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Productivity, Adaptability, and Reproduction of Yaks Under Adverse Climate Change Scenario

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Abstract

Yak (*Bos grunniens*) is a very important animal for the people who make their living through animal herding in the hilly areas since it is a source of milk, meat, fiber, and draught power. But climate change poses a major risk to yaks due to changes to their immediate environment, heat, poor quality feed, and diseases that might arise from global warming. This review is primarily based on the performance and fecundity of yaks under different climate change stresses and addresses different challenges that predispose the yaks, including high temperatures, poor grazing land, incidence of diseases, among others, and how these impact performance and fertility. Further, the genetic predisposition to coping with such harsh environments of yaks, especially in terms of thermos regulation genes, disease resistance and metabolic efficiency are explained along with ways on how resilience of yaks may be improved, which includes traditional and modern management practices like selection, range management, improved animal health and management and water resources management. Moreover, potential climate change adaptation measures such as the restoration of pastures and improved construction of shelters hardy to climate change can be taken by the community. Its implementation seeks the survival of yaks as well as to enhance the welfare of local communities that depend on yaks. Combining more traditional views of managing natural resources with recent scientific developments, and developing policies that are easy to adjust, yaks can be protected despite continuing issues of climate change.

Introduction

The Yak (*Bos grunniens*) is an important species that inhabits the higher altitudes of the country in the form of the Himalayan, Karakorum, and Hindu Kush mountains. These animals have evolved perfectly to survive in some of the finest conditions anywhere, and are usually found at altitudes ranging from 3,000 to 5,000 meters, where the temperatures can plummet to freezing for weeks on end [1]. Yaks are well-adaptable animals and have been able to adapt to life in the most extreme conditions, including low temperatures, increased altitude, little oxygen availability, and lack of vegetation coverage. Their skin is well covered with thick woolly coats, and the general body built of the animals allows them to endure harsh weather. Further, they also have well-developed cardiovascular systems as a result of living in high-altitude areas; they are best suited to manage the threatened resources that are available within these regions [2]. Yak occupies an important socio-economic status and acts as a major source of income to subsidize local people inhabiting the mountainous area in Gilgit Baltistan, Pakistan, and provides many useful products. From such animals, people get their milk, which is a necessary product that is usually turned into butter, cheese, yogurt, etc. It is an important source of protein for residents of those regions where the animals are hunted or marketed. Besides, the products of yak wool, such as Yak wool clothing and Yak wool blankets, are necessary for herders against cold and other extreme climates, as well as a commercial benefit in regional markets [3]. Moreover, yaks serve as draft animals and are used in carrying goods in areas where it is almost impossible for other animals to traverse. This capability provides proof of their function as economic support to a lot of the highland communities through facilitating trade as well as obtaining important supplies. The multiple functions and values of the yak are much more valuable for the improvement of the socioeconomic conditions of indigenous people [4].

The ecological importance of yaks is significant and multifaceted. Being herbivores, they serve the bodies with important roles of providing and maintaining good health of the high-altitude biodiversity through their practices of pastoralism. Yaks help to ensure the preservation of grassland ecosystems because they move through different grades of altitudes and eat different types of vegetation; moreover, they become carriers of plant seeds. But where not well controlled, overgrazing poses a considerable danger to these highly sensitive environments. As such, yaks have the capacity for what can be beneficial or risky based on the handling of the grazing of the yaks [5].

The yak also holds significant cultural value for the pastoral communities in northern Pakistan. This bond between humans and yaks has developed over centuries, with herders cultivating a wealth of traditional knowledge on managing these animals in harsh environmental conditions. Practices such as seasonal migrations, rotational grazing, and selective breeding are integral to indigenous methods that have enabled yak herding to thrive alongside nature for generations. In these regions, yaks are often honored during local festivals, embodying qualities of strength, endurance, and resilience that reflect the spirit of the communities themselves [6]. In recent years, the significance of the yak has become even more pronounced as climate change begins to disrupt traditional pastoral livelihoods. Yaks, traditionally seen as resilient animals, are now facing new challenges brought on by changing weather patterns, shrinking grazing areas, and unpredictable seasonal shifts. Their continued survival and productivity are critical not only to the ecological balance of high-altitude pastures but also to the food security and economic stability of the people who depend on them.

Climate change acts as a major factor in destabilizing the ecosystem by raising the temperature in high altitudes, seasonal and climate changes (extreme hot and cold weather), and natural disasters (floods by melting of glaciers, and landsliding) which result in food security for both animals and local village population on high altitudes. Changes in climate affect yaks' production and reproduction. Climate changes affect the grazing behavior of yak, as in extremely low temperatures, vegetation is not possible, which will lead to the starvation of yak and will ultimately affect its production quality, adaptability, health, and reproductive efficiency. This reduced production of milk, meat, and wool will affect the local population in such an extreme climate [7]. This review aims to explore how yaks can produce (milk, meat, and leather), adapt to harsh climates, and reproduce under adverse climate change scenarios.

Performance and Adaptation of Yak Under Climate Change

Effect of temperature

One of the most direct effects of climate change on yaks is increased heat stress. Yaks are adapted to cold environments with sub-zero temperatures, and their thick coats, robust bodies, and slow metabolism make them vulnerable to heat. As temperatures rise in their native high-altitude habitats, yaks struggle to cope with warmer conditions. Higher temperatures can lead to reduced feed intake, lower milk production, and general lethargy, affecting their overall health and productivity. Prolonged heat stress also weakens the immune system, making yaks more susceptible to diseases and infections that were previously not prevalent at such altitudes [8]. As yaks are primarily adapted to cold environments, in some cases, the temperature might decrease further below -40^{o}C during winter, which will also affect the yak.

Heat stress

Yaks adapt to heat stress conditions at lower altitudes on summer days. Their adaptations to deal with occasional heat stress are more behavioral than physiological. In warmer conditions, yaks often search for shaded areas and rest during the hottest parts of the day. This behavior minimizes exposure to direct sunlight and helps regulate their body temperature. Also, like other cattle, yaks pant and sweat to cool down when they become overheated. However, their limited ability to cope with heat stress is a vulnerability that restricts them to colder, high-altitude regions for most of the year [9].

Cold stress

Yaks are remarkably well-adapted to the severe cold conditions of high-altitude environments. Their physical and physiological adaptations to cold stress include thick, woolly coats, fat reserves, reduced peripheral blood flow, efficient metabolism, and a low surface-to-volume ratio. Yaks have an exceptionally dense undercoat of fine wool beneath an outer layer of long, coarse hair. This double-layered coat provides excellent insulation against freezing temperatures by trapping body heat and preventing cold air from reaching the skin. Moreover, during the warmer months, yaks build up significant fat reserves, which they metabolize for energy during the winter when food is scarce. These fat stores not only provide energy but also serve as insulation to protect against cold stress [10]. In extremely cold environments, yaks can reduce blood flow to their extremities (such as legs and ears) to conserve heat in the body's core, preventing heat loss. Yaks also have relatively short legs, small ears, and a stocky body, reducing their surface area relative to their volume. This physical structure minimizes heat loss to the environment. Along with that, yaks have a slow and highly efficient metabolism, which reduces the amount of heat lost through respiration and allows them to conserve energy in cold environments. Unlike other cattle species, yaks are less active in winter, conserving energy and heat by reducing their movements [11].

Shrinking grazing lands and poor forage quality

Another impact, which has been attributed to climate change, includes the limitation of the efficiency of grazing areas. In the Himalayas, Karakoram, and Hindu Kush ranges, climate change has caused the imbalance of snow and rainfall patterns, reduced snowfall, and erratic rainfalls. This has effects on the growth of tall grasses and other plants found at the high-altitude plains on which yaks feed. As pastures shrink or become degraded, yaks experience nutritional stress, which can affect their growth, milk production, and reproductive success. In some arid and semi-arid regions, desertification rates and soil erosion are rising, which has only decreased the limited available range for grazing. This makes herders take their yaks to other cattle or overgraze the remaining resources, making the cycle of destruction continue [12]. Different species of flora and fauna that are found in rocky, snowy regions have little to eat due to the cold weather prevalent in such regions during winter. Because yaks have to feed on dried shrubs, coarse grasses, and similar types of feed available on the Tibetan plateau, they have better digestive tracts to cope with tough feed. The rumen, one of their complex digestive systems, has some specific microorganisms adapted to ferment fibrous plants and derive nutrients from scarce dietary food items [13]. Yaks are adept at grazing in harsh terrains and can use their strong hooves to dig through snow in search of buried grasses. These animals have large flat feet to enable them to walk long distances in search of food as well as not to get stuck in the snow. Yaks have a base metabolic rate that is not so high which implies yaks need less feed compared to some other related cattle. This adaptation assists in them pulling through during most probable food shortages. Additionally, yaks, acting like cold country animals, gain weight during the months of summer and autumn when fodder is easily available, and they draw on these during winter because there is very limited vegetation available for feeding. This is so important for storing fats for such vital functions as providing energy and regulating body temperatures during cold periods [6].

Increased vulnerability to diseases and adaptation

With temperatures rising and weather increasingly unpredictable, yaks have been left exposed to

Table 1 Candidate genes underlying selection signatures of yak adaptation to high altitudes [18].

Candidate genes	Functions	References
Camk2b, Gcnt3, Hsd17b12, Whsc1, Glul	High utilization of nutrients at higher altitudes	[19]
HIF1A, MMP3, ADAM17, ARG2	Adaptation to high altitudes	[19]
DEXI, DCC, MRP4	High-altitude environment adaptation	[20]
PDE4D, RPS6KA6, ITPR1, GNAO1	Adaptability to a high-altitude cold environment	[21]
EPAS1	Oxygen-regulated gene expression activators	[22]
ABCG8, COL4A1, LOC102287650, PDCD1, NUP210	High-altitude cold environment adaptation	[23]
VEGF-A	Regulation of blood vessel size regulation	[24]
MMP3	Regulator of the cellular response to hypoxia	[25]
HIF-1α	Transcription of genes involved in oxygen homeostasis	[26]
AQP4	Cerebral edema resistance	[27]
ATP8, ATP6	Mitochondrial ATPase assembly	[28]
DCC, GSTCD, MRPS28, MOGAT2	Adaptation to high-altitude environments	[29]
MT-ND1 and MT-ND2	Electron transport chain of oxidative phosphorylation	[30]
GRIK4, IFNLR1, LOC102275985, GRHL3, LOC102275713	Physiological regulation under a hypoxic environment	[31]

diseases. Warmer temperatures mean that parasites and deadly diseases are normally confined to lower. altitudes could spread shooting deaths. Warmer temperatures are causing parasite endemic among yaks to spread to higher-altitude regions, which were previously still free last snow climate change. With the climate warming faster than in other places, yaks are facing all sorts of new diseases that their immune systems are not adapted to. Disease outbreaks can be associated with high mortality rates, which may increase the vulnerability of yak populations [14]. Yaks have evolved resilience to some diseases and parasites that are common in high-altitude environments, but they are susceptible to others when exposed to lower altitudes or warmer climates. The colder high-altitude climate usually had few warm-dwelling parasites and pathogens. Thus, yaks have fewer problems with parasitic infestations, such as those caused by ticks and flies, than do cattle. For example, yaks are particularly affected when moved to lower altitudes where they have more exposure to parasites and infectious diseases that they have not evolved to survive. In such circumstances, the herders have to medicate their animals [15].

Altered seasonal patterns and adaptation

Changing seasonality due to a warming climate is the other sign of disruption at the frontline. To keep the yak strong and the health of the pasture, seasonal migration or rotational grazing is important. Unseasonal meteorological patterns, such as the melting of glaciers or late winters, affect these migratory activities, which can make yaks sexually inactive. Climate events like warmer winters or rainfall out of season also cause disturbances in reproductive cycles, hence lower conception rates, problems in calf survival, and the reduction of the fertility of the herd. Further, the stress from environmental changes can lessen reproductive success more due to lower sexual activity and sperm quality in male yaks [16]. In response to the seasonal variations in high-altitude environments, yaks show specific behavioral adaptations. Yaks are usually herded to the lowlands during the winter to reduce the effects of the season and also to look for pastures. This cyclic movement of people is characteristic of historical and still existing nomadic animal breeding in Asia. Yaks go back to the highlands during the period when there are plenty of pastures in the region. As for predators, their activity is also low during winter because yaks slow down their energy expenditure in their bodies naturally during this season. By moving less, they save energy, especially when the food competition is high, thus surviving through harsh weather [17].

Role of Genetics in Adaptation

The genetic makeup of yaks plays a critical role in their ability to tolerate extreme environmental stresses such as cold temperatures, low oxygen (hypoxia), and nutritional scarcity. Over millennia, natural selection has shaped the yak genome, allowing these animals to thrive in the challenging, high-altitude environments of the Himalayas, Tibetan Plateau, and other mountainous regions [18]. Understanding the role of genes in stress tolerance can provide insights into how yaks have adapted to such harsh conditions and how they might continue to adapt in the face of climate change. The function of some identified candidate genes, along with their functions, are mentioned in Table 1.

Mitigation Strategies

Mitigating the effects of climate change on the Himalayan yak requires a combination of adaptive management practices, technological innovations, and policy interventions. The goal is to reduce the vulnerability of yak populations to climate-induced stressors such as heat, disease, and pasture degradation while supporting the livelihoods of herders [32]. Some potential proposed strategies are given in Table 2.

Future perspectives

The future of yak populations in Pakistan, especially in the face of climate change, will depend on proactive strategies that address the challenges posed by warming temperatures, changing weather patterns, and increasing vulnerability of ecosystems. Key aspects shaping the future of yak adaptability, productivity, and reproduction under adverse climate scenarios include research and technological

Table 2 Possible proposed key mitigation strategies, advantages, and interventions for climate change.

Strategy	Implementation advantage	Interventions
Improved grazing and pasture management	Rotational grazing	Encouraging herders to use rotational grazing systems can allow pastures time to recover, preventing overgrazing and promoting long-term pasture health.
	Pasture reseeding	Local authorities and communities can collaborate to introduce reseeding programs that use climate-resilient plant species to restore degraded pastures and maintain vegetation.
	Fodder banks	One intervention measure to reduce nutritional pressure on yaks is paying for fodder banks and other feed reserves during severe winters or past poor grazing conditions.
Improved water management	Water harvesting systems	Installing rainwater harvesting and snowmelt collection systems can help store water during the wet season and provide drinking water for yaks during the dry season.
	Restoring natural water sources	Efforts to restore springs, ponds, and streams in high-altitude areas can improve water availability for both yaks and local communities.
Selective breeding and genetic conservation	Breeding for heat and disease resistance	Implementing selective breeding programs that focus on enhancing yaks' tolerance to heat stress and their resistance to emerging diseases can help improve their overall resilience to climate change.
	Conservation of local yak varieties	Preserving genetic diversity within the yak population is important by conserving local breeds that may carry traits important for adaptation to different environmental stressors.
Disease monitoring and veterinary support	Disease surveillance	Establishing systems for disease monitoring and early warning can help yak herders respond quickly to outbreaks of diseases like tick-borne illnesses and respiratory infections.
	Vaccination and veterinary care	Enhancing access to vaccinations and veterinary care for yaks can reduce mortality rates and increase resilience to climate-induced disease pressures.
Climate-resilient shelters	Thermal shelters	Developing climate-resilient yak shelters that offer protection from both extreme cold and heat can reduce the impact of temperature fluctuations. Shelters can be designed with insulating materials for cold weather and ventilation systems for hot weather.
	Windbreaks and shade structures	Creating natural or man-made windbreaks and shade structures in grazing areas can help protect yaks from harsh winds and heat during warmer months.
Supplementary feeding programs	Nutritional supplements	Offering nutritional supplements rich in vitamins and minerals can help yaks maintain good health during times when natural forage is scarce or of poor quality.
	Enriched feed resources	Introducing climate-resilient crops like barley, oats, and legumes, which can be grown in high-altitude regions, can help herders supplement the yaks' diet.
Strengthening traditional knowledge and practices	Integrating traditional knowledge with modern science	Engaging herders in knowledge-sharing initiatives that combine their traditional herding practices with modern scientific approaches (*e.g.*, sustainable grazing and disease management) can improve adaptation efforts.
	Community-based resource management	Empowering yak herding communities to take a leading role in managing local pastures, water resources, and disaster preparedness through community-based resource management initiatives can enhance resilience at a local level.
Alternative livelihoods for herders	Eco-tourism	Promoting eco-tourism and yak-based tourism (such as yak safaris and cultural experiences) can offer alternative income streams for herders while helping preserve yak populations and high-altitude ecosystems.

	Yak products	Expanding markets for yak products such as milk, butter, cheese, wool, and leather can create new income opportunities. Developing value-added products (*e.g.*, yak milk-based skincare or luxury yak wool garments) can tap into niche markets.
	Climate-resilient agriculture	Encouraging herders to adopt climate-resilient farming techniques, such as agroforestry and cultivating high-altitude crops, can help diversify livelihoods while maintaining ties to their traditional ways of life.
Policy support and climate resilience programs	Climate resilience programs	Government and other stakeholders can design climate change coping strategies targeting sustainable rangeland operations, quality of veterinary services, water resource systems, and pasture enhancement in marginal and highly elevated areas.
	Subsidies and financial support	To mitigate the economic losses occasioned by climate change, solutions such as subsidizing supplementary feed, veterinary services, and livestock risk cover for losses are recommended.
	Disaster preparedness	Disaster preparedness is effective when early warning systems are created for extreme weather occurrences like snowstorms and floods, or evacuation corridors when climate disasters strike to reduce death rates on yaks.
Research and development	Genetic research	Sibling and paternal summated crosses, families, including using such milk obtained to invest in genetic traits that can help to identify such solutions as heat and disease tolerance, to prioritize the breed improvement schemes for yaks.
	Climate adaptation studies	General information regarding the climate adaptability of high-altitude ecosystems and livestock systems is also useful for understanding how best to cope with the current situation of yaks.

advancements, sustainable livelihoods, and economic resilience, policy interventions, climate resilience programs, climate-smart pasture and water management, disease surveillance, veterinary support, and climate change mitigation and adaptation policies. Genomic research for stress adaptation holds the potential to unlock critical genetic traits that enhance yaks' resilience to heat stress, disease, and nutritional deficits. Advances in genomic selection and biotechnological tools could facilitate the development of yak breeds better suited to warmer climates without compromising productivity. Assisted reproductive technologies (ART) could play an increasingly important role in managing yak reproduction under changing environmental conditions, optimizing breeding season, enhancing fertility, and improving the genetic diversity of herds. Sustainable livelihoods and economic resilience are also crucial for yak herders. The demand for high-altitude products like yak wool, milk, and meat is expected to grow, particularly in niche markets focusing on sustainable, eco-friendly, and artisanal products. Developing robust supply chains for yak-based products could boost rural economies and provide yak herders with the financial resources needed to invest in adaptive strategies. Tourism and eco-conservation offer new economic avenues for yak-dependent communities, highlighting traditional yak herding practices, local culture, and the unique ecosystems of the high-altitude regions. Community-driven resource management and conservation strategies that focus on sustainable grazing, pasture restoration, and water management will be crucial for maintaining the long-term viability of yak herding. Climate-smart pasture and water management will focus on sustainable land use practices, water resource conservation, disease surveillance and veterinary support, vaccines and treatments, and climate change mitigation and adaptation policies. Pakistan's efforts to combat climate change must align with global climate initiatives and agreements such as the Paris Agreement, focusing on reducing greenhouse gas emissions while investing in adaptation strategies for high-altitude regions. Resilience planning for high-altitude communities is essential, with specific policies aimed at protecting the unique ecosystems of the Himalayan region. Governments must take a proactive approach to funding climate adaptation projects, supporting research into high-altitude ecosystems, and ensuring that herding communities receive adequate financial and technical support.

Conclusions

The Himalayan yak is an essential part of the livelihood of the local communities in the high altitudes of Pakistan, which contributes nutritionally in terms of milk, wool, and meat, and is used for transport as well. But the climate change factors are now rapidly emerging as difficult for these tough creatures; temperature, availability of pastures, and sickness become tough issues. Climate change affects the productivity, adaptability, and reproduction of yaks and the herder community at large through impacts that range from habitat to embryos that compromise their survival. Addressing these

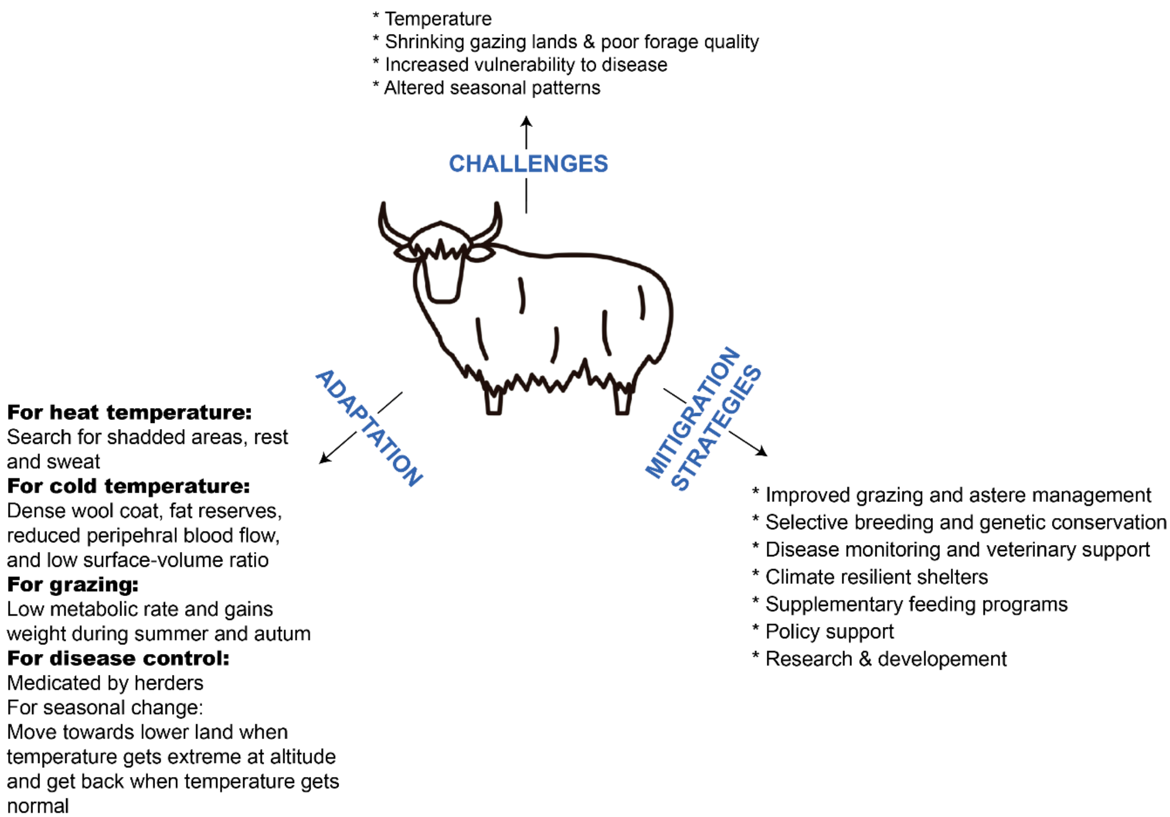

Fig. 1 Overview of challenges, adaptation, and mitigation strategies of yak.

challenges involve better knowledge about the yak's genetic behavior in relation to pressures in its natural habitats, and finding ways on how the species' future can be protected. Preservation of sustainable selection, feeding, and quality veterinary care of the yaks is critically important towards the improvement of the animal's resilience in the context of the changing climate. Moreover, funding research on breed improvement programs, including the search for relevant genes for heat and disease tolerance, will be of paramount importance to counter climate change to affect the growth of yaks. Survival of Yak in Pakistan due to climate change will be determined through working together with the support of the local communities, government, scholars, and other conservationists. Through the interaction of elders with modern scientists, using conservation-oriented pasture and water resources, and by providing solutions and funding for the herders, it is possible to reduce the extensive effects of climate change on yaks. These actions are not only important for the maintenance of the Yak's future but also for the future of hundreds of thousands of families that have based their way of life around the Yak for centuries. Hence, the breed's prospects in the future of Pakistan will be determined not only by the yak's biological prowess but also by the socio-political and technological advancements since the environment continues to challenge the breed's existence in the region.

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Conflict of Interest

The authors had no conflicts of interest to disclose.

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