of their parents' dwellings and establish a new family group. Female reproductive fitness positively correlates to higher fatty reserves accumulated before winter and oestrus phases.

Kits can disperse from the age of 1 year, varying due to habitat availability, connectivity, population density, and parental age. Sub-adults are more likely to remain on site with ageing parents going into reproductive senescence than with young parents. Following trigger factors, they depart on exploratory journeys up to 10km away from home range to gain pre-dispersal knowledge on potential new territory, neighbouring beavers' statuses and data on population density (resident adults will also perform forays, but without going beyond neighbouring territories). Dispersal record distances from 27 to 500km have been noted, although the average seems to be from 5–10 km to over 25–85 km (Pucci et al., 2021), rather more willingly downstream than upstream. Extra-pair copulations are not uncommon in either of the sexes, and may occur during forays and patrols, and with neighbouring beavers. A copulatory plug hardens sperm coagulates after copulation; blocking the vaginal opening, a technique shared by many rodents.

Due to their high fibre diet, they have a very well-developed cardio-gastric gland, and specialized mucous stomach lining, aiding digestion and protecting from injury. Their caecum does most of the cellulose digestion, using anaerobic microflora members to complete the work. Like other hind-gut fermenters, they are also caecotrophs, optimizing protein and mineral retention from coarse plant parts. Their strict herbivorous diet consists of aquatic and land plants, herbaceous browse, tree bark, branches, saplings and leaves depending on tree species, and even fruits and mushrooms.

There are some serious preferences regarding plant species and quantity but once beavers decide on one prey, they can and will take advantage of the whole felled tree, using every part either as immediate or reserve food, or as construction material. Herbaceous and aquatics may be integrated according to seasonal availability. Beavers have also been known to survive on a purely herbaceous diet. When given the choice, they tend to select foods with higher energetical value and according to nutrient contents, and with shorter retention times which allows for greater food intake. Always optimizing energy intake against distance needed to travel from the safety of water.

To make sure they have enough for the winter season, beavers will invest considerable amounts of their time in creating one or more food caches nearer to their lodgings. Climate is a key variable that influences these behaviours: in the northern environments with freezing temperatures, tree coverage and food caches become pre-requisites to long-term survival, whereas in warmer conditions, food reserves may not be necessary, and burrows may suffice to keep warm year-round. Food cache instinctive behaviour initiates after the first freeze – as ice impeding water navigability may make food sourcing harder.

Beavers are territorial and will frequently delimitate their territory with scent mounds producing insoluble anal gland secretions and castoreum exudates. Scent mounds are regularly re-charged by resident beavers in good health during their patrolling rounds and seem to offer important chemical intel on other individuals health, reproductive and social statuses, and possibly more still undiscovered. A beaver territory will follow shorelines for an average territory size of 3 km2 (this can vary from as little as 100m to more than 20km) and should provide for all their dietary needs. When they don't, beavers abandon the site if territory expansion is not an option (landscape limiting factors, high population densities or high predatory pressure or other disturbances).

Dam Building Behaviour

Apart from beavers and with exception for humans, no other animal builds dams, transforming simple natural items such as wood, branches, rocks and mud into highly sophisticated infrastructures. Lifting up to 5kg and triple that weight when collaborating with another beaver, dams are built with precision and diligent effort. Record dams can be as tall as 5m, and an extravagant dam with an 850m width was recorded in Alberta, Canada, and is visible from space. Dam building is performed in response to unstable or unsuitable watershed conditions but is not always worth the trouble. Beavers can build several consecutive dams, stabilizing water flow and increasing retention capacity – placed upstream from their main family pond. The most predictive aspect for dam building is water depth, with less water meaning reduced food availability, poor swimming terrain and exposed lodge entrances that therefore increase vulnerability to predation. Dam building is mostly performed in late summer and in autumn, seeming to be a winter preparation strategy. Dam reparation stops when "target" water levels are met (~ 70cm), starting again if water level decreases but not necessarily when the sound of water trickling out can be heard.

Beavers prefer first and second order streams, but they've been spotted living even in fifth order ones. Favourable locations such as river width between 2 and 6 m, steepness gradients < 12 %, water depths < 68cm, and fluctuations in seasonal water levels are all factors that favour damming behaviour. Riparian vegetation availability is, of course, the first aspect to consider in determining dam location, as without sufficient hardwood, sticks and rocks might not be enough to erect a proper structure. In fact, proximity of trees increases damming probability, as do clay and silt substrates compared to rocky ones. Lakes, rivers wider than 20m or, slopes of >18%, or on land managed for cattle grazing, are rarely dammed on, and if the cost of building and maintaining overruns the benefits, or no benefits arise from the damming (such as a lake), beavers will not utilize this skill.

Beavers will readily use fallen logs or boulders as the skeletal structure on which to start building their dam. A narrowing in the water course or an accessible road culvert are both deemed excellent starting spots for dam building, with techniques varying according to local hydrological regimes. In slow shallow waters, the intentional accumulation of organic debris may suffice, whilst in higher regimes or deeper waters, a sturdier frame is needed. To create one, beavers use sticks placed at a 30° angle from the upstream current – sinking them with weights of sediment and stone. Depending on the current, the dam is started at the edges, or evenly erected on all its length. Certain woody sources are preferred to others here too, and often coincide with non-edible plant species or parts (such as conifer and alders). Dams require daily maintenance, and modifications are done in certain conditions to allow excess water to overflow – reducing dam collapse risks. Dam collapse may happen when water speeds to more than 40km/hour, or due to human or other animals (invasive muskrats or otters) hindering its integrity. Time since construction does not seem to be a primary influencing factor as dam longevity increases (tinder loses buoyancy over time, yet wood loses weight and structure with decomposition). An average of 10 years dam persistence has been recorded, but once again there is an enormous variability with dams maintained inter-generationally over 150 years having occurred.

(Rosell and Campbell-Palmer, 2022).

Figure 2. Beaver dam (Photo credit - Grand Teton – Ecohustler)

BEAVER DISTRIBUTION THROUGH HISTORY

Past Range

Castor *fiber* and Castor *canadensis* are the two remaining species of a once varied rodent family. Castor *fiber,* originating from Eurasia, was once found in most freshwater habitats except for some islands (Ireland, Iceland, Corsica, Crete, Balearics, Malta, Sicily, Sardinia), the southernmost parts of Italy, Greece and Asia (also easternmost Asia) and north of the Arctic tundra. C. *canadensis,* instead, roamed Alaska and Canada from below the northern tundra, most of North America, even spilling down to northern Mexico – and into its Gulf. Substantial evidence of beaver meat-eating by prehistoric humans has been documented, with beaver bones showing specific butchery instrument type incisions. The native Americans represented them as spirit totems, whilst offerings of beaver remains to hunter god Artemis was regularly performed by the Etruscans in Italy.

Their numbers globally are thought to have been as high as 400 million in North America before European settlers. Current distribution whether in Europe or North America is nowhere near those previous numbers (1.5 million and 15 million respectively) due to accumulating factors that led to a near extinction episode in the early 1900s via massive over-hunting for fur, pelt and gland goods, as well as growing anthropological pressures on riparian ecosystems, exacerbating habitat loss not only for beavers but all wetland thrivers.

Although they are nearly identical in morphology, having no external differentiating features (and sexually monomorphic), there are just a few minimal body size and skull differences, not enough to conclusively differentiate the two species or genres just by looks and behaviour. This led the scientific community to suppose that C. *fiber* and *canadensis* were sub-species to each other, but not separate species. Major chromosomal differences (48 for C. *fiber* and 40 pairs for C. *canadensis*) have now explained why no inter-breeding has occurred – ever, neither in overlapping territories, nor in captive conditions (although copulatory acts do occur in captivity – unsuccessfully though). The two modern species originated from the palearctic regions 9.5 million years ago, differentiating 7.5 million years ago with the separation of Eurasia and North America, engendering true speciation. There have been attempts to classify beavers into further sub-species due to some mtDNA haplotypes significantly diverging between populations from isolated regions. However, due to the significant and widespread population loss and the subsequent bottleneck effect, at least a quarter of these unique allele combinations were lost, and preliminary reintroductions not taking genetic haplotypes into account promoted the hybridization between once isolated potential sub-species populations.

Present Range

Today, IUCN species Red List classifies beavers as a species of “least concern”. Although not close to reaching previous quota, population numbers and ranges are expected to continue increasing globally (IUCN, 2016), with an annual growth rate of approximately 11% and a range expansion of 550% over about 70 years. The first conservation efforts aimed at maintaining a wild reservoir for fur and other beaver products following the dramatic decline provoked by previous over-hunting. The fur trade was not a negligible aspect of flourishing economies, and in fact several flags, coins and emblems chose the beaver symbol. Where there were beavers there was water, food to use, and fur to trade. More recent efforts - legal and illegal, competent and amatorial - have enabled their return to much of their previous range in Eurasia. South America saw the release of fur trade residual beavers into its Tierra del Fuego. The consequence of their unmanaged spread led to furtherly unmanageable consequences. The arctic is also accommodating more beavers due to the rising temperatures, seeing them disperse to previously inaccessible ice-covered areas.

After their unofficial release, the north-east of Spain has become the southernmost spot Eurasian beavers had been sighted, although one comeback was announced in Tarvisio, Northeastern Italy in 2018, and another in Alto Adige, most probably arriving from the earlier reintroductions in bordering countries (Pontarini et al., 2018). In 2021, a reproducing pair instead was sighted in central Italy, with no evident connection between the two- indicating unauthorised reintroduction as vector (Pucci et al., 2021) and becoming the southernmost area to be reconquered yet.

Greece is currently void of beavers, but reintroduction plans are under study. Until the 1800s and for up to 100 years later, proof of beavers in Syria and Iraq and possibly even Turkey have been signalled. This is not improbable, as beavers’ habitat (although having strong preferences when given a choice), can vary and adapt to the most unpleasant of climates, over time creating mirage-like oasis if given the chance, and enough water to start up the process.

(Rosell and Campbell-Palmer, 2022).

BEAVERS AS AN OPPORTUNITY: ECOLOGICAL ROLE AS A KEYSTONE SPECIES

Beavers tend to engender chaos and diversity where they settle: creating meandering, swampy, mossy water holds; tearing down trees and leaving them right where it's most challenging for humans' sense of aesthetics, but most logical in beaver terms. Dead, fallen trees in waterlogged areas create a life-brooding system that could appear to most tidy landscape designers as resembling a flooded adolescent's bedroom. These entropic pond systems are received by the public with mixed feelings, from support to utter horror. Yet beaver - managed wetlands, whether pleasing to the eye or not, have been proven by countless publications a capable of inducing an overall positive effect on important environmental and economic nodes, generating profit rather than losses when properly understood and preventatively managed. Beavers are amongst the few keystone species: they are ecosystem modifiers and maintainers; beaver dams are degraded habitat's greatest natural asset; and their capacity to change natural features has disproportionate effects on the whole ecosystem. Beavers' label as keystone species derives greatly from the long-term effects that damming induces. Their presence alone provides important elements for both predator and plant conservation, as indicated by native populations' high densities, beavers could've comprised large proportions of predator's diets before humans nearly extirpated them.

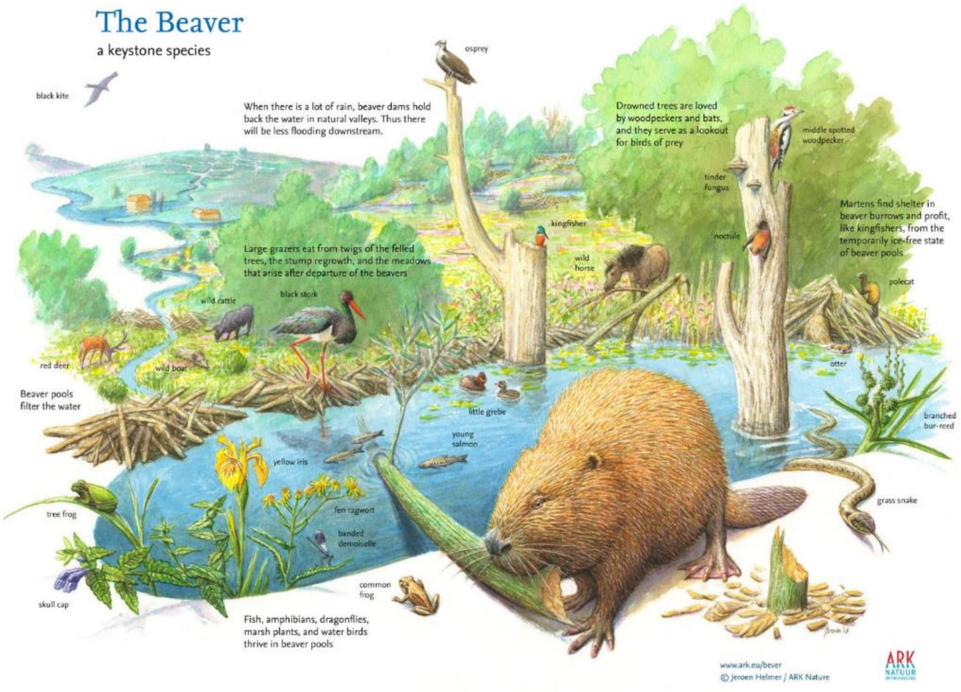

Figure 3. As a keystone species beavers create habitat for many other wildlife species, Jeroen Helmer ('The benefits of the beaver', 2022).

Benefits of building and foraging activities on Biodiversity

Building, digging (burrowing) and foraging activities lead to landscape changes which already in themselves are capable of benefitting many. The felling of trees, provides new canopy openings in which the sun can shine through, benefiting young plants' growth, facilitating amphibians' dispersal and increasing reptile basking opportunities. Freshly fallen trees provide browse that was previously inaccessible to other herbivores, and these fallen trees, piled-up in constructions whilst decaying, are an additional source of shelter and protection for a whole array of species as well as creating ideal overwintering and hibernation spots. Deadwood and sediment accumulation, together with the expansion of the water's reach (through canal digging and foraging patterns), create an alternation of wet, humid and dry ground on which plants can thrive thanks to increased water availability and connectivity.

Benefits to Plants

Plants have adapted alongside beavers for millions of years and have found strategies allowing them to protect themselves from overgrazing, or indirectly profit from beaver's consumption of them. Plant defence mechanisms against beaver predation, is a co-evolutionary strategy demonstrated only by plants endemic to native beaver territory. Numerous plant species considered poisonous for most other vertebrates are well tolerated by beavers, managing to reduce plant toxicity by concentrating the toxins in their urine, with these chemical components being found in castoreum gland exudates.
As co-evolution occurs, beavers develop a retaliatory response to chemical toxins, leaving stems from younger more toxic trees in water for a few days to reduce toxicity. Cottonwood (P. *fremontii)* instead, uses the physical response, correlating metamorphosis with distance from water; where beaver foraging rates are higher, cottonwood grew as a shrub-like plant, reproducing through vegetative form, not growing upright nor reaching reproductive maturity. Aspen and P. *angustifolia* reproduce clones of the felled parent through root buddings at the stump's base, while Poplar and willow invest their energy in new shoot production under heavy attack, utilizing this as a spreading strategy rather than suffering from it. Another spreading mechanism aided by beavers is plant parts dispersal through food cache loss or discarded pieces floating downstream. Beaver grazing on riparian herbaceous plants' amplified species richness by 25%, also promoting the notion that the beaver's absence may further impoverish native landscapes instead of allowing plant species to recover as one would think.

Deadwood Benefits

The increase in deadwood provided through beaver s' felling activities is the biggest benefit brought to land invertebrates, food source, shelter and spawning grounds to many of these species (more than 20 species of beetles for example), as well fish, birds, amphibians, reptiles and small mammals.

Mosses and lichens, indicators of ecosystem health also thrive on decaying matter, along with many fungal species. Foraging activities and increased disturbance indirectly create microhabitats where detritivores proliferate – providing in turn resources for a further array of vital ecological species.

Benefits to Vertebrates

As indicated by native populations' high densities, beavers could've comprised large proportions of predator's diets before humans nearly extirpated them. Adult beavers fall prey mostly to larger predators capable of handling their important weight, claws and jaws. The lynx, the cougar, bears and mostly wolves are all potential adult beaver hunters, but the beavers' prolonged absence in Europe forced predators to adapt and prey on other sources. More recently, beaver parts have been shown to compose up to 36% of a wolf's diet in Eastern Europe (up to 60% in some North American locations), and Poland's wolves seem to feed beavers to their pups three times more than what they eat for themselves. Some highly specialized beaver hunting wolves and a cougar have been observed; they patiently wait, blending into the surroundings until the beaver is on land and its access to water can be cut off. Beaver kits instead fall prey to a wider array of predator species including many raptors, as well as foxes and otters. Beavers also indirectly benefit big and smaller predators by increasing prey availability such as insects, arthropods and other invertebrates such as slugs and mussels, all important food sources for other species such as the vulnerable hedgehog and otter, rare insectivorous birds as well as bats, endangered amphibians and fish. Another interesting contribution has been noted in Nordic water systems and where water freezes-over during the coldest months: their frequent 'disturbing' activities in and out of water bring new air under the icy layer, creating a gap between the ice and underlying waters' surface. Habitat creation and connectivity lead to an overall increase in plant and animal biodiversity. In central Italy, a recent study sighted the European bittern Botaurus stellaris and the endemic water vole Arvicola *italicus*, on dams and lodges frequently, both are of conservation concern. (Viviano et al., 2022)

The Benefits of Dam building

Long-standing dams provide for even more ecological benefits than newer ones. Once stable, the water retained behind the dam slowly disperses to vast areas – slope permitting. In degraded lands dam building may be impossible without support structures to start-off with, or if tree cover is insufficient. However, if they succeed in building one, the positive effects of these newly created ponds can transform arid, leeched and eroded bare land into vibrant habitats that significantly gain in soil quality and biodiversity as time passes, as well as restoring incised streams to previous bed heights (Pollock et al., 2014).

Dam Hydrology Benefits

An actively maintained dam will induce geomorphological and hydrological changes capable of moderating water speed as well as regulating thermal and chemical variations (Pollock et al., 2014). The retention of surface water within the valley or plain spreads this fundamental resource, rendering it available to a larger area, and together with increased debris dispersal in and around the water, contribute to the local nutrient cycle. Dams also act as filters; not only trapping nutrient-rich debris, but also pollutants, which in highly managed grasslands may be an asset (Puttock et al., 2017). The reduction in water speed crossing beaver dammed waterways allows for greater sedimentation rates, and the consequent creation of ponds allows groundwater to seep back into the earth in the process – recharging depleted aquifer reserves. The ponds also prevent heating of underlying groundwater by shielding it, and with increasing water depths, dams can also buffer water temperatures both downstream and upstream, but only if the pond is deep enough. Moreover, their activities allow for persistent discharge and perennial water supply, retaining > 60% water than in their absence even in the hottest months. Providing water year-round for wetland and riparian residents. Just one pair of beavers (released and studied in Devon), in constructing 13 dams on 1.8 ha, held back and helped store ~ 100 tonnes of sediment, ~ 16 tonnes of carbon, and 1 ton of nitrogen. Beaver created meadows participate to up to 23% of carbon sequestering in certain areas and can sequester up to 44 times more nitrogen through sediment deposition.

Figure 4. Beaver pond "(1) with a stick lodge (2). Dams (3) are built to regulate water levels to maintain sufficient depth. A feeding station (4) is visible as a pile of discarded sticks. The extension canal (5) provides access to a riparian area. A beaver burrow (6) can sometimes act as a tunnel to access foraging areas. The wetland (7) contains beaver-felled trees, characterized by the pencil-like shape. Benthic canals (8) are excavated in the bed of the waterbody. A beaver slide is also visible (9). By creating canals beavers can spend less time on land when accessing foraging areas, limiting risk of predation (10). The final canal type shown is a connector canal (11) which joins two previously isolated areas". (Illustration of Oskar Lacy Corral). (Rosell and Campbell-Palmer, 2022).

Dam Benefits to Biodiversity: Plants, Invertebrates and Vertebrates

Wetlands cover less than 1% of the globe, yet in that small amount, houses more than 10% of the planet's biodiversity. In Scotland, 12 years after beavers' return, plant species richness and heterogeneity increased by 46% and 71% respectively. A species capable of modifying the habitats composition is considered a keystone species – if performing this in its endemic ecological range. The same effects are not seen in Chile for example, where the beaver is non-native, and plants never evolved coping mechanisms to deal with the beaver's ravenous exploitation. Considered as inhospitable and unusable land, millions of hectares of wetland ecosystem were drained, sanitized or isolated during human expansion's booming years, with over 60% total wetland lost in some regions. Many species currently considered as endangered may depend on wetland's rich and abundant biota as food sources. The disappearance of such habitats may provide an ulterior explanation to the high vulnerability statuses amongst wetland-influenced and resident species.

Deciduous trees have been shown to tolerate transitory periods of flooding better compared to coniferous species, which may offer an advantage to deciduous forests' regeneration. Flooding was shown to be the most impactful element of beaver activities on biodiversity. Ponds with beavers, having generally higher disturbance rates, promote more diversity than ponds without them. They are capable of changing riparian plant compositions through the variating water levels, as well as felling and grazing activities that allow light to penetrate both land and water differently. This, combined with higher nutrient availability promotes algal bloom and aquatic plant growth which in turn are food sources to others. Globally, beaver presence promotes landscape and species heterogeneity as well as spread and survival thanks to additional and stable water regimes and increased local disturbance levels, both in water and on land.

Reduced water flow, increased leaf, debris as well as deadwood availability stimulate invertebrate species abundance and diversity – positively affecting freshwater sessile (non-motile shells) and benthic community members (motile riverbed inhabitants) upstream of dams. These benthic macroinvertebrates serve as water quality indicators. Zooplankton also increased due to higher nutrient levels, whilst aquatic invertebrate emergence rates were more than 200 times higher. these in turn, falling prey to other terrestrial invertebrate species engender a positive cascade effect, also proven by the consequent abundance of predatory invertebrates on beaver colonized riverine banks.

Fish welfare relating to dam building have engendered a lot of controversy and a difference must be made between lotic (high flow speed) and lentic (slow, standing) aquatic environments. The highest concern is for Salmon, and other migratory species of economic or ecological value, believing that dams impede fish' upstream travelling, hindering their reproduction and thus reducing population numbers. However, recent findings indicate that beavers' dams, contrary to most human-made ones, enable the passage through side openings – allowing bigger and fit fish to migrate unhindered, and the greater connectivity between water holdings actually improves their migration. Debris accumulated for dam or other beaver buildings' also increase safety and stability, allowing for ideal spawning location for the eggs, and improving chances of fertilization thanks to the slower water movements. As strict water inhabitants, water quality directly affects fish – so its improvement and the decrease of floating sediment indirectly benefits them through the improvement of habitat quality, most of all for lentic species. Food diversity and abundance increases thanks to the varied elements added to the water (beaver faeces included), providing nutrients and substrates for fish and their prey to thrive on. Beavers are pivotal to amphibian abundance in headwater streams, which compose up to 80% of all temperate water bodies in Europe. Otters, another wetland inhabitant that most probably co-evolved with beaver constructions. In fact, holes made by these animals in dams, and use of beaver lodgings indicates easy coexistence (at least from the otter's point of view).

Not only aquatic and semi-aquatic species, but droughts and wildfires endanger every species and by retaining water for longer, and retaining other chemical substances in the process, beaver ponds act as refuge spots for all seeking it. During fire threats, beaver ponds do not lose biodiversity and stay green (Fairfax and Whittle, 2020). Beaver ponds even reduce tap water risks for human settlements downstream of wildfire episodes through the greater retention of solutes, their sedimentation and their slow transformation by the pond's residents into less noxious molecules (K. Roth et al., 2022). By staying green and storing water, their role in combating desertification may yet to be discovered as an ulterior asset to be employed as mitigation strategy (Norman et al., 2022).

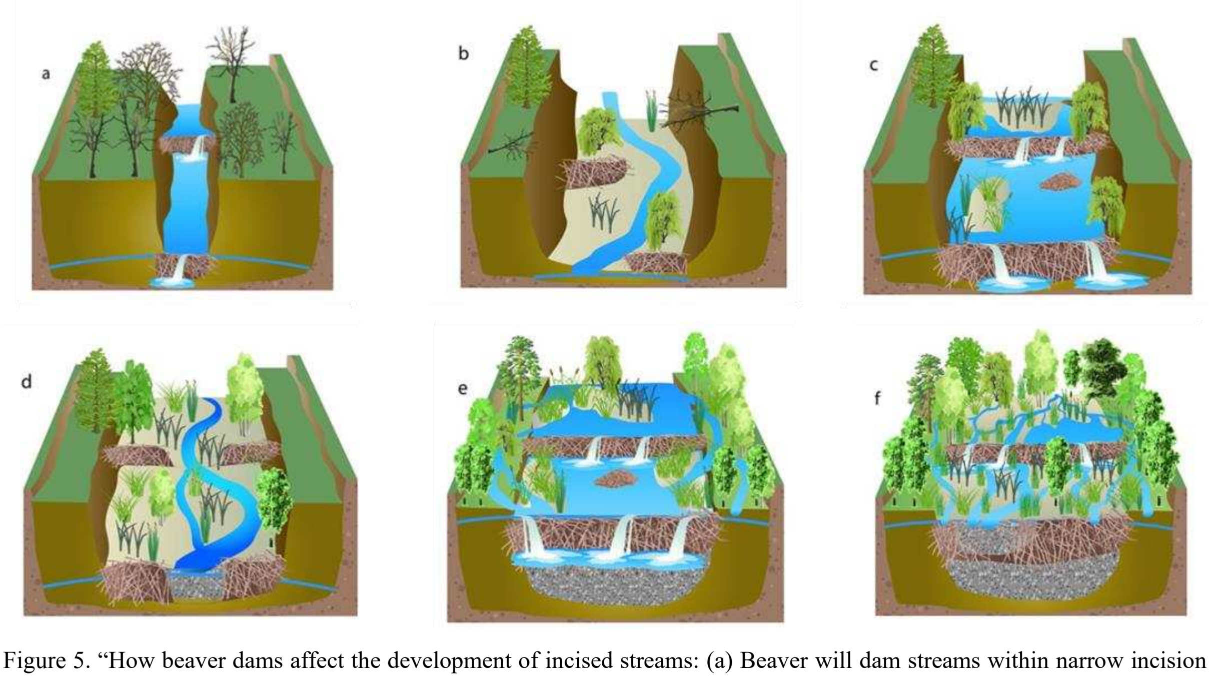

Figure 5. "How beaver dams affect the development of incised streams: (a) Beaver will dam streams within narrow incision trenches during low flows, but stream power is often too high, which results in blowouts or end cuts that (b) help widen the incision trench, which allows an inset floodplain to form. (c) The widened incision trench results in lower stream power,

which enables beaver to build wider, more stable dams. (d) Because streams that have recently incised often have high sediment loads, the beaver ponds rapidly fill up with sediment and are temporarily abandoned, but the accumulated sediment provides good establishment sites for riparian vegetation. This process repeats itself until (e) the beaver dams raise the water table sufficiently to reconnect the stream to its former floodplain. Eventually, (f) vegetation and sediment fill the ponds, and the stream ecosystem develops a high level of complexity as beaver dams, live vegetation, and dead wood slow the flow of water and raise groundwater levels such that multithread channels are formed, often connected to off-channel wetlands such that the entire valley bottom is saturated" (Pollock et al., 2014).

(Rosell and Campbell-Palmer, 2022).

Further Cross-Dimensional Benefits

On 25 September 2015, the 193 countries of the UN General Assembly adopted the 2030 Development Agenda titled "*Transforming our world: the 2030 Agenda for Sustainable Development.*" The agenda is structured around 17 globally agreed development goals, called the **Sustainable Development Goals** (**SDGs**), with the aim of securing "peace and prosperity for people and the planet, now and into the future." Some SDGs set specific targets to deal with important ecological challenges that are relevant in the context of the present dissertation: SDG 6 (Clean water and sanitation); SDG 13 (Climate action) and SDG 15 (Life on land) most of all, but also indirectly aiding goal 14 (life below water) and goal 17 (partnerships for the goals).

More specifically, regarding SDG Goal 6 (Clean water and sanitation) states how:

- "Demand for water is rising owing to rapid population growth, urbanization and increasing water needs from agriculture, industry, and energy sectors.
- The demand for water has outpaced population growth, and half the world's population is already experiencing severe water scarcity at least one month a year. Water scarcity is projected to increase with the rise of global temperatures as a result of climate change.
- […] protection and restoration of water- related ecosystems; among the steps necessary to ensure universal access to safe and affordable drinking water for all by 2030, … ." (SDGs, 2015).

Access to water being important for the survival and well-being of the majority of living species and is included in the basic rights for animal welfare. Freedoms as stated by the world organization for animal health are Freedom from hunger, malnutrition and thirst; Freedom from fear and distress; Freedom from heat stress or physical discomfort; Freedom from pain, injury and disease; Freedom to express normal behaviour (WOAH, 2023). A species capable of creating water-logged areas that stay green year-round, thus providing water for an array of local resident species, could and should be highlighted as fundamental in the pursuit of both human and animal basic welfare needs. Furthermore, beavers' innate capacity to filter and nourish fresh water, as well as regulate its flow and extreme floods through the construction of dams, make beavers an ecological asset in the face of current climatic and water crisis escalations. Beavers' dams are already being mimicked by humans in several areas to revitalize degraded waterways in the absence of beaver resident populations. They have been cited in the works and proceedings of the UN Convention for Combating Desertification (UNCCD, 2013) as a promising natural strategy, a nature – based solution that could effectively contribute to resilience strategies. Beavers can also be a viable strategic option to reach the new "Global Framework for Managing Nature", adopted by the CBD – Convention for Biological Diversity - aiming to stem and reverse ecological destruction of Earth (CBD, 2022); as well as contributing to reach SDGs 13 and 15:

Goal 13 (Climate Action):

- "With a climate cataclysm looming, the pace and scale of current climate action plans are wholly insufficient to effectively tackle climate change. Increasingly frequent and intense extreme weather events are already impacting every region on Earth. Rising temperatures will escalate these hazards further, posing grave risks." (SDGs, 2015).

Goal 15 (Life on land):

"Conserving life on land to protect and restore terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation and stop biodiversity loss. In particular:

- […] The world is facing a triple crisis of climate change, pollution and biodiversity loss.
- […] We need to shift humanity's relationship with nature to achieve Goal 15 and realise that nature is the root of our life of earth.
- […] Globally, one fifth of the Earth's land area are degraded, an area nearly the size of India and the Russian Federation combined. Land degradation drive species to extinction and intensifies climate change, biodiversity and the ecosystem services it underpins can also be the basis for climate change adaptation and disaster risk reduction strategies as they can deliver benefits that will increase the resilience of people. " (SDGs, 2015).

Mitigation strategies that enable beavers to establish in their previous ranges, while mitigating and anticipating conflict risks, are imperative for their keystone abilities to manifest on surroundings. Now more than ever, their landscape and water engineering capacities seem worth the management challenges they might procure.

Figure 6. (SDGs, 2015)

BEAVERS AS A CHALLENGE: MAIN ISSUES RELATED TO BEAVERS' REINTRODUCTION AND PRESENCE

Negative Impacts of Building and Foraging Activities

Foraging Modifications to Plant and Animal Composition

The felling of mature trees of ecological importance may pose a problem, due to increased light penetration through the canopy, and certain trees rarely being found in mature forms anymore. This is a problem when other conservation efforts might've been trying to restore rare and co-dependent lichens and mosses with specific upward growing tree forms of a certain age. Beavers' herbivorous diet also competes with other herbivores for common preferred food sources. The combined, non-controlled grazing of several species on newly sprouted saplings, for example, significantly reduces sapling's chances of surviving to recruitment age.

The quantity of forage beavers alone consume annually remains impressive, with an estimated consumption of 1 hectare of deciduous-covered land annually for a family of 6. There are also qualitative impacts to be considered, such as the removal or destruction of resident species prior to beaver presence, and the removal of prime shelter and nesting spots through foraging activities.

Living and Foraging Near Human Settlements

The flexibility of the beaver's diet makes it capable of profiting from a wide range of crops and ornamental trees. This may directly affect income for local crop producers as well as change the aesthetics of urban designed landscapes. Their interference with human landscapes and designs are seldom welcome by humans in urban contexts, and given the chance, beavers may spread quickly on water courses, even within areas of high human density. In addition, depleted amounts of riparian tree roots and increased canopy openings may respectively permit higher rates of bank erosion, water evaporation, and temperatures, which can all in turn be further exacerbated by increased algal blooms, overgrazing and other burrowing species' presence. On banks occupied by humans or transportational routes, bank collapse may pose a severe risk.

Seasonal aggression (with the presence of kits) increases the likelihood of unfortunate encounters between pets and territorial beavers, negatively impacting local population views of this species.

Negative Impacts of Damming

The return of beavers to unoccupied areas may initially decrease numbers of resident species during the extensive landscape modifications and consequent drowning. with regard to fish migration, young individuals are hindered in dam upstream passage attempts. Methane emissions is also accelerated with this initial rise in decay due to beaver's initial impounding efforts (Whitfield et al., 2015).

The expansion of the water's reach may further increase local leaching activities and eutrophication of water basins. Exacerbated near intensive agriculture and urban activities, fertilizer or toxic chemicals, together with heavy metals such as cadmium have been detected in larger concentrations in beaver-maintained ponds compared to other water sources (although water downstream is improved) with direct and indirect toxic consequences for local biodiversity and leisure activities such as fishing.

Road culverts (man-made tunnels channelling water flow) under certain width and water depth conditions, do encourage damming by beavers, resulting in flooding of roads, crops or human settlements. Abandonment of dams is also a main flooding concern as large quantities of water and debris are released from the unkempt structures with consequences downstream most of all for human settlements and road infrastructure. In a survey involving 52 countries, beaver management implementations and repair costs were on average of 2.5 million USDs annually.

Further Cross-Dimensional Negative Impacts

Beaver's wet habitat creation may be vector for invasive alien species of both plants and animals that also profit from enriched wetland systems to thrive, reducing local biodiversity through competitive advantages in certain instances. This may conflict with alien species' eradication efforts.

Beavers may also themselves be vectors for diseases, although incidents of cross-contamination between species don't indicate major concerns in comparison to others. They may act as ulterior vectors for final hosts through their semi-aquatic lifestyle that allows eased dispersal (slug-vectored parasites for example). Studies suggest beaver activity causes enough water disturbance to diminish the breeding of air-borne vectors of disease, laying eggs in stagnant waters such as mosquitoes compared to abandoned beaver impounding's (Northeast Massachusetts Mosquito Control and Wetlands Management District, 2024).

(Rosell and Campbell-Palmer, 2022).

DISCUSSING ADAPTIVE MANAGEMENT STRATEGIES THAT MITIGATE CONFLICT

Active Beaver Population Management for Conflict Mitigation

Where Beavers are already established or actively colonizing, conflicts may be greater. Conflicts due to beaver disturbances depend on length of time elapsed since the beavers' return to the area as well as territory stability. Certain countries undertook beaver reintroduction promptly – meaning beavers have been back and stabilized locally over the last 100 years. Except for the rare, overpopulated areas, most beaver-caused damage happens due to most recent beavers' returns, disrupting years of beaver-free adaptations to fit their needs. Refining early detection techniques and response is the first step in ensuring proper current and future population management.

Signs of Beaver Presence and Active Territories

As a mostly nocturnal rodent, signs of a beaver's activity may be easier to observe than the individual itself. Information about beavers' territorial preferences also provides important management inputs. Freshwater spots and details of its routes should be mapped out, as these are prime areas for beavers. In areas of high densities or in poor habitats, beavers are also able to adapt to unfavourable locations and therefore may be found in unpredictable areas. The combination of different techniques such as aerial assessments and physical surveys allows the collection of both preliminary range information about beaver territory, as well as more precise population data through field observations, ensuring best population estimates. From the sky, the period that predisposes to best visibility of beaver activities is during the fall, when trees have shed their foliage and before standing water freezes over. Geographical information system programs capturing territorial data attached through a drone, and sending back high-resolution imagery of beaver land is the most non-invasive and highly trustworthy method for active territory spotting. 3D modelling may also have a role to play in beaver landscape modification previews.

Fresh teeth marks on trees and cut stems as well as de-barked branches indicate recent foraging activity, which is lighter in colour than older felling marks. Trails, canals and digging activity also provides cues and the difference between active and inactive foraging areas and can be spotted from soil disturbance on plant cover. Another useful tool is smell: castoreum has a particular scent and familiarizing with it may be useful before population censuses are performed. Last but not least, the detection of faeces near the water's edge provides a further cue on beavers' presence and proximity.

Figure 7. Beaver Signs, ('Living with beavers', 2023)

Family Composition and Sampling

The count of individuals within one family, is performed preferentially around the end of August and throughout Autumn, when beaver land and bank activities are at peak. Several invasive techniques exist that provide exact data: dead-trapping removes a whole family whilst providing exact family data; live-trapping with the "mark and release" method can also be used, although it has been shown that beavers learn from others and avoid traps a family member has returned from; finally, the least invasive - but most time consuming - consists of night-time observation and head count, although this can be performed only in small lakes and ponds, where one observation point provides enough visibility to ensure all animals are seen exiting and entering (not the case for most rivers and big lakes). Tail scars are one of the only usable elements given enough visibility, to discern different individuals within a same family.

From both an ethical and an animal well-being perspective, dead and live trapping are problematic. Dead trapping may be an optimal tool for the combination of lethal control and population census, and it may also provide a faster solution than mismanaged live-trapping. Live-trappings present challenges: beavers, although resistant to cold water effects, if left too long in semi-aquatic trap locations may enter hypothermia; young kittens may not last more than 4 hours in cold wet water, so this should be taken into consideration in difficultly accessible areas as it may become a welfare concern for the trapped animal awaiting sampling; family stability is also affected by live – trapping, as there have been instances where the trapped members do not return home upon release but rather disperses elsewhere for reasons still unknown; litter size and reproduction also initially diminish before beavers become habituated to handling. Family data is not the most necessary tool to efficiently managing beavers, knowing where active territories lie is more informative for less time consumption and welfare concerns.

Hair trapping can procure good samples, including the underfur layer and in 70% of cases even a guard hair, giving invaluable information through DNA analysis such as species (Eurasian or North American) and sex of the individual. In case of recent colonization, this method provides a less invasive approach to dead and live trapping, or when hair stuck in foraging brambles (Pucci et al., 2021) or from carcasses is not available to differentiate the specimen, always a good first step before deciding what to do next (for example if it is a North American specimen found in Europe, the management plan would be different) (Rosell and Campbell-Palmer, 2022), When DNA is not needed or to spot typical trails, routines and territory boundaries as well as get an idea less time consuming than in the night-time physical observation studies, camera trapping remains the most useful tool at hand. (Pucci et al., 2021).

Halt Foraging Activities on Key Vegetation

Key factors in determining the most appropriate techniques to protect vegetation from beavers' destruction include cost – effectiveness, labour intensity, personal preferences and aesthetics, proximity to beavers' population and potential for scaled – up application.

Studies tend to demonstrate that crop loss due to beaver damage is relatively low or negligible when compared to other impacting factors. Deterrents such as human scents or scaring devices don't last long, beavers quickly habituate to low threat cues. Edibles treated with casein hydrolysate, egg or blood traces are generally avoided by beavers, and those treated fiercely with a predator's scent. For important trees and other species of great interest, or around plots already present too near to beaver territory, double electric fences are required at 15 and 40 cm minimal and maximal heigh from ground level. Among the most financially viable along with commercial anti-herbivore sprays, dissuasive game paint seems to work well by rendering trees unappetising. Aesthetically, paint is also the least invasive to landscape design, which is often considered important in urban areas. Although it may not be suitable for older, rugged lumpy tree stands, it is a fast solution with low labour intensity and good applicability to smooth trees medium sized trees in active conflict areas.

Figure 8. (a) Tree protection through wire mesh (b) Fencing (ie. Exclusion zones) (c) Tree painting deterrence *Beaver Management (2021).*

In areas already highly populated by beavers, the outcome of their presence has been shown to depend strongly on the presence and quantity of both food sources, and competition from other large herbivores. Beavers are generalists though they have preferences, and other generalists competing for all the same vegetation if overdone, may exacerbate habitat degradation and induce biodiversity loss instead of gain. In such areas, the management of domestic grazers with total or seasonal restrictions to riparian areas allows plants the time to recuperate, unless the land is too depleted already.

Managing Land and Bank Damages

Repair might be needed in zones with high erosion rates, sandy or rootless banks. Immediate handling of bank collapse should be undertaken to avoid further water modifications with new access to the crumbled side. Managing grazers, whether domestic or wild, is essential to reaping most benefits out of beaver return instead of them becoming an additional nuisance to local ecological stability.

Since burrows can be deep and have multiple underwater entrances, they are difficult to detect. Bank monitoring, ensuring riparian health and repairing collapsed parts is the simplest way to tackle this hindrance provoked by beavers. Collapsed beaver burrows can be infilled with different substrates such as rocks and soil and stabilized to avoid further problems. If beavers remain in the area, probability of damage remains high where bank collapse has happened before.

Managing Inappropriate Damming and Excessive Flooding

Light beaver foraging on crops may be accepted more by local residents than the effects of flooding. The greatest problems arise from the damming in agricultural and urban areas as well as transportational routes – with road culverts being a beaver's favourite to start damming on. Dam removal does not seem to be an appropriate mitigation strategy and should be advised against, as it will only promote dam repair and re-building (can be completed in one day), unless persistent disturbance is provided to cause relocation of the whole family group. Seasonality is important too and with kits in lodges, removing dams during reproductive phases could cruelly determine the youngest's' fates.

Felling will also increase both with dam removal, and previously felled tree removal, so it is important that freshly felled trees are left in place when possible (finding a compromise between human and beaver aesthetics criteria). Dam manipulation is rather advised if the local population is to be maintained on site and not eradicated. Drainage/deception pipes to limit water increase like a sink's drain hole and is a good solution for when beavers are already actively flooding an area, although it could take some time before the system is installed. Notching (vertical opening of dams to allow water outflow) can be used as a quick budget friendly alternative, but it is a temporary solution as beavers will quickly reconstruct. Flow devices act the same and are permanent safety systems, they need to be protected by metal mesh, and their diameter needs to be enough as to allow necessary outflow. Too low, and the water basin will drain itself.

Figure 9. (a) Dam notching (b) Flow devices (c) Culvert protection. Beaver Management (2021).

Road culverts and road ditches covered with a simple mesh protection but should be frequently checked on and cleaned to prevent natural debris accumulation which may promote beaver damming instinct onto the protective mesh. Dam removal, artificial dredging (deepening), family translocation, and lethal removal are also options to those facing flooding consequences of damming. Although maintenance of beaver colonized waterways may be costly and time consuming, it will eventually cost less and be more efficient than the other curative dam-damage control methods listed above. The addition of gravel-like substrate to road ditches works well as a preventative strategy and may be implemented as to avoid future reoccurrences

Fish migration during the spawning period can be helped through repetitive notching of dams. Literature tends to demonstrate that beaver dams do not hinder mature fish migration, on the contrary, promote optimal spawning grounds by slowing the water down. Several consecutive dams reduce the water level differences up and downstream from each dam, also promoting fish passage by reducing obstacle height. Human built dam analogues (BDA's), stimulate beaver damming behaviour so can also be used here, to influence beaver's location choice for damming, and increase the number of dams constructed in a single area. This technique could lower single dam water levels, increasing flood resilience by decreasing water velocity and thus also reducing chances of dam failure. (Rosell and Campbell-Palmer, 2022). NIDS, similar anthropologic structures with the same functions have proven efficient too (Norman et al., 2022).

Coexistence With Humans and Between Species

Beavers' return has already been documented in urban settings too: they can now be found even on London's River Thames. Most conflict arises in areas of high human density or in agricultural land, where competition for space and food sources increase and must be dealt with promptly.

Health hazard to humans and pets is not a matter of significant concern at present. Beavers in poor health conditions can be seen by unkempt, matted clumps instead of bright homogeneous pelage. In case of dietary restrictions and habitat limitations, dental overgrowths of the two incisor pairs are possible, indicating improper nutrition. Parasite and toxic accumulations may be found in the liver and kidney, also a good indicator of health status. Body condition score references exist for beavers.
Being crepuscular/nocturnal, beavers' encounter probabilities are low. The period most likely to lead to unpleasant encounters is during the breeding season when territoriality is at its peak, and where pets and beaver territories overlap. Once again, buffer wetland zones can function as a safeguard against unfortunate encounters, whilst also increasing habitat availability.

Population Control

Yellowstone reserve is a great example for wolf and beavers' keystone and symbiotic role in the regeneration of natural parks. Although beavers are often omitted as co-protagonists of these efforts, their contributions have been pivotal to the successful outcomes and to the long-term scientific data acquired through the Park's regeneration project. The wolf's presence allowed a modification from a previously elk-dominated riparian grazing to beaver's ones, modifying local plant compositions in the process. The combination of both animals may be responsible for the improved ecological conditions whilst alone, each species might not have had access to enough food to thrive on.

Management of North American and Eurasian beavers differ depending on the country and area. The North American beavers in Europe are considered invasive and therefore dealt with differently than the endemic species. Their ecological role remains identical, their presence may still be beneficial, discouraging lethal eradication plans, but efforts of fertility control may become necessary.

There are many advantages of fertility control for beavers, and one main disadvantage, as it involves capturing of the animals, and since beavers learn what to avoid from family members, the capture of more than one family member decreases the capture chances for the following attempts. Gonadal removal is not advisable either: although successfully sterilizing the animal, hormonal changes impact behaviour and family cohesion. Laparoscopies are less invasive and have better operative and recovery prognostics. Compared to lethal control and eradication plans control techniques, fertility control methods have shown better results than the complete removal of beavers from the territory. This is due to the benefits they bring to local biodiversity and water qualities, and for the fact that vacant territories attract newcomers, eager to settle in the free lodgings. Hunting increased rebound fecundity levels so is also thought to be in fact, a sub-optimal solution, with fertility control, fencing and maintenance of deterrent tools being better suited as population and colonization control methods.

Figure 10. Trapping and transport, Beaver Live Traps, (Taylor J., 2017).

Beaver translocation trials received much study and was first attempted decades ago. Mortality rates were and still are extremely high, and even with current veterinary skills fatalities must be considered and may therefore cause justifiable welfare concerns during translocations. Moving whole families also require the initial trapping of each individual, an extraordinary task with high probability of failure due to trapping learnt avoidance capacities. Until carrying beaver capacity is met, translocation is a valid strategy to move beavers to more convenient areas although site fidelity is very low and empty areas risk being reconquered by dispersers and floaters.

The most important element to consider as to what regulates population growth, is territory availability, with space, food availability and disturbance levels being key determinants. The general rule for beavers to attempt colonization, or chronically return even after eradication, is set when water, habitat and territories remain available and when dispersal routes and wetland zones are fragmented. When sites are successfully managed or even totally blocked and beavers no longer consider these areas as ideal or even sub-optimal places to settle in, only then will population growth rates plateau into stability and auto-regulating numbers. Population growth is therefore territory dependent.

Their classification as *least concern* in the IUCN red list still makes the Eurasian beaver protected across much of its range. (IUCN, 2016). Only specific licensing and derogations allow hunting and killing of this animal, and only in specific seasons (non-reproductive). Most of these are allowed only if no satisfactory alternative is available. Not only are most beavers protected, but any of their constructions are too, as these are part of survival strategies, depending on them to thrive.

Where no other solution, not even predator introduction is deemed possible for population control, euthanasia methods deemed most ethical are body and most of all (difficult) head shots. The animal loses consciousness on the spot, avoiding useless and conscious suffering. Neither drowning, cervical dislocation, thoracic compression and bleeding are considered ethically acceptable ends.

Preventative Conflict – Prevention Strategies

Where beavers are still absent This provides an opportunity for risk – anticipation and preventive management strategies ahead of possible recolonization. Today's biometric tools allow population growth, dispersal and range expansion rates as well as territory location predictions. On a global scale, riparian buffer zones and corridors have been shown to not only help beaver dispersal but all other wetland users as well. On the contrary, fragmented or unavailable habitats induce inappropriate species dispersal, leading beavers to wander into unfavourable human territories.

Distribution and Monitoring

Beaver management should focus primarily on beaver habitat selection and quality, research of general population status for predicting colonisation potential of areas, as well as focusing on potential sources of conflict. New infrastructure in proximity to freshwater sources would be better suited and present less management hassles if a scenario of a possible beaver recolonization is already factored in at the planning stage, with tools such as GIS (geographic information systems) and reproductive rate information proving useful in predicting the beavers' optimal territory range, in defining acceptable and unaccepted beaver territories and connected wetland buffer zones, mimicking the EU "Natura 2000" connectivity project which aimed at restoring and connecting fragmented nature reserves across Europe.Other suitability models such as habitat suitability index (HIS), beaver foraging index (BFI), and beaver dam capacity (BDC) models can help the planning (Graham et al., 2020). High resolution datasets are more readily acquired – enabling planning on larger areas with higher certitude. These models have been tested out successfully in Scotland's extensive beaver restorative field studies.

Defining Compatible and Incompatible Areas for Beaver Colonisation

Enlarging river or culvert size when planning for beaver return and when building new culverts would reduce improper dam incidence and negative flooding consequences. Any freshwater unit that isn't occupied and has at least some plant coverage, may be settled on by beavers, even extreme landscape can serve as temporary homes during dispersal and in highly populated areas. Preferred territories include those containing edible vegetation year-round. Willow, aspen, and enough other young broad-leaved species within 50m of water i.e. Enough deciduous tree cover and hardwood species along the water's edge, is ideal (<6m from bank, up to 400m up and downstream). Bank gradients < 15% are preferred to settle on. Higher bank gradients will definitely require damming, but these will more likely get washed out (up to 36% bank gradients may be dealt with) impacting survival chances. Beavers will first choose areas that don't require damming, then when high population densities mean best territories are occupied, their tastes can adapt to pretty much any hazard. Fine silt soil is preferred over other substrates for burrows and digging, sand and rock should be avoided instead. Locations with high trapping, hunting or even high levels of human disturbances discourage beavers from settling (possibly more so for Eurasian than North American). Urban disturbances seem to deter Eurasian beavers more, being found more often between agricultural areas than in urban ones with low to medium disturbance tolerated.

For damming instead, stream gradients of up to 10% can be dealt with, whilst < 3% is preferred.
Slow to medium moving water > 1 m deep or more, if possible, with course width of > 2 m and no less is optimal for beavers and for conflict control. Areas of annual drought and high levels of water fluctuations are unfavourable to beavers and may require previous human work to render conditions more accommodation to beavers for them to settle.

Preserving Key Vegetation

Land use planning has the potential to reduce conflict in both rural and urban areas by either leaving sufficient buffer zones or creating exclusion zones on important dispersal routes, as habitat connectivity must be considered a priority to avoid population isolation, inbreeding and overpopulation problems. Permanent barriers as well as electric (2400mV) fences delimitating beaver access should always be placed far enough from the protected vegetations to avoid animal attempts at leaning in for a bite with potentially fatal consequences.

For specific tree protection, the same methods employed for active beaver conflict are valid. In addition, with more time and resources at hand, permanent protective structures could be built around trees of ornamental value and in specific sites where tree cover is planned as a permanent feature, or species vulnerability status requires severe protection of rare specimen. Adding and designing useful features such as solid benches around trees in parks, could serve multiple functions of both protecting the trees and augmenting local usage of public spots for leisurely activities. Creative solutions have suggested that instead of focusing on deterrent strategies, planting alternative and preferred plant types such as willow could favour the protection of other more important trees by deviating the beavers' felling efforts. Less preferred species can also work as deterrents close the riverine edges.

Preventive Measures for Land and Bank Management

Bank protection through strengthening, limiting or completely blocking is helpful to decreasing conflict sources. Medium and coarse sized rocks < 40 cm thick is advisable covering banks, with underlying mesh noted within the bank's walls ensures local burrowing activity exclusion. As for land fencing, depth is important as otherwise beavers may dig part the solid walls to reach more diggable substrate. Hardcore long-term coverage of banks is expensive, time consuming and although being extremely efficacious, may not always be preferred over the more naturalistic landscape features. It remains a valid option in urban areas where high sense of aesthetics and human usability of land is primordial. Planting trees is a cheaper yet permanent option too in helping bank regain its stability through root support. In other beaver occupied territories such as rural areas, naturalization, and so the exact opposite method might be more advisable to ensure bank and riparian ecosystem health and stability. Methods that leave banks green, like vertical mesh insertion behind bank frontiers may be preferred as a softer landscape modification, preventing beavers from digging further than accorded limits (where they would damage most).

In degraded areas, limiting overgrazing is a good idea even before beavers' return, as well as preventatively planting trees and reinforcing banks. Knowing soil type, conflict probabilities and sources of the area, as well as reducing risk of collapse are fundamental. The primordial element as always, being the planning for acceptable and unacceptable beaver colonisation spots. Adapting management strategies according to the local goals.

Preventive Damming and Flooding Management

Floods are the biggest inconvenient caused by beaver presence and so extra attention is needed at the planning stage to avoid conflict and growing negative public perception. GIS programs may help construct current and future beaver ranges, defining wetland area, or conflict risk. Where damming is desired, right bank features, water speed and food availability need to be provided and reintegrated in the landscape before beavers' return. Instead, where beaver dams are not deemed viable, dredging may be performed as a preventative measure to increase water depth and thus reduce damming instinct in beavers. This however has questionable ecological impacts for the benthic layers of waterbeds and should be performed before a beaver dam is established, or after having destroyed the previous one. Less pleasing to the eye, are buoys or other tactically suspended objects placed on top of ideal damming locations, acting as a dissuader. By moving unpredictably, and not allowing for debris accumulation because of its unstable structural support, buoys can prevent dam building.

Preventive Infrastructural design and planning, focusing on catchment and floodplain distribution and seasonal data variations, optimal flood mitigation strategies can be implemented, prioritizing high-risk areas and deciding on exclusion zones. In this way and with enough time at hand, wetland connectivity and buffer zones can be planned out and ideated, and their proximity to exclusion zones calculated. Eastern European countries have had beavers back for longer than most European regions. Trial and error over generations has led to management plans that could be used as skeleton for even more strategic and ethical management strategies in light of most recent scientific knowledge on beavers. As was the case for foraging activities, agricultural land should be planned out, and if too close to flood land, beaver exclusion or better, proper crop choice according to water tolerance and beaver palatability might be even more shrewd than totally preventing their presence (which is difficult and time consuming). In general, crops too close to freshwater streams and tributaries should receive most strict management, subventions for biological farming methods might be of value with or without beavers present to prevent excessive leeching and eutrophication of water sources. Buffer zones are an important tool, that in many places could be seen as an asset for wildlife tourism opportunities. Where possible, wetland habitats, their proximity to rural and urban activities as well as the probability that beavers return, should all be considered for conflict avoidance but also optimal land use in light of stringent environmental and biodiversity objectives.

Population management and Exclusion Zones

Longevity of territories is a key limiting factor of population size, as temporary residents with smaller ranges and sub-optimal territories do have higher impacts on the environment. Sterilizing the breeding couple or the whole family but allowing them to remain in situ, will allow the same pair to hold the territory but without actively reproducing and the population will not expand. In areas with excessive beavers' presence, one stable family is more indicated than continuous removal.

Where no beavers are desired, through preventive planning, exclusion zones can be planned for and constructed using appropriate long-term infrastructure. Exclusion zones often reflect major conflict hot points, so their prevention allows for a big chunk of beaver problematics to be dealt with by excluding their colonisation and or first removing current residents.

Invasive Species Control

Preventive management works much better in some instances, for example invasive alien species, many of which thrive in beaver's presence, are recommended to be dealt with before the beavers return. Whether plant or animal, although complicated, efforts will be useless and consequences much worse. This is one of the key issues that remain hard to manage even in the absence of beavers but should be timely dealt with to avoid serious biodiversity modifications from spreading further.

Further studies are needed to assess the nutria's presence in contemporary with the beaver, current efforts to control this invasive species already encounter time and collaboration obstacles, whether beavers hinder these efforts or help is yet to be confirmed. However, the river otter (Lutra lutra) has been displacing the invasive Mink by competing for similar niches but with a major size advantage. Beavers help otters by providing appropriate environments and may thus help IAS control. Recent studies seem indicate the beaver's presence modifies coypu's activity pattern, preferring to be active earlier – before the beavers started their later nocturnal activities. Appearing sooner in the evening could help management of this species. (Mori et al., 2022)

North American beavers in Europe, although not an optimal presence, do still bring benefits to ecosystems by performing the same ecological modifications as Eurasians would, so eradication might not be the appropriate answer. Fertility control and slow phase-out might be better, allowing the beavers to live out their days, whilst contributing to the ecological regenerative processes.

South America saw the release of fur trade residual North American beavers into its Patagonian wilderness. The consequence of their unmanaged spread led to a furtherly unmanageable situation, with stresses to the non-adapted local vegetation, and impossibly high budgets for eradication (between $26 and $30million in project cost estimates). With the arctic ice melting, plans should be made to limit beaver expansion further. They benefit endemic wetland ecosystems, but Arctic Alaska never cohabitated with beavers, evolved differently and does not need beavers to regenerate, rather on the contrary – beavers working as anti-freezers of standing water hinder arctic conditions and would exacerbate climate change actions here. (Tape et al., 2022)

Reintroduction

Before beavers are released, whether from a captive source or translocated animals, there are some main aspects to keep in mind. The main are habitat availability (enough water and food), and local community census. As any threatened creature would do, upon release beavers tend to disperse - rarely remaining near the release site if they are not constrained to. This means beaver releases are not local initiatives only but involve whole catchments. Unless beavers are tagged for remote monitoring, it is impossible to predict anything apart from a higher probability of them dispersing downstream. Where individuals will end up precisely, whether a pair will remain together, and maximal distance of dispersal are all hard to determine and depend on many local variables in water regime, land status and connectivity. Water depth of >1m is ideal except if damming activity is tolerated in the area, in which case raising water levels may be left to the beavers to do.

Many degraded areas will need initial BDA's and other human interventions such as tree planting and protection from grazers for up to five years before it is suitable to sustain a beaver family. Endemic tree and plant types that profit from beaver presence and help bank integrity should be privileged, and areas containing invasive alien species although not a direct issue for beavers (apart from common diseases), promote IAS growth and dispersal. Land connectivity has been shown to be primordial too in permitting the population to function properly.

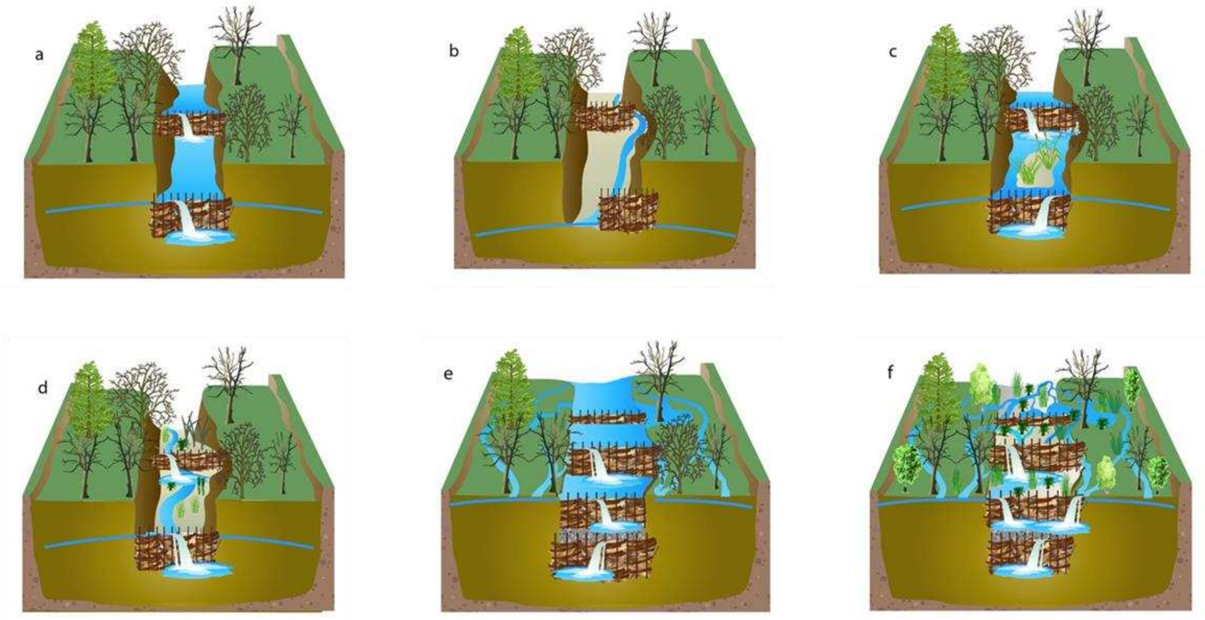

Figure 11. "Sequence of observed stream ecosystem changes when beaver dam analogues (BDAs) are used to aggrade a stream. BDAs mimic many functions of beaver dams but can be placed where they will most benefit streambed aggradation and at higher densities than those typical of natural beaver dams. Their key advantage over beaver dams is that they are structurally sound enough to be used in narrow incision trenches and have less potential for failure once ponds are formed. This can substantially lower the time required for floodplain reconnection, because the volume of fill needed is lower in narrower trenches. Where sediment supplies are abundant, high BDA densities can rapidly reconnect streams to their former floodplains." (Bouwes et al., 2016).

Communication to Mitigate Conflict

The acceptance of beavers' presence by local population is a significant determining factor for this species. Public opinion on the matter has been evolving in an uneven manner: in some areas, human – beaver conflicts may lead to more intense hunting, in others it may trigger over-protection claims. In general, there is a growing consensus on the use of non-lethal control methods and on the need to ensure animal well-being. Further studies for beaver population sampling should be undertaken to improve welfare standards matching local expectations. Assembling information from the public on human - beaver conflicts also help spot most common issues, aiding in the setup of preventative measures that can be put in place to avoid future damages.

Beavers' popular perception may favour their return in some instances. Whilst other species are perceived as pests and associated to the spread of disease, beavers are an emblematic species in popular perception. This may aid their conservation and the dialogue in urban conflict zones. In Agricultural conflict areas instead, communication can help in a different way and that is by managing to convey beaver's importance to land richness and fertility, as well as stabilizing water reserves and trapping pollutants, all useful factors in production profitable outcomes.

Sharing knowledge on both their conservation status as well as their species' characteristics can lead to better local comprehension of their needs and increased tolerance for most beaver - induced disasters, and more tailored management strategies. Hunters' education on beavers' behaviour and biology is also crucial: knowing both their conservation status and why lethal control does not work on may trigger more responsible hunting practices. Zones of high conflict potential only results in a vicious cycle of continuous pursuit or critical population decline. Even with adequate communication and public information, beavers' chances in highly conflictual areas are slim, with reintroductions in such areas better avoided. Habitat availability and management are preferred options over numbers' control, focusing on behaviour, territory knowledge and science – driven solutions.

Communication and public information are non-negligible tools and can modify - if not change - both conservation and reintroduction programmes by first changing opinions and spreading knowledge.

(Rosell and Campbell-Palmer, 2022).

Figure 12. Recovery sequence of an incised stream ecosystem over a 20-year period. In 1993, (a) the stream was open to annual summer grazing by cattle. After 1999, (b) grazing was limited to cow–calf pairs during spring and fall. By 2012, (c) beaver had established a persistent colony for several years. The size of riparian vegetation had substantially increased, and vegetation now extended across the entire width of the incision trench, because beaver dams had elevated the water table.

CONCLUSIONS ON BEAVER RETURN AND CONFLICT MITIGATION

All wild species, including beavers, rely on functioning habitats to secure flourishing lives. Yet, humans control most of the terrestrial and marine ecosystems, with significant impact on all forms of life. Human population has spread out into formerly animal territories, reducing their vital space and food supply sources. And human activity is also central to an acceleration of changes in climate patterns, causing habitat damage, rapid transformations, droughts, floods, fires and famine. The return of a species like the beaver into now human – dominated territories requires active stewardship, finding solutions that are respectful of what the animal needs in order to live as "itself".

Management strategies can now successfully rely on precise scientific data. Their use has proven to help deal with beavers' hindrances both in case of active population management, and when planning preventative strategies. Beavers could, and possibly should, be considered in climate action and resilience plans by local authorities and decision-makers: their dams and canals can hold up to 60% more water in peak summers (Hood, 2012), and their flow attenuation capacities resist even in significant storms (Westbrook et al., 2020). Compared to the flooding risks they may cause, if well managed, beavers' gradual return could be of greater benefit than harm to most European biota, including humans. As many other rodents, if left untended, beavers can affect entire human settlements, major transportational routes, and unsettle construction foundations. Beavers' management consists of mitigating or avoiding predictable damage and maximizing potential benefits.

Ensuring habitat connectivity when reintroducing beavers, as well as territory availability are also primordial, considering that beavers hold their territories from one generation to another and that one stable family unit near an urban area or other conflict hotspot, might be more indicative than a vacant territory with regular digging, fighting and remodelling of newly acquired spaces. In this respect, when assessing control techniques, the lethal population control option carries negative consequences, as reproductive rates surge during predation (rebound phase), creating more kits in problematic areas. Curative management is less efficient and leads to increased conflict incidence, with last minute reduced aesthetic solutions, dangerous damage, high repair costs, and negativized public opinion. Integrating beavers' presence in urban design is therefore possible and at times beneficial,

Ethical stewardship of this species is a key factor if Castor *fiber's* capabilities (for instance, in climate change adaptation strategies) are to be protected and proactively used. Conversely, reactive, post – facto control interventions can only encourage illegal, unplanned reintroductions. Illegally introduced beavers are increasingly detected around Europe and they should be managed, studied and tested before further management plans are made (Serva et al., 2023). Billions are spent annually worldwide on river restorations, and efforts could be made to use beavers' landscape engineering capabilities to provide more viable, cost-effective solutions to halt land degradation and effectively conduct restoration initiatives (Law et al., 2017), (Gorczyca et al., 2018).

Science – based, data – driven, ethically - inspired planning is a key to govern the return of the beaver, particularly in areas of high human presence or activity. The ethical aspect is paramount to consolidate viable management practices which should end the reliance on instruments that violate wild animal life, health and bodily integrity; or cause unnecessary animal deaths and suffering, even when not intended. With the consensus of local communities, a successful beavers' management project will not only protect their natural habitats but also will also create tangible benefits in reconstituting degraded habitats, increase resilience to climate change and environmental degradation, benefitting all stakeholders impacted by climate change, around wetlands and riparian zones.

Figure 13. Aerial photograph of a beaver pond and lodge during fall. Photo credit: Thomas D. Gable. (Johnson-Bice et al., 2020)

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