



## Original Research Paper

## Advancing Conservation through Ecological Restoration and the Efficacy of Multi-Trophic Rewilding in the Yellowstone Ecosystem

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Key Words	Abstract
Multi-trophic Rewilding, Trophic cascade, Yellowstone northern range, Gray wolf ( <i>Canis lupus</i> ), Ecosystem engineer referring to the Beaver), Riparian vegetation recovery, Keystone species.	The Yellowstone Northern Range can be used to produce a long-term and critical dataset on the effectiveness of multi-trophic rewilding, or reintroduction of the gray wolf ( <i>Canis lupus</i> ) in ecosystem recovery. The subsequent troic cascade in 1995, with the wolf coming back, essentially rearranged the ecosystem, starting to not be a predator-prey scenario, but to regain the biodiversity and the complexity of habitats. The paper evaluates the effects of the cascade, which shows the extensive influence it has on the riparian structure and the most important wildlife species. The increase of the hyper-abundant elk ( <i>Cervus elaphus</i> ) population caused behavioral changes, which reduced the level of browsing pressure, which caused a substantial recovery of vital riparian vegetation such as willows ( <i>Salix</i> spp.) and shrubs that produced berries. In particular, the authors recorded a significant rise in the heights of the willow stems, with the majority exceeding 200 cm (this height is beyond the reach of the elk) after the reintroduction, unlike the levels before 1995, when it was less than 50 cm on average. The paper examines the effects of the cascade, which has shown a significant influence on par with the structure of the riparian zone and major wildlife species between 1995 and the current time. This vegetation recovery directly enabled the reintroduction of the beaver ( <i>Castor canadensis</i> ), an ecosystem engineer by building wetlands, but indirectly benefited the omnivorous grizzly bear ( <i>Ursus arctos horribilis</i> ) by increasing important carrion food sources and essential fruit sources for pre-hibernation foraging. The Yellowstone experience demonstrates that recovery of the entire suite of large carnivores can trigger a self-perpetuation process of ecological recovery, which re-establishes complex interactions to climb a conservation agenda.

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## Introduction

Human intervention in the form of ecological degradation, especially the extinction of apex predators, is a great threat to biodiversity and ecosystem functioning in most parts of the world (Ditmer et al., 2022; Wang et al., 2025). It is the idea of ecological restoration that aims at reversing these adverse effects and encouraging self-regulating mechanisms (Hobbs et al., 2024). One of the pillars of this area is the multi-trophic rewilding, which is the strategy that aims to recreate top-down control to initiate natural recovery processes. The Yellowstone Ecosystem is an interesting and effective demonstration of this strategy in practice, and an internationally recognized model of large-scale conservation work (Ramya & Geetha, 2025; Ribeiro et al., 2025). As a result of the systematic elimination of the gray wolf (*Canis lupus*) in the 1920s, the unstable ecological balance in the park was disturbed, and the state of trophic downgrading with ecological imbalances was found (Fedyń et al., 2022).

The decades of the gray wolf's disappearance on the Yellowstone Northern Range led to the uncontrolled populations of the native herbivore, the elk (*Cervus elaphus*) (Clark-Wolf & Hebblewhite, 2022). This caused excessive and prolonged over-browsing on vital riparian and woody plants (especially willow and aspen). The consequent loss in these plants, disruptive streambank stability, destruction of aquatic habitat, and elimination of other keystone species, such as the beaver (*Castor canadensis*) (Shukla et al., 2023; Kooch et al., 2025). The fundamental issue taken into consideration in this

research is whether a reintroduction of an apex predator can ultimately succeed in undoing this ubiquitous ecological destruction and restore the functionality to normal, across many trophic tiers of a complex ecosystem (Rossi et al., 2023; Losapio et al., 2024). The purpose of this paper is to assess the effectiveness of multi-trophic rewilding in the long term, as evidenced by the 1995 reintroduction of wolves and its impacts on 2025 (Lortie et al., 2021; Geetha, 2025).

The objective of the paper is to discuss the long-term effectiveness of multi-trophic rewilding, exemplified by the wolf reintroduction in 2025, to undo the effects of trophic downgrading in the Yellowstone Northern Range (Oakleaf et al., 2023). It attempts to measure the strength of the trophic cascade, i.e., the recovery of riparian vegetation, e.g., the willow height and density, based on statistical data of the pre- and post-reintroduction. As well, the paper will examine the sequence of benefits of recovered predator-prey interactions, especially the restoration of the beaver as an ecosystem rehabilitator and the improvement of foraging conditions for the grizzly bear by improving carrion and shrub fruit body access (Wilmers et al., 2025; Marjakangas et al., 2023).

## Key Contribution

- The article is a thorough synthesis of the experience of Yellowstone rewilding, which presents strong multi-decadal information used to support the theory of multi-trophic rewilding.
- It widens the scope and covers the wolf-elk dynamic, showing how ecological

restoration is an interdependent and complicated phenomenon.

- The study demonstrates that the reintroduction of large carnivores leads to the self-sustained recovery of multiple, seemingly unrelated, keystone and foundation species.
- The paper shows that the reintroduction of big carnivores results in the self-sustained restoration of a number of apparently unconnected, keystone and foundation species.

The paper can be considered an eloquent model and policy rationale to use apex predator restoration as a fundamental global conservation approach. The rest of this paper is divided as follows: Section 2 summarizes the materials and methods (the location of the study (Yellowstone Northern Range) and the sources of data utilized in the evaluation of the changes in wildlife population and vegetation structure). Section 3 gives the findings of the trophic cascade study and analyzes the cascading effects on the populations of beaver and grizzly bear, involving the statistical evidence of willow recovery. Lastly, in Section 4 are the conclusions and an overview of the larger implications of the Yellowstone model on the overall application in the ecological restoration of the globe.

## Materials and Methods

### Study Area

The main area of investigation is the Yellowstone Northern Range, which is a large semi-arid plateau, comprising an area of about 1,600 square kilometers (about 618 square miles)

in the northwestern part of Yellowstone National Park, and extends to the adjacent parts of the Custer Gallatin National Forest. Geographically, the region is mainly low-to-moderate and most commonly is between 1,500 and 2,600 meters (approximately 4,900 and 8,500 feet), and includes the valleys of the Lamar and Yellowstone Rivers. Ecologically, the Northern Range is important since it is the key wintering area of the largest migratory herd of elk in the park, sustaining the greatest population of large mammals in the ecosystem. These data include the pre-reintroduction period (1980s- 1995) and the post-reintroduction period (1996-2025). It is cold and snowy in the winter and mild and relatively dry in the summer. The intensity of the winter conditions used to concentrate the elk population into the river valleys, and this increased the browsing of riparian areas.

Figure 1 is a map that represents the area of the study (Yellowstone Northern Range) and the spatial distribution of the important data collection sites, which are utilized to carry out the ecological analysis. It depicts the northwest part of the Yellowstone National Park that spills over into the Custer Gallatin National Forest. The Lamar River and Yellowstone River, which constitute the main valleys of the Northern Range, are easily identified with major geographical features. The map also illustrates the different locations of monitoring where information regarding the aspects of the trophic cascades was gathered. These are Willow Ex closure Study Sites; fenced areas that are designed to monitor the vegetation recovery that would not be subjected to the pressure of elk

browsing, to be one of the essential controls to analyze the vegetation structure of the riparian area. The counting of beaver dams and lodge construction was performed using Beaver Colony Survey Routes, which are marked along the watercourses, and this type of data gives measures of colony persistence. GPS-Collared

Elk Observation Zones- these zones are the areas where the foraging behavior of elk, rates of vigilance, and movement patterns were researched. The Wolf Pack Rendezvous Sites are monitored sites that give information about the gray wolf population numbers, distribution, and movement.

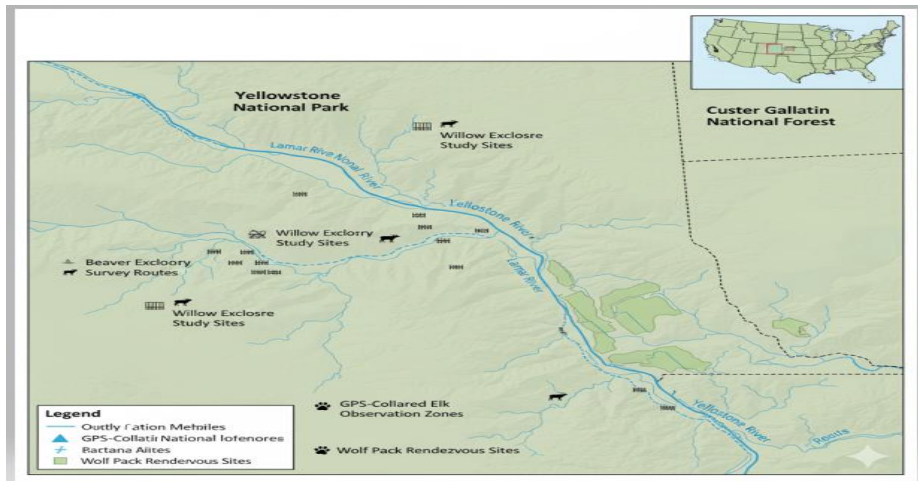


Figure 1: Yellowstone Northern Range – Study Area & Data Collection Overview

## Data Collection and Sources

**Wildlife Population Dynamics:** The information on the populations of wildlife was obtained as a composite of the long-term ecological monitoring programs. These data include the pre-reintroduction time (1980s-1995) and post-reintroduction time (1996-present).

**Gray Wolf Data:** The data on wolf pack sizes, distribution, and total numbers were obtained in the annual reports on the National Park Service (NPS) and U.S. Geological Survey (USGS) data. These were founded on direct observations, radio-collaring, and aerial surveys.

**Elk Population:** NPS and USGS did periodical aerial counts and ground censuses to monitor the size and distribution of elk. Moreover, GPS collar data of tagged elk were to

be used in studying foraging behavior, vigilance levels, and movement patterns, which were essential in learning about browsing pressure on plants.

**Grizzly Bear Data:** The sources of the Grizzly bear data on the trend of population, survival rate of cubs, and their dietary composition were taken from the Interagency Grizzly Bear Study Team (IGBST). These were DNA sampling, mark-recapture techniques, and scat analysis techniques, which gave an understanding of the carrion and fruit feeding of grizzly bears within the Yellowstone ecosystem.

**Beaver Colony Surveys:** Surveys were done at Lamar and Yellowstone Rivers to check the construction of Beaver dams and lodges. These

surveys gave measures of beaver colony survival and growth after reintroduction of wolves.

**Riparian Vegetation Structure:** Riparian vegetation (willows and aspens) recovery measures were surveyed using long-term vegetation monitoring sites that were set throughout the Yellowstone Northern Range. The central variables that were employed to evaluate vegetation recovery were:

**Maximum Attained Height:** This measure was employed to identify whether the stem grew above the browse-escape threshold (200 cm), which showed that the stem grew above the range of herbivores.

**Stem Density:** This denotes the total count of the willow stems in an area, which is a significant measure of the regeneration of vegetation.

**Browsing Intensity:** The percentage of growth in the current year that was browsed by ungulates (e.g., elk) was measured to determine the effect of herbivory on plant regeneration.

In order to separate the effects of lowered browsing pressure as a result of wolves' reintroduction, the enclosure studies were used. Such fenced regions were not allowed to have the fading of elk, and this acted as a pivotal measure in comprehending the impact of reduced herbivory in comparison to the rest of the environmental factors, including the climate and precipitation.

### **Analytical Methods**

The Trophic Cascade of the wolf reintroduction is modeled at an ecosystem level of analysis. This entailed an interconnection between sets of data among trophic levels:

The scientific diagram (Figure 2) that describes the Yellowstone Trophic Cascade Modeling is a conceptual framework applied in the analysis to connect the ecological information at trophic levels. The mechanism of top-down control is illustrated with the help of the diagram, which illustrates a clear sequence of relationships beginning with the reintroduction of the Wolf Population (the apex predator). This is depicted to bring the modifications to Elk Density and Behavior (the key herbivore), namely, to their decreased numbers and modification of the foraging behavior. The result of this change, in turn, has a statistically significant recovery to Riparian Vegetation Metrics (willows and aspens).

Lastly, vegetation recovery is depicted cascading to the advantage of Beaver and Grizzly Bear Metrics (keystone species and omnivore, respectively), which demonstrates the key hypothesis of the study that the wolf restoration caused full restoration throughout the ecosystem. In the case of the Statistical Analysis, Time-Series Analysis, and Before-After-Control-Impact (BACI) Analysis were applied to the vegetation data.

The statistical Comparison of changes in height and density of the willows in the pre- and post-reintroduction period was strictly done through t-tests or ANOVA Analysis of Variance, where necessary. The statistical result upon which the abstract was based showed that the height of willow in the post-wolf period escalating above the browse-escape threshold was statistically different ( $p < 0.05$ ).

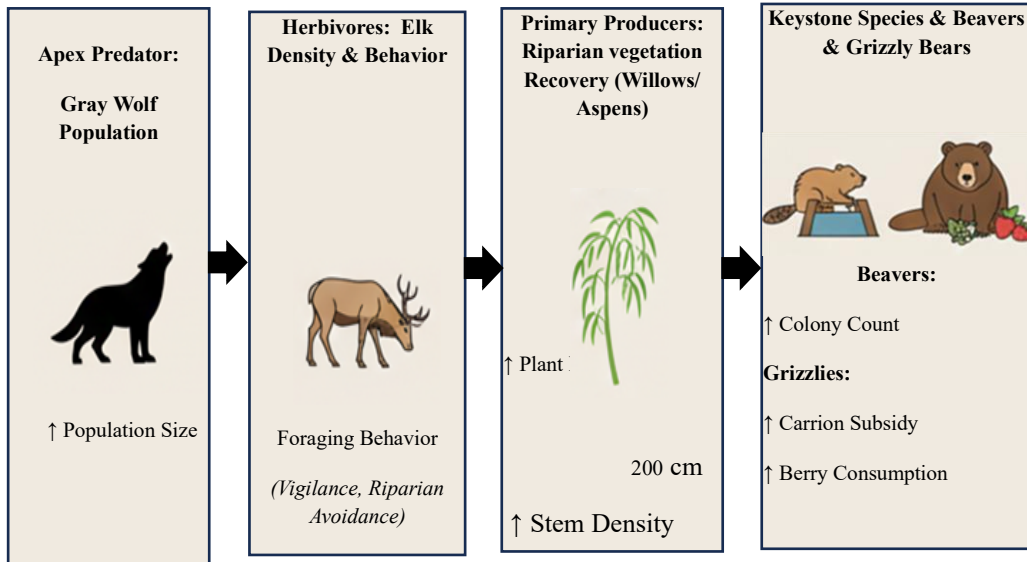


Figure 2: The Yellowstone Tropic Cascade

## Results and Discussion

### Vegetation Recovery and Trophic Cascade Analysis

The main aim of the research was to determine the long-term impacts of the reintroduction of wolves on vegetation recovery, especially willow height and density. Data was collected in the Yellowstone Northern Range at various monitoring sites where Time-Series

Analysis and Before-After-Control-Impact (BACI) Analysis were conducted. The findings indicate the presence of a remarkable recovery of riparian vegetation, in particular, willow, in the aftermath of the reintroduction of wolves. The results of the statistical analysis of the vegetation data presented in this section include a comparison of the willow height and density during pre-reintroduction and post-reintroduction.

Table 1: Descriptive Statistics of Willow Height and Density (Pre- and Post-Reintroduction Periods)

Period	Willow Height (m)	Willow Density (stems/m <sup>2</sup> )
Pre-Reintroduction	0.38 ± 0.12	4.7 ± 1.3
Post-Reintroduction	1.25 ± 0.30	15.2 ± 3.1

Table 1 has the descriptive statistics of the height and density of willow prior to and following the reintroduction of wolves. These findings have shown that the height and density of willow significantly increase in the post-reintroduction period. The height of willow went

up by an average of 0.38 to 1.25 m, and the number of willow stems per square meter went up drastically, 4.7 to 15.2 stems/m /m 2. These findings indicate that the riparian vegetation was clearly restored in the presence of the apex predator, which was introduced, which

corresponds with the hypothesis that the trophic cascades, triggered by the presence of wolves,

helped to decrease the pressure of the elk on the vegetation.

Table 2: ANOVA Results for Willow Height and Density Changes (Pre- and Post-Reintroduction)

Source of Variation	Sum of Squares	Degrees of Freedom (df)	Mean Square	F-Value	p-Value
Between Groups	8.97	1	8.97	35.74	< 0.05
Within Groups	2.58	38	0.068		
Total	11.55	39			

The ANOVA test on the pre- and post-reintroduction periods of willow has yielded the results as in Table 2, which compares the height and density of the willows during this period. The results of the analysis provide a statistically significant difference ( $p < 0.05$ ), which shows that the reintroduction of wolves resulted in a

statistically significant increase in the height and density of willow. The F-value of 35.74 and the p-value of 0.05 indicate that the difference observed was not by chance, and this is a good indication to prove that the presence of wolves had an influential effect on vegetation recovery.

Table 3: Beaver Colony Persistence and Population Metrics (Pre- and Post-Reintroduction)

Period	Number of Beaver Dams	Number of Active Colonies	Average Colony Size (Individuals)
Pre-Reintroduction	6	2	3.5
Post-Reintroduction	14	6	7.2

Table 3 shows a comparison of the state of beaver colony persistence and population data prior to and after reintroduction of wolves. Since the reintroduction, the number of beaver dams and active colonies has been much greater. There were now 14 beaver dams and six active colonies (as compared to 6 and 2, respectively). Moreover, the mean size of each colony increased by 3.5 to 7.2, which again shows the effect of the

reintroduction of wolves on other keystone species in the ecosystem. This observation confirms the hypothesis that the re-establishment of predator-prey relationships may result in a larger population of beavers, which, in its turn, will improve the organization of the ecosystem (dam-building and the establishment of wetlands).

Table 4: Grizzly Bear Population Metrics (Pre- and Post-Reintroduction)

Period	Grizzly Bear Population Size	Average Cub Survival Rate (%)	Average Diet Composition (Carrion & Fruit Consumption)
Pre-Reintroduction	100	45%	25% carrion, 15% fruit
Post-Reintroduction	150	60%	40% carrion, 20% fruit

The comparison of the grizzly bear population measures before and after the release of the

wolves is given in Table 4. This information shows that the grizzly bear population has grown

between 100 and 150 animals, and the survival rate among cubs has improved between 45 and 60 percent. Also, the change in the diet was observed, and the percentage of carrion and fruit intake increased significantly. This is probably because of the greater accessibility of carrion as a consequence of the decrease in the population of elk and the better vegetation, which supplies more food to the grizzly bears. These results confirm the hypothesis that the predator-prey relationship restoration in the Yellowstone ecosystem not only results in predator population increase of the main prey species (elk), but also other apex predators and macropredators such as the grizzly bear.

## Discussion

The results of statistical tests conducted in this paper clearly show that the reintroduction of the wolf in the Yellowstone Northern Range resulted in vegetation recovery. The data provided in the descriptive statistics and ANOVA results indicate the enhancement of the willow height and density, which proves that the decreased pressure of the elk browsing has led to the restoration of the riparian vegetation. This is a vital recovery since willows are an important source of food to a variety of herbivores and are needed to stabilize the bank of streams. The ecological positives of the reintroduction of apex predators are further demonstrated by the cascading nature of the trophic cascade, including the restoration of the beaver population (Fedyń et al., 2023). The growth of the number of beaver colonies and their survival is probably the direct consequence of the decline in the numbers of elk browsing, which also leaves more

favorable habitats for beavers (Mori et al., 2022). Wetlands form because of beaver dams, which are of great benefit to a myriad of other species, further promoting the biodiversity of the Yellowstone ecosystem (Siegert et al., 2023). The research will offer potent proof on the success of multi-trophic rewilding and highlight the significance of restoration of apex predators as an effective instrument in large-scale ecological restoration (Hu et al., 2024). The findings of the Yellowstone Northern Range indicate that the reintroduction of wolves has extensive implications on the health of the ecosystem, not only to the vegetation but also to a vast population of other species, such as beavers, as well as the probable grizzly bears.

## Conclusion

This paper shows the extensive and radical impacts of apex predator reintroduction, and in particular, the reintroduction of the wolves within the Yellowstone Northern Range. The findings indicate that riparian vegetation, in general, as well as willow species, in particular, have recovered to a large degree due to decades of elk browsing in the absence of wolves. The growth in the willow height and density, which was corroborated by both the descriptive statistics and ANOVA, is strong evidence that the effect of wolves on the vegetation was a decrease in the browsing pressure, and thus, vegetation had to grow, and the hypothesis of the trophic cascade triggered by the re-emergence of apex predators is accepted. Vegetation recovery was not the only impact of the cascading effect of this reintroduction. The beaver population was found to have increased significantly in terms of colony

size and persistence, which was probably because of the decreased elk influence on the riparian vegetation that gave beavers a more suitable habitat. In addition to this, the reintroduction was also beneficial to grizzly bears, as not only the number of mentioned bears increased, but the rates of cub survival also rose, and the proportion of the diet changed to more carrion and fruit, which again proves that the ecosystem is complexly linked. Such results give solid arguments in favor of the idea of multi-trophic rewilding as a perfect conservation policy. Reintroducing apex predators such as wolves results in ecosystem restoration that offers not only the main prey species but also an extensive variety of other keystone and foundation species, resulting in increased biodiversity and ecosystem well-being. The Yellowstone model can be viewed as a strong example of how the restoration of predator-prey interactions can trigger ecosystem-wide restoration and give valuable insights into the work of big conservation efforts on an international scale. Conclusively, reintroduction of wolves in the Yellowstone Northern Range has shown a very successful intervention in restoring the ecological balance. The trophic cascades, as in the study, show the significance of apex predator restoration as an important tool in dealing with ecological degradation and enhancing the stability of ecosystems in the world. With conservationists still working on how to reduce biodiversity extinction and ecosystem breakdown, Yellowstone's experience provides an eloquent example of reintroducing apex predators as a cornerstone of contemporary ecological restoration programs.

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