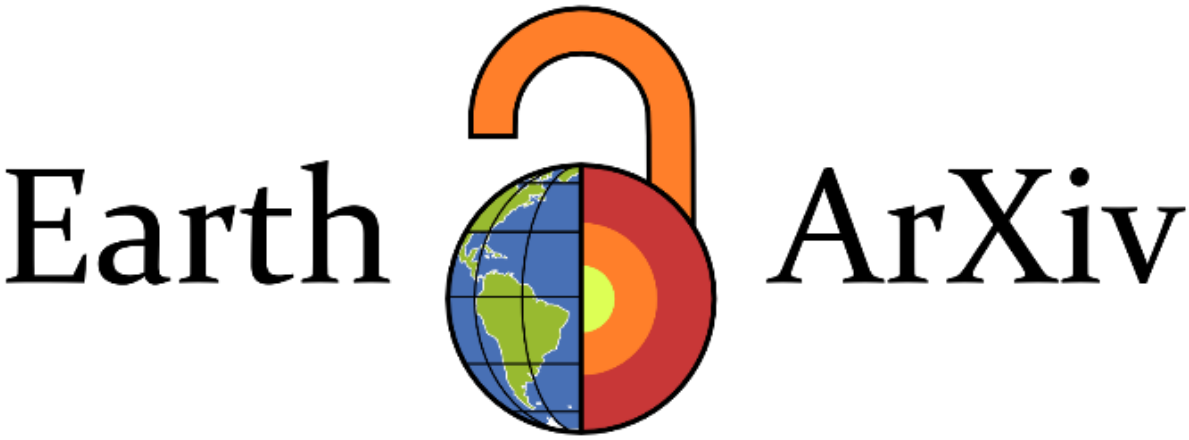

Opuntia Invasion Risk and Management Strategies in China: A Comprehensive Review Under Climate Change Scenarios

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Abstract

Including China, the genus *Opuntia*—prickly pear cactus—has grown to be a quite troublesome invading species in many different countries. With an eye toward *Opuntia's* ecological effects, present management practices, and suggestions for future control activities, this review assesses the possible distribution and invasion risk of the plant under climate change conditions. We investigate the species' present distribution in China, the biological traits allowing its proliferation, and the environmental elements driving its expansion. Mechanical, chemical, and biological control techniques are among the management strategies under careful evaluation; integrated pest management (IPM) shows great potential. We address issues including ecological concerns, limited efficacy of mechanical and chemical approaches, and non-target consequences of biological controls. Reducing future invasions depends on proactive preventative plans involving early identification, public awareness, and biosecurity measures. The study emphasizes the need for continuous research to better grasp the dynamics of *Opuntia* invasions and the evolution of more sensible, region-specific control strategies. Improving early-warning systems, increasing stakeholder involvement, and developing adaptive management techniques to handle the expanding threat *Opuntia* presents in China's ecosystems and agricultural sectors should take the front stage in future initiatives.

Keywords: *Opuntia*; Invasion Risk; Climate Change; Distribution Patterns; Management Strategies

I. Introduction

Native to the Americas, the genus *Opuntia*—often known as prickly pear cactus—is a quite broad collection of succulent plants. These plants have attracted a lot of interest because of their possible commercial use as food, feed, and source of several other items (Martins et al., 2023; Stintzing & Carle, 2005) . *Opuntia* species introduced beyond their natural habitat have, however, also raised questions over their possible invasiveness and effects on nearby ecosystems (Bakewell-Stone, 2023). Comprising more than 200 species, the genus *Opuntia* belongs to the Cactaceae family; *Opuntia ficus-indica Mill* is the most often grown and commercially important species in this group (Stintzing & Carle, 2005). These plants differ mostly in their flat, paddle-like cladodes (stem segments) and spines, which vary in density and size (Reyes-Agüero et al., 2006). *Opuntia* species' great adaptability to many environmental conditions—including drought, high temperatures, and poor soil—allows them to be resilient and successful both in native and introduced ranges. Climate change is expected to affect the distribution patterns and invasion potential of certain species even more (Bakewell-Stone, 2023; Jorge et al., 2023)

Their unique cladodes, act as the main photosynthetic organs and allow water storage in their fleshy tissues, therefore enabling their survival in arid and semi-arid conditions. These characteristics enable *Opuntia* species to especially fit for challenging environmental circumstances (Eggli & Nyffeler, 2009)

Beyond their fortitude, *Opuntia* is quite important in ecology, farming, and culture. Their edible fruits, pads (cladodes), and seeds—which provide food, fodder, and other uses—are grown Ecologically, they are vital in dry and semi-arid environments since they give different species food and habitat. Culturally, the prickly pear cactus has symbolic and cultural importance—especially in Latin America, where it is closely entwined with regional customs and ceremonies (Ciriminna et al., 2019; Mayer & Cushman, 2019; Yahia, 2012).

Commonly known as prickly pear cactus, the genus *Opuntia* shows a wide distribution including both its natural range in the Americas and areas where it has been introduced. This covers a review of its historical and present distribution patterns as well as forecasts for future developments under scenarios of climate change (JON P. REBMAN1AND DONALD J. PINKAVA, 2001; Jorge et al., 2023).

Native to the Americas historically, *Opuntia* species are most diverse in Mexico and the southern United States. Mostly for agricultural and decorative reasons, these species have been brought to other areas over time including Africa, Europe, Asia, and Australia (Bakewell-Stone, 2023; Chávez-Moreno et al., 2013). With established populations in many nations, *Opuntia* species now exist on every continent except Antarctica. Their distribution is affected by elements like climate conditions, soil properties, and human activity including both deliberate introductions and inadvertent dissemination. Efforts at mapping have given important new perspectives on their present distribution (Erre et al., 2009; Yahia, 2012). Looking ahead, climate change is expected to greatly influence the future distribution of *Opuntia*. Modeling approaches predict changes in suitable habitats for different species under different climate scenarios, so guiding the identification of areas that might become more or less suitable for *Opuntia* growth and invasion in the next decades (Fuller et al., 2010; Ureta et al., 2018).

The complete evaluation of invasion hazards for the genus *Opuntia* calls for a careful investigation of the elements influencing their invasive capacity, including biological traits, ecological interactions, and the impact of human activities (Jorge et al., 2023; Stintzing & Carle, 2005). Rapid vegetative development, effective seed distribution systems, tolerance to different environmental stresses, and the capacity to outcompete native plant species help *Opuntia* species exhibit several biological traits that increase their invasiveness, so enabling them to colonize and dominate disturbed habitats (CABI, 2019b). Ecologically, by changing habitat structure and species composition and hence upsetting native plant-animal interactions like pollination and seed distribution networks, *Opuntia* incursions can greatly affect local ecosystems. Furthermore, their introduction can help other invading species to establish using habitat changes (Essl & Kobler, 2009). Major causes of *Opuntia's* proliferation have been human-mediated actions including deliberate introductions for agricultural, horticultural, and ornamental uses as well as inadvertent dissemination through contaminated goods and transportation. In some places, the absence of efficient management and control strategies aggravates invasion threats (Bakewell-Stone, 2023). Several biological traits of *Opuntia* species improve their invasive potential: fast vegetative growth and propagation via cladode fragmentation (Essl & Kobler, 2009; Reyes-Agüero et al., 2006), effective seed distribution systems sometimes made possible by animals, and a great tolerance for many environmental circumstances including drought and poor soils. These species inhabit damaged areas and outcompete native plants (Bakewell-Stone, 2023; Essl & Kobler, 2009). Ecologically, *Opuntia* invasions can greatly change habitat structure and species composition in natural and semi-natural ecosystems, disturb native plant-animal interactions including pollination and seed dispersal networks, and help other invasive species to establish themselves by habitat modifications (Belayneh, 2018; Weber, 2004). Human activities also significantly contribute to their spread: deliberate introductions for agricultural, horticultural, and ornamental uses; inadvertent dissemination via contaminated agricultural products, machinery, and vehicles; insufficient management and control measures in some areas (Bakewell-Stone, 2023; CABI, 2019b).

The purpose of this review is to explore the potential distribution patterns and invasion risk of the genus *Opuntia* under climate change scenarios in China and globally. The objectives of the review are: (1) to examine the historical and current distribution patterns of *Opuntia* species in both native and introduced regions; (2) to assess the invasion risk based on biological characteristics, ecological interactions, and human activities; (3) to evaluate the impacts of climate change on the future distribution and invasion potential of *Opuntia* species; and (4) to discuss strategies for managing and mitigating the invasion risks, including prevention, control, and eradication efforts.

II. Biological Characteristics and Invasion Mechanisms of *Opuntia*

The research on the invasion and control of *Opuntia* species, such as *Opuntia stricta*, *Opuntia ficus-indica*, *Opuntia monacantha*, and *Opuntia humifusa*, highlights the complex interactions between these invasive species and their environments. Among the several ways these organisms are known to upset natural ecosystems, allelopathy and mutualism disturbance are two. Managing these species calls for a multimodal strategy including ecological, chemical, and technological considerations. Because of their great impact as invading species, many studies on invasion and control have concentrated on *Opuntia* species including *Opuntia stricta*, *Opuntia ficus-indica*, *Opuntia monacantha*, and *Opuntia humifusa*. Originally introduced, these cacti have spread around the globe mostly avoiding domestication and becoming invasive in areas including the Mediterranean, Africa, and Australia. Variations in local abiotic conditions, invader quantity, and native community traits and composition mean that the impacts of a biological invasion on native communities are expected to be unequal over invaded areas. One approach to improve prediction capacity about the impact of an invading species given changing conditions is by exploiting the recognized mechanisms behind their success. Commonly seen in invading species are allelopathic traits, which can be either

directly or indirectly harmful to plants via altering root symbionts such as mycorrhizal fungi. The indirect approach is expected to affect plants depending on mycorrhizas by upsetting mutualism; non-mycorrhizal plant species will not be affected (Roche et al., 2023).

Native Lactuca indica combined with four invasive species found that the response of the native plant relies on the identification and variation of the invading species. The total biomass of the native plant rises at low invasive plant richness and falls at high density, the study found. The native plant's leaf nitrogen concentration rises with increasing invasive plant richness, suggesting more influence from invading plant identity (Kama et al., 2023).

Climate change, global trade, and human mobility are all helping exotic invasive vegetation to spread. Their secondary metabolite emissions—that of root exudates and volatile organic compounds—VOCs—change ecosystems. These molecules have been well investigated and are known to increase invasiveness. Still, their ecological effects are little known. Invasive plants show more chemical variety and different chemical behavior in native versus invaded areas, according to a systematic evaluation of research spanning 2012–2022. Herbivory, soil microorganisms, temperature rises, and carbon dioxide levels all affect VOC emissions. Environmental changes could cause invasive plants to show lower variability in VOC emissions (Clavijo McCormick et al., 2023). The biodiversity and ecological services are seriously threatened by invading alien species. Managing them depends on knowing their dispersion and proliferative processes. Data collecting is much improved by unmanned aerial vehicle (UAV) monitoring. Six RGB indices were evaluated using UAV images for their ability to detect invading plant species. For the common milkweed cover area, results revealed that TGI and SSI indices were the most correct; for the blanket flower cover area, the index was the most appropriate. For those working in conservation, these techniques allow quick, cheap, and effective data processing (Bakacsy et al., 2023). While the invasive traits of *Opuntia* species take front stage, it's important to recognize their potential benefits as a food source and in arid terrain agriculture.

Nonetheless, their invasive traits frequently surpass these advantages, requiring meticulous control to safeguard local ecosystems. As provided in the table below, we summarized the current research findings on some *Opuntia* Species and their regions or countries of study.

Table 1. Summary of current research findings on some Opuntia Species and their Regions or countries of studies

Continent	Country	Species	Findings of the studies	References
America	Crimea	*Opuntia engelmannii,* *O.fragilis,* *O.humifusa,* *O.macrorhiza,* *O.phaeacantha,* *O.polyacantha,* *O.tortispina,* *O.tunoidea*	Distribution and Naturalization	(Bagrikova & Perminova, 2022)
	Mexico	15% of *Opuntia species* *O.ficus-indica* *O.albicarpa* *O.megacantha*	Genetic Diversity and Taxonomy, Implications for Biodiversity and Agriculture	(Caruso et al., 2010)

		O.xoconostle, *O.robusta* *O.streptacantha* *O.vulgaris,* *O.microdasys,* *O.dillenii O.dejecta* *O.hyptiacantha,*	Knowledge of Flower-Visiting Insects, Cultural and Economic Importance, Biological and Environmental Factors, Beneficial effects of *Opuntia spp* Geographic Distribution and Habitat Suitability Phytochemical and Health Benefits Global Studies on *Opuntia ficus-indica*	(Moctezuma et al., 2015) (Escandón et al., 2022) (Nondumiso Dlamini, n.d.) (Orozco, 2024) (Eseverri et al., 2023) (Jiménez et al., 2023) (Santillán et al., 2022, p. 1) (Shoukat et al., 2023)
	Santiago, Chile	multiple *Opuntia species*	Agricultural Applications	(Jacobo & González, 2001)
	Brazil	*Opuntia species*	Initial performance evaluation of *Opuntia spp.*	(Santos et al., 2023)

		O.bonaerensis	Conservation and Biogeographic History	(Köhler et al., 2020)
	Uruguay	*Opuntia bonaerensis*	Conservation and Biogeographic History	(Köhler et al., 2020)
	United States Midwestern United States	*prickly pear cactus* *O.fragilis* *O.humifusa* *O.macrorhiza*	Detection and Spatial Patterns Environmental Constraints and Genetic Studies	(Jaime et al., 2023) (Majure & Ribbens, 2012)
	Argentina	*Opuntia anacantha* *O.bispinosa* *O.brunnescens* *O.discolor* *O.distans* *O.hildemannii* *O.kiskaparrot* *O.pampeana* *O.sulphurea* *O.vulpina*	Taxonomic Studies	(Oakley et al., 2024)
	Canada	*Opuntia dillenii*	Studies in Tropical and Subtropical Regions	(Lu et al., 2023)
	South-East Pacific Islands	naturalized alien species richness and native species richness	Ecological Impact and Naturalization	(Polgrossi et al., 2023)
	----------	*Opuntia stricta,* *O.ficus-indica, O.monacantha*	Challenges in Management	(Humphries et al., 2022)

Europe	Spain	*Opuntia ficus indica*	Global Studies on *Opuntia ficus-indica*	(Shoukat et al., 2023)
	Italy	*Opuntia ficus indica*	Global Studies on *Opuntia ficus-indica*	(Shoukat et al., 2023)
Africa	Morocco	*prickly pear* *Opuntia dillenii (Ker Gawl.) Haw.* *O.ficus-indica (L.) Mill*	Propagation and Conservation Phytochemical and Health Benefits	(Marhri et al., 2023) (Bouhrim et al., 2021)
	Ethiopia	*Opuntia ficus-indica* *O.stricta* *O.robusta*	nutritional and chemical composition of *Opuntia species,* Climate Change and Distribution Modeling, Socio-Economic Impacts	(Teklu et al., 2023) (Hussein & Estifanos, 2023) (Shackleton et al., 2017)
	South Africa	Alien plants *Opuntia fcus-indica (L.) Mill*	Decline in Invasion Risk in Southern Africa, Genetic Diversity and Adaptation, Economic Contribution Demographic Insights Lack of Awareness Socio-Economic Factors	(Omer et al., 2024) (Modise et al., 2024)

			Gender Dynamics Uses of Prickly Pear Policy Implications Global Studies on *Opuntia ficus-indica*	(Moshobane et al., 2022) (Shoukat et al., 2023)
	Tanzania	*Opuntia stricta*	Socio-Economic Impacts	(Shackleton et al., 2017)
	Kenya	*Opuntia stricta*	Socio-Economic Impacts	(Shackleton et al., 2017)
	Tunisia	*Opuntia dillenii*	Studies in Tropical and Subtropical Regions	(Lu et al., 2023)
	Algeria	*Opuntia dillenii*	Studies in Tropical and Subtropical Regions	(Lu et al., 2023)
	Nigeria	*Opuntia dillenii*	Studies in Tropical and Subtropical Regions	(Lu et al., 2023)
	----------	*Opuntia stricta,* *O.ficus-indica,* *O.monacantha*	Challenges in Management	(Humphries et al., 2022)
	----------	*O.streptacantha,* *O.hyptiacantha,* *O.albicarpa,* *O.megacantha* *O.ficus-indica*	Phytochemical and Health Benefits	(Santillán et al., 2022, p. 1)
Asia	Taiwan	*Opuntia dillenii*	Biological Properties and Applications	(Lu et al., 2023)

	Pakistan	*Opuntia dillenii, O.ficus-indica,* *O.monacantha*	Distribution and Naturalization Studies in Tropical and Subtropical Regions	(Bartolomeo, et al., 2021) (Lu et al., 2023)
	Bangladesh	*Opuntia dillenii*	Studies in Tropical and Subtropical Regions	(Lu et al., 2023)
	South Korea	*Opuntia ficus-indica* *Alien plant species*	Biological Properties and Applications Climate Change and Distribution Modeling	(Nam et al., 2023) (Adhikari et al., 2022)
	China	Invasive species *Opuntia dillenii*	Distribution Modeling Studies in Tropical and Subtropical Regions	(Wang et al., 2023) (Lu et al., 2023)
	----------	*O.streptacantha,* *O.hyptiacantha,* *O.albicarpa,* *O.megacantha* *O.ficus-indica*	Phytochemical and Health Benefits	(Santillán et al., 2022, p. 1)
	----------	*Opuntia stricta,* *O.ficus-indica, O.monacantha*	Challenges in Management	(Humphries et al., 2022)
	----------	*prickly pear cladodes*	Nutritional and Health Benefits	(Kashif et al., 2022)
	----------	*Opuntia ficus indica*	Product Development and Storage	(Sakhraoui et al., 2023)
	----------	*Opuntia ficus-indica*	Phenotypic Plasticity and Invasion Success	(Tesfay et al., 2023)

	----------	*Opuntia maxima* *O. dillenii,*	Material Science	(Castellano et al., 2021)

III. Global and Local Distribution of *Opuntia* and Its Expansion Potential in China

Historical Distribution

Native to the Americas, the genus *Opuntia*, sometimes known as prickly pear cactus, ranges from Canada to Chile (Bakewell-Stone, 2023; Jorge et al., 2023). *Opuntia's* native range consists of desert, semi-desert, and dry, subtropical areas in which the plants have evolved to flourish in arid and semi-arid surroundings. Often used as a fruit crop, cattle fodder, or decoration, *Opuntia* species have been extensively brought and grown throughout the world including Africa, Europe, Asia, and Australia (Yahia, 2012). Over time, some introduced populations have become naturalized and invasive in these new regions, posing a threat to native ecosystems (Jorge et al., 2023).

Opuntia's successful introduction in many parts of the world can be ascribed to several elements, including its capacity to propagate vegetatively, the dispersal of its fruits and seeds by animals, and its adaptation to many environmental conditions, including drought tolerance and the capacity to grow in nutrient-poor soils (Bakewell-Stone, 2023; Reyes-Agüero et al., 2006). Often for use as a fruit crop, cattle fodder, or decoration, *Opuntia* species have been extensively introduced and grown over time in many parts of the world, including Africa, Europe, Asia, and Australia.

Sometimes native ecosystems are threatened by introduced *Opuntia* populations becoming naturalized and invasive in these new areas. This can be ascribed to the genus's propensity to spread vegetatively, the way its fruits and seeds are distributed by animals, and its adaptation to many environmental circumstances, including drought tolerance and the aptitude to grow in nutrient-poor soils (Parker et al., 2013; Rojas-Sandoval & Acevedo-Rodríguez, 2014).

Current Distribution

Though the genus is most common in the Americas, where it is native, *Opuntia* species are now found in many other areas worldwide. *Opuntia* has been brought and naturalized outside of its native area in numerous regions including Africa, Europe, Asia, and Australia (Bakewell-Stone, 2023; CABI, 2019a; Yahia, 2012).

Opuntia species have been brought into and grown in China mostly for their edible fruits and as a fodder crop. Some brought populations, especially in the southern and central parts of the nation, have grown invasive, though. Other areas, including sections of Europe and Africa, have also recorded the naturalization and invasive spread of *Opuntia* species, which can have major effects on local ecosystems and biodiversity (Jorge et al., 2023; Tesfay & Kreyling, 2021; Witt et al., 2020). Tracking the spread and distribution of *Opuntia* species in China and other areas is dependent on constant monitoring and surveillance as their potential for invasion and effect on native ecosystems can be substantial.

Mapping of existing populations in China and globally

Though the genus is most common in the Americas, where it is native, *Opuntia* species are now found in many other areas worldwide. *Opuntia* has been brought and naturalized outside of its native area in numerous regions including Africa, Europe, Asia, and Australia (Jorge et al., 2023; Yahia, 2012).

Below is a diagram indicating the native range and invasion of *Opuntia* Species globally.

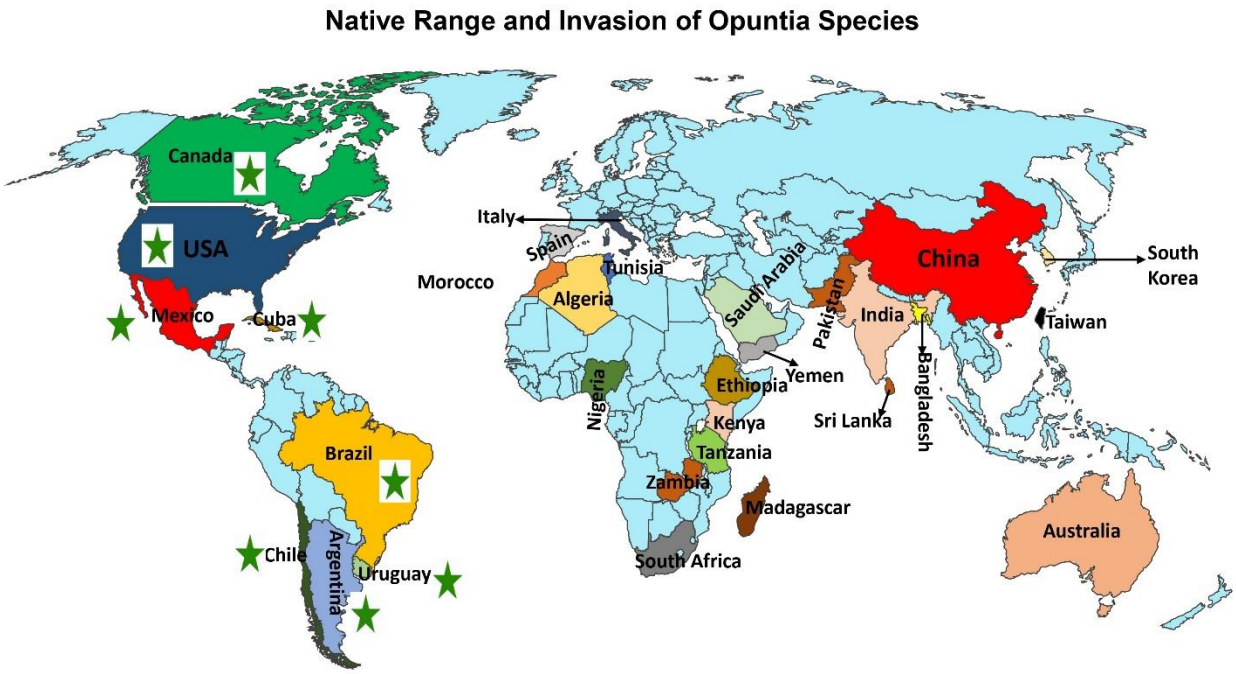

Figure 1. The map depicting the native range (marked with green stars) and the global invasion of Opuntia species.

Figure 2. The map of Opuntia Invasion in Chinese Provinces

Factors influencing the current distribution

Many elements influence the present range of *Opuntia* species, including historical introductions and cultivation for uses including decorative, agricultural, and cattle feed. Their flexibility to many environmental conditions—including drought tolerance and the capacity to flourish in nutrient-poor soils—has helped them to establish an even more broad spectrum. Often helped by animals, *Opuntia* species also show efficient vegetative propagation and seed distribution systems, which helps them to disperse and build populations in new areas (Dudai, 2012; Missiakô Kindomihou, 2020).

In areas where *Opuntia* has been introduced, ongoing monitoring and management initiatives are crucial to help minimize any possible effects on local ecosystems.

Projected Distribution under Climate Change Scenarios

The possible distribution of *Opuntia* species—in both their natural ranges and in places where they have been introduced—is likely to be considerably altered by climate change.
Changes in precipitation patterns and rising temperatures are probably going to affect the suitability of habitats for *Opuntia*, thereby perhaps causing range expansions in some areas and contraction in others.
Areas that *Opuntia* finds inappropriate now could turn out to be a better fit, so creating new introductions and invasion opportunities. On the other hand, locations that are now fit could become less so, maybe resulting in the extinction or reduction of current populations (Langille et al., 2017; Strum et al., 2015; Yadav et al., 2018).

Projecting the possible distribution of *Opuntia* species under various climate change scenarios using several modeling techniques including species distribution modeling and climate-based risk assessment These models assess areas that might become suitable or unsuitable for *Opuntia* in the future by using elements of temperature, precipitation, and other climatic variables together with knowledge on the species ecological needs and current distribution (Erre et al., 2009; Mtengwana et al., 2021; Ureta et al., 2018).

Projections on climate change suggest that *Opuntia* species distribution will vary in the next decades. Currently, inappropriate regions could become more appropriate, therefore helping *Opuntia* to be introduced and established in other places. On the other hand, certain regions that are now fit could become less so, resulting in the extinction or reduction of present populations. *Opuntia's* history of invasiveness in various regions of the globe calls for careful thought on introduction or cultivation (Erre et al., 2009; Jorge et al., 2023; Yahia, 2012).

IV. Ecological and Socioeconomic Impacts of *Opuntia* Invasions

Current Climate Change Trends

The Earth's climate is undergoing considerable changes, mostly caused by human activities that have transformed the global atmosphere and environment. Since the late 19th century, global average temperatures have risen by around 1.1°C, a trend that is anticipated to continue (Jorge et al., 2023). Precipitation patterns have also changed; some areas now get more severe rain while others suffer protracted drenches. These variations in temperature and precipitation have broad effects on ecosystems, biodiversity, and human populations all around (Jorge et al., 2023; Rajpoot et al., 2020). Rising atmospheric carbon dioxide concentrations, global temperature variations, and changes in precipitation patterns define key climate change elements impacting *Opuntia's* distribution and invasion potential. Since the Industrial Revolution, atmospheric carbon dioxide levels have risen by more than forty percent, directly influencing plant development including the photosynthetic efficiency and water-use capacity of *Opuntia* species (Langille et al., 2017). Although precise reactions to elevated CO2 remain poorly known and need more study, elevated CO2 levels may improve the growth and productivity of *Opuntia*, hence enhancing its competitive ability and invisibility (Skendžić et al., 2021; Ziska et al., 2018).

Opuntia distribution is likely to be much influenced by rising world temperatures. Warmer temperatures might let *Opuntia* spread into previously confined areas of higher latitudes and elevations from colder times. In some areas, nevertheless, higher frequency and intensity of heat waves and droughts could have harmful effects on specific *Opuntia* populations. With most of this warming occurring in recent years, the average surface temperature of the Earth has already risen by about 1.1°C; predictions show further warming dependent on future greenhouse gas emissions (Jorge et al., 2023; Langille et al., 2017; Sharma & Prabhakar, 2014).

The spread and invasion potential of *Opuntia* are also greatly shaped by variations in precipitation patterns. Changes in precipitation patterns, such as extended droughts or heavy rainfall events, could influence habitat appropriateness for *Opuntia*, so allowing spread into previously unsuitable regions and so lowering suitability in others. *Opuntia* distribution and establishment could be much influenced by changing water supply in certain areas and declining availability in others (Skendžić et al., 2021).

Future climate change scenarios—including those presented by the Representative Concentration Pathways of the Intergovernmental Panel on Climate Change—offer insightful forecasts for evaluating possible changes in *Opuntia*

distribution and invasion hazards in diverse areas. These realizations will guide policies for controlling how climate change affects *Opuntia* population (Gong et al., 2020; Langille et al., 2017; Skendžić et al., 2021; Ziska et al., 2018)

Future Projections

Projections for future climate conditions are offered by models and scenarios including the Representative Concentration Pathways created by the Intergovernmental Panel on Climate Change. These simulations imply that with major consequences for the distribution and invasion potential of many plant species, including *Opuntia*, the degree and speed of climate change are probably going to rise in the next decades.
Evidence points to climate change's major influence on the distribution and abundance of invading species, including the genus *Opuntia* (Skendžić et al., 2021). Variations in important climatic variables, such as temperature and precipitation, might affect a species's capacity to survive and flourish in new areas, raising or lowering invasion risks.
Regional climate models pertinent to China and other nations:
Different climate change scenarios—including the Representative Concentration Pathways—offer forecasts for future temperature and precipitation trends across diverse areas. These simulations imply that with major consequences for the distribution and invasion potential of many plant species, including *Opuntia*, the degree and speed of climate change are probably going to rise in the next decades.
Climate models, for instance, suggest that the possible distribution of *Opuntia* may widen in northern latitudes, where milder winters and higher temperatures could let the species establish and proliferate. However, in other regions, the increased frequency and intensity of droughts and heat waves associated with climate change may negatively impact *Opuntia* populations. (Jorge et al., 2023; Langille et al., 2017)

Expected impacts on ecosystems and biodiversity

Shifts in species distributions, changes in community composition, and potential threats to vulnerable habitats and species are anticipated as a result of climate change (Bebber, 2019; Liao et al., 2023; Rajpoot et al., 2020).

Invasions of invasive *Opuntia* species can have major effects on native ecosystems including changes in habitat structure and resources, modification of fire patterns, and competition with native plants.
As *Opuntia* can outcompete and replace native plant communities, the possibility for more distribution and abundance under climate change scenarios could endanger the biodiversity of areas where it is introduced (Bakewell-Stone, 2023).

V. Invasion Risk Assessment

Definition and Importance of Invasion Risk Assessment

Evaluating the possibility for a non-native species to become invasive in a new area depends critically on invasion risk assessment.
It entails methodically assessing elements that might affect the probability of a species effectively establishing, dispersing, and generating negative effects in a habitat where it is not native.

By assessing the invasion risk of *Opuntia* species, decision-makers and land managers can make informed decisions about the introduction, cultivation, and management of these plants, to minimize the potential for negative ecological and economic impacts (Bakewell-Stone, 2023; O'Loughlin et al., 2019; Weber, 2004).

Factors Contributing to Invasion Risk

Opuntia species' invasion risk is caused in several main ways. *Opuntia* can respond to a wide spectrum of environmental circumstances, including different temperature and precipitation patterns, hence climate adaptation is rather important. Furthermore helping their proliferation and establishment in new places are their effective reproductive and dispersal systems, including vegetative propagation and animal-mediated seed distribution (Bakewell-Stone, 2023; O'Loughlin et al., 2019). *Opuntia's* competitive prowess—including its tolerance of drought, nutrient-poor soils, and capacity to outcompete native vegetation—adds even more to its invasive potential (Bakewell-

Stone, 2023). Their invasive success in introduced areas also stems from the absence of natural enemies including predators, diseases, or herbivores. Furthermore affecting the probability of their establishment is propagule pressure, determined by the frequency and extent of introduction events as well as the amount of people introduced (Essl & Kobler, 2009).

The biological characteristics of *Opuntia* species underline their adaptability and resilience. These plants can tolerate harsh environmental conditions, including drought, poor soils, and high temperatures, and reproduce both sexually and asexually through vegetative propagation (Bakewell-Stone, 2023). The seeds are frequently dispersed by animals, aiding in their colonization of new areas. *Opuntia* can change ecosystem structure and composition by outcompeting and replacing native flora. Developing sensible risk assessment systems for *Opuntia* species depends on an awareness of these traits and invasion routes.

Ecological Interactions

Invasions of *Opuntia* species can have significant effects on ecosystems and human activity. Often changing the mix and arrangement of native plant communities, *Opuntia* invasions outcompete and replace native species. Furthermore, influencing soil characteristics and nutrient cycling are these incursions, so altering the functioning of the ecosystem. *Opuntia* disturbs interactions with native animals including pollinators and herbivores as well. Appreciating the effects of *Opuntia* invasions and creating sensible management plans depends on an awareness of these ecological relationships.

Opuntia invasions have major ecological effects since the species can outcompete native plants and change ecosystem structure and function, therefore compromising biodiversity and ecosystem services (Essl & Kobler, 2009). *Opuntia* has a competitive edge over native species since it thrives in disturbed, nutrient-starved environments (Essl & Kobler, 2009). Its effective dispersal systems—including vegetative propagation and animal-mediated seed distribution—help it even more to reach new areas (Jorge et al., 2023; Weber, 2004).

Furthermore, difficult economically are *Opuntia* invasions. These comprise lower property prices, more management and control expenses, and less agricultural output. An important instrument for assessing the possibility of non-native *Opuntia* species becoming invasive in new areas is invasion risk assessment, which helps to guide preventative actions to minimize their ecological and financial effects.

Human Activities and Spread

Different human activities have greatly affected the introduction and distribution of *Opuntia* species in recently acquired areas. One main reason is commercial farming, where *Opuntia* has been extensively brought as a crop for fruit, feed, and other agricultural uses, so establishing it in many different countries all over (Bakewell-Stone, 2023; Ciriminna et al., 2019; Mohamed–Yasseen et al., 1996). *Opuntia* species are also frequently grown for their decorative value as ornamental plants, which can lead to wild escape and naturalization. Beyond deliberate cultivation, *Opuntia* has been used for agricultural purposes including food crops and animal feed, therefore encouraging its dissemination (Bakewell-Stone, 2023). The unintentional spread of *Opuntia* has been facilitated in great part by human-mediated pathways. *Opuntia* fruits and seeds have been unintentionally moved thanks to the transportation of cattle, machinery, and goods; vehicles and machinery have been especially successful in spreading these species into new habitats (CABI, 2019a, 2019b). Further helping to spread the species are traffic and transportation activities including commodities and animal movement. Whether deliberate or inadvertent, human-driven paths have been vital in *Opuntia's* global distribution. A thorough evaluation of these elements is necessary to solve this problem together with consideration of their ecological and socioeconomic consequences. Such assessments can guide efficient management and decision-making, therefore helping to prevent future introductions, control of current populations, and reduction of negative effects on native ecosystems and human activities.

Assessment Methodologies

Combining several methodological approaches can let one evaluate the invasion risk and possible distribution patterns of *Opuntia* species under climate change scenarios. These call for both quantitative and qualitative techniques. While quantitative methods use species distribution modeling and climate niche modeling to forecast possible invasion

patterns, qualitative risk assessments depend on expert-based judgments of *Opuntia's* traits and invasion history (Essl & Kobler, 2009; Jorge et al., 2023).

Case studies from areas where *Opuntia* is either present or can spread—such as China—offer insightful analysis of the species's behavior, effects, and probability of future expansion. Important considerations in such case studies include historical patterns of *Opuntia* introduction and spread, interactions with human land use and economic activities, environmental factors influencing its distribution and invasiveness, ecological and economic impacts on native ecosystems and human activities, and the efficacy of present management strategies (Bakewell-Stone, 2023; Essl & Kobler, 2009; Jorge et al., 2023; O'Loughlin et al., 2019). Integrating these case studies can help build a comprehensive understanding of the invasion risks and distribution patterns of *Opuntia* under climate change.

Examining *Opuntia's* possible invasion hazards holistically calls for a multifarious strategy. While also evaluating the species' present distribution, habitat preferences, and ecological and socioeconomic effects, this entails combining qualitative and quantitative evaluation techniques with regional case studies. Developing sensible plans to reduce the dangers connected with *Opuntia* invasions in the framework of a changing environment depends on such a combined approach (Bakewell-Stone, 2023; Jorge et al., 2023; O'Loughlin et al., 2019; Ziska et al., 2018).

Risk Assessment Results

The significant invading potential of *Opuntia* species presents ecological, financial, and management problems requiring thorough risk assessments and proactive mitigating solutions. Important results from risk studies show that, especially under climate change conditions, *Opuntia* species have a high probability of continued spread and invasion. These species exhibit a wide climatic tolerance, thriving in diverse habitats, including nutrient-poor and disturbed areas, which gives them a competitive advantage over native species. This adaptability underscores the potential for *Opuntia* to expand its distribution and invade new regions as climate patterns shift (Bakewell-Stone, 2023; Gong et al., 2020; Jorge et al., 2023). The species' prolific vegetative reproduction and efficient seed dispersal mechanisms, combined with its adaptability to various climatic conditions, enable rapid establishment and spread. *Opuntia* invasions can have major financial effects including lower property prices, higher management expenses, and lower agricultural output (Bakewell-Stone, 2023; O'Loughlin et al., 2019). Furthermore, the proliferation of *Opuntia* can upset natural ecosystems, therefore changing the composition and structure of the plants and animals.

Reducing these hazards depends critically on good management techniques. *Opuntia* infestations have been managed successfully with early identification, fast response, and mechanical, chemical, and biological control strategies combined. Preventing and lessening the detrimental effects of *Opuntia* invasions in China and other areas depends on proactive, all-encompassing strategies including containment and focused control actions. Emphasizing the need for better control and risk management techniques, the widespread human-mediated introduction and cultivation of *Opuntia* for both commercial and ornamental uses has greatly helped to explain its global proliferation.

By comprehensively assessing the potential distribution patterns, invasion risks, and impacts of *Opuntia* under climate change scenarios, policymakers, and land managers can create better educated plans for minimizing the effects of its intrusions. Understanding the species' invasive potential and developing sensible management strategies depends on a multifarious approach combining qualitative and quantitative techniques and regional case study analysis (Pyšek & Richardson, 2010).

Identified high-risk areas

Through the analysis of climatic suitability, habitat preferences, and historical invasion patterns, several regions in China and other parts of the world have been identified as high-risk areas for potential *Opuntia* invasions under climate change scenarios. These include regions with similar climatic conditions to the species' native range or areas where it has already demonstrated invasive behavior (Bakewell-Stone, 2023; Jorge et al., 2023; Ziska et al., 2018). Moreover, places with a great degree of human-mediated disturbance—such as agricultural fields, cities, and traffic hubs—can help *Opuntia* grow and proliferate (Jorge et al., 2023).

Opuntia species closely match their ecological needs by thriving in areas with a high proportion of suitable habitats, including nutrient-poor, semi-arid, and disturbed settings (O'Loughlin et al., 2019). Prioritizing preventive and management activities as well as putting early detection and quick response systems into use to help avert possible

incursions depends on an identification of these high-risk regions. Well-documented invasiveness of *Opuntia* ficus-indica in many areas, including the Mediterranean and drylands, where it has had major effects on native ecosystems and human activities both ecologically and economically.
Opuntia's invading potential and distribution patterns under climate change scenarios are driven by several elements. Important players include its adaptability to a broad spectrum of climatic conditions, including drought tolerance and the capacity to flourish in disturbed, nutrient-starved ecosystems (Bakewell-Stone, 2023). Its fast establishment and long-distance dissemination are made possible by its abundant vegetative reproduction through fragmentation and effective seed distribution systems sometimes supported by animals. Furthermore, facilitating its spread has been human-mediated introductions for agricultural, decorative, and other uses. Historical patterns of invasion also reveal that *Opuntia* usually establishes effectively in areas with climatic conditions like those of its natural range.
An integrated, multidimensional methodology is required to fairly evaluate *Opuntia's* invasion danger and possible dispersion patterns in China and other areas of the world. Together with quantitative models of climate adaptability and habitat preferences, this involves qualitative evaluations of historical invasion patterns, ecological requirements, and human-mediated introductions (Erre et al., 2009; Essl & Kobler, 2009). These evaluations can point up locations particularly vulnerable to invasion and direct focused preventive and management policies.

A thorough risk assessment, incorporating case studies from different regions and examining the species' adaptability and reproductive traits, is critical to evaluating its invasive potential under climate change scenarios. The species' wide climatic tolerance and ability to outcompete native species underscore its capacity to establish and spread rapidly in new regions (Jorge et al., 2023; Yahia, 2012).

Combining qualitative and quantitative approaches will help policymakers and land managers create well-informed, workable plans to control *Opuntia* invasion concerns and safeguard sensitive habitats.

Potential economic and ecological impacts

The invasion of *Opuntia* species can have major effects on native ecosystems and human activities, therefore upsetting both ecological and financial aspects. The displacement and competition with native plant species raises a main issue since it reduces biodiversity and changes the structure and function of ecosystems (Bakewell-Stone, 2023; Essl & Kobler, 2009; Jorge et al., 2023; O'Loughlin et al., 2019). The spread of *Opuntia* on pastures and farms also lowers agricultural output and cattle grazing capacity, therefore costing farmers and herders financial losses. Furthermore, the development of thick, impenetrable forests inhibits human and animal mobility, reduces resource access, and disturbs infrastructure (Belayneh, 2018).

Opuntia's flammability and ability to change fuel loads raise even another major issue about fire risk. Invaded areas risk more severe fire regimes and fire breakouts, therefore compromising natural habitats as well as human communities. Apart from that, *Opuntia's* sharp spines and glochids cause human health and safety hazards that result in injuries and infections; on the other hand, the invading species could also have negative effects on tourist and leisure activities in impacted regions.

The ecological effects reach disturbances in nutrient cycling systems and ecosystem services in invaded regions (Belayneh, 2018). This covers effects on cattle output, lower agricultural yields, and damage to natural habitats. Moreover, the expenses related to mechanical, chemical, and biological control strategies for *Opuntia* infestations impose a financial load. Reduced agricultural output, environmental damage, and negative consequences on infrastructure and human well-being generate indirect costs.

The degree of these effects depends on the particular area, environment, and socioeconomic background; so, proactive management techniques become even more important to stop and lessen *Opuntia* invasions. Prioritizing prevention and applying early detection and fast response strategies depend on the identification of high-risk locations, especially under conditions of climate change. To guide resource allocation, inform risk management plans, and solve the problems presented by *Opuntia* invasions, one must first quantify their ecological and financial effects (Bakewell-Stone, 2023; Belayneh, 2018; Jorge et al., 2023).

VI. Case Studies and Management Strategies for *Opuntia* Invasions: Global and Regional Perspectives

Global Case Studies: Lessons for China

Although *Opuntia* has been extensively brought and grown all around, the genus has also become invasive in many areas of the globe with major effects on ecology and economy.

While the focus of this review is on the potential distribution patterns and invasion risk of *Opuntia* in China, it is also important to consider examples from other parts of the world where the genus has become invasive.

For instance, in Australia, several *Opuntia* species have been introduced and have become significant environmental and agricultural pests, causing substantial economic and ecological damage.

Similarly, in parts of Africa, *Opuntia* has been reported to outcompete native vegetation, reduce biodiversity, and negatively impact livestock productivity.

Different management techniques have evolved and been applied following the invasion of *Opuntia* in several areas. *Opuntia* numbers have been somewhat managed using biological control strategies like the cochineal insect and the prickly pear moth—natural enemies. Furthermore, successful in handling *Opuntia* incursions are combined mechanical, chemical, and biological management strategies.
These worldwide case studies provide insightful analysis and lessons that might direct the creation of specific management plans for possible *Opuntia* invasions in China. Learning from these events helps stakeholders use better-educated and successful strategies to lessen *Opuntia's* effects on ecosystems and human activities (Bakewell-Stone, 2023; Essl & Kobler, 2009; Jorge et al., 2023; Yahia, 2012).

1. Invasion in Mediterranean and Developing Countries

The Mediterranean region is recognized as a global invasion hotspot, hence the invasion of alien species in developing countries and the Mediterranean itself presents serious ecological and financial issues.
Invasive species have exploded in this area mostly due to human-mediated routes including commerce and aquaculture, which have resulted in significant financial losses and damage to biodiversity. The Mediterranean basin has lost invasion expenses of around $27.3 billion over the previous three decades, mostly resulting from damages rather than administration expenses (Kourantidou et al., 2021). These challenges underscore the urgent need for coordinated management efforts across nations to address the impacts of invasive species effectively.

Particularly with species like *Opuntia stricta* and *Opuntia* maxima establishing themselves in different areas and aggravating land-cover changes impacting native ecosystems, the invasion of *Opuntia* species in the Mediterranean and developing countries presents major ecological and agricultural challenges. These cacti disturb native flora and wildlife, causing biodiversity loss (Vilà et al., 2003); their successful invasion is aided by mutualistic interactions with nearby seed dispersers, such as birds and animals, therefore improving their spread (Padrón et al., 2011). Agricultural effects are especially noteworthy as the *Opuntia* cochineal scale (Dactylopius opuntiae) has evolved from a biological control agent to a pest endangering key Mediterranean prickly pear crops for food security (Mazzeo et al., 2019). *Opuntia* species have exploded in locations where agricultural land has been abandoned, filling once-used crop fields (Vilà et al., 2003). Their efficient reproductive strategies and the creation of long-term seed banks (Munné-Bosch, 2024). complicate the eradication of these invasive species and call for careful management using a twin approach of prevention and long-term eradication strategies to reduce their impact.

Apart from that, the invading nature of *Opuntia* stricta has become a big concern in many countries, particularly in the Mediterranean basin where it has just been discovered as a pest. Originally common in many different places, including Africa and Asia where it has not yet been recorded as a pest, this species has evaded domestication. Apart from Spain, several North African nations have reported *Opuntia* stricta, highlighting its ability to disturb native ecosystems (Pasiecznik & Rojas-Sandoval, 2007). While successful biological control programs have stopped its

spread in some areas, the possibility of future introduction remains a big issue, particularly concerning the nursery trade.

2. Invasion in Australia and Africa

Originally brought for decorative purposes, the invasion of *Opuntia* species especially *Opuntia aurantiaca* and *Opuntia stricta* has greatly affected ecosystems in Australia and Africa, where these plants have thrived and caused ecological and financial problems. Changes in soil nutrient dynamics define their invasiveness; O. aurantiaca has been demonstrated to raise soil nitrogen and phosphorus contents by factors of up to 7 and 44, respectively (Kawanza et al., 2019). Furthermore, the number and biomass production of native grass species decreases in invaded regions, therefore compromising rangeland productivity (Kawanza et al., 2019). With notable infestations recorded in many areas, O. stricta has established sizable populations across Australia, South Africa, and Namibia.

In Australia, *Opuntia stricta* and *Opuntia aurantiaca* are the most notable invasive species, having escaped cultivation and established widespread populations in southeastern Queensland and northeastern New South Wales (Kawanza et al., 2019; Pasiecznik & Rojas-Sandoval, 2007).

In Africa, the ornamental trade poses a threat to new introductions, as O. pubescens in South Africa (Adamopoulou & Legakis, 2016) shows. Biological control agents including cactus moths and cochineal have been used in management plans to assist in lowering O. aurantiaca numbers (Kawanza et al., 2019). Although invasive, *Opuntia* spp. can also be a valuable feed source for cattle—especially in semi-arid environments (Sipango et al., 2022).

3. Insight in China

Opuntia Invasion in China

Opuntia farming, especially O. ficus-indica, has long been a part of China for different agricultural and horticultural needs. Although *Opuntia* has been extensively brought in and naturalized in many parts of China, the potential distribution patterns and invasion risk under climate change scenarios have not been extensively studied.

Some preliminary studies imply that China's varied climatic conditions—from temperate to subtropical and dry areas—could offer favorable habitats for the spread of Opuntia species (Jorge et al., 2023).

By facilitating the development and dissemination of *Opuntia*, the rising frequency and severity of extreme weather events, including droughts and heat waves, linked with climate change may aggravate the invasion danger.
These elements underline the need for a thorough evaluation of *Opuntia's* possible distribution and invasion risk in China as well as the development of sensible management plans to minimize the financial and environmental effects of possible invasions.

Regional Impacts

The degree of naturalization and invasion by *Opuntia* species in China varies greatly according to the different climatic conditions and habitats found there. *Opuntia* has been recorded to spread widely in arid and semi-arid regions of northwest China, including the Xinjiang Uygur Autonomous Region, sometimes outcompeting native vegetation (Bakewell-Stone, 2023; Essl & Kobler, 2009). In Inner Mongolia and other northern regions, similarly, degraded grasslands and rangelands have seen the development of dense, impenetrable *Opuntia* thickets, so upsetting cattle grazing and restricting access to vital supplies.
Furthermore, greatly affected are coastal areas and islands such as Hainan Province and Taiwan. Here *Opuntia* has invaded and changed coastal ecosystems, therefore changing their dynamics. Southern China's subtropical areas,

including Guangdong and Guangxi provinces, raise further questions since *Opuntia* thrives in these conditions and could endanger nearby ecosystems (Jorge et al., 2023; Yahia, 2012).

These geographic case studies show how easily different Chinese ecosystems might be invaded by *Opuntia*. They stress the need for a thorough, national evaluation to direct policies of management. Minimizing environmental and socioeconomic effects and optimizing *Opuntia's* use depends on balancing its possible advantages with the hazards of invasion.

4. Management Strategies Employed in China

Southern China's Guangdong and Guangxi provinces, where *Opuntia* has been seen to create dense thickets and upset native ecosystems. These regional case studies highlight the several climatic conditions and ecosystems in China that are vulnerable to *Opuntia* invasions, therefore stressing the need for a thorough, national evaluation to direct management activities (Essl & Kobler, 2009; Jorge et al., 2023). *Opuntia* invasions in China have been handled using several tactics with different degrees of effectiveness. Small-scale infestations have been addressed by mechanical management techniques including cutting and hand removal. These techniques, meanwhile, are labor-intensive and frequently unable to stop regeneration from plant fragments left behind. Although chemical control with herbicides has also been investigated, its efficacy is limited and the use of chemicals has hazards of unanticipated environmental effects.

Opuntia might find ideal climatic conditions for establishment and spread in temperate parts of northern China, especially given climate change. Potential *Opuntia* invasions in these regions have environmental and financial effects that need immediate attention and the formulation of sensible management plans.

Combining sustainable practices such as targeted grazing, biological control, and varietal selection could offer more workable long-term fixes for *Opuntia* management (Bakewell-Stone, 2023; Essl & Kobler, 2009; Jorge et al., 2023; Yahia, 2012). These regional case studies highlight the several climate conditions and ecosystems in China vulnerable to *Opuntia* invasions. They underline the need for a thorough, national evaluation to lead and inform management initiatives in line.

5. Successful Management Scenarios and Lessons Learned

Apart from effective management practices, foreign expertise can also offer insightful knowledge to handle possible Opuntia invasions in China. The requirement of early detection and proactive prevention is one of the key lessons. Early detection and management of many invasive species, including *Opuntia*, greatly helps to control them before they have had the chance to spread extensively and inflict major ecological and financial harm. Engagement of stakeholders and cross-sectoral cooperation are still very important lessons as well. Managing *Opuntia* invasions successfully usually calls for the cooperation of several stakeholders, including local people, government agencies, and the sectors of agriculture and forestry. Including these teachings in the evolution of management plans for possible *Opuntia* invasions in China would help to guarantee more durable and successful results.

Although *Opuntia* invasions have presented major difficulties in many areas, China may learn from the successful management initiatives that have been shown here. For example, the cochineal insect's introduction as a biological control agent has been blamed for greatly lowering the abundance of invading *Opuntia* species in numerous Australian regions (Bakewell-Stone, 2023). Likewise, in some regions of Africa, the integration of mechanical, chemical, and biological management strategies together with the encouragement of alternative, non-invasive cultivars has managed to lessen the effects of *Opuntia* invasions (Jorge et al., 2023). These cases show how well a multi-pronged strategy, catered to the local circumstances and problems, can control *Opuntia* invasions.

Although Opuntia has a history of invading various regions of the globe, care is advised when bringing the plant to new sites. For example, the invasion of *Opuntia* species has been observed to alter habitat structure and species composition in the Mediterranean region; albeit dense and extensive stands are restricted to a few species (Essl & Kobler, 2009).

Likewise, in some underdeveloped nations where *Opuntia* was brought for agricultural use, the plant has grown invasive and causes environmental issues, therefore complicating attempts to stop its growth.

One of the most often used and commercially valuable cactus species, *Opuntia* ficus-indica, has caused major environmental problems when it has grown invasive.

O. ficus-indica is even classified as a controlled invasive alien plant in Portugal, indicating awareness of its possible ecological damage (Bakewell-Stone, 2023). These case studies underline the need for a sophisticated approach to the management of *Opuntia*, which balances the possible advantages with the invasion hazards.

Finally, under climate change scenarios, the potential distribution patterns and invasion risk of Genus *Opuntia* in China and other regions of the world demand immediate attention and the creation of sensible management plans (Bakewell-Stone, 2023; Prior et al., 2018; Pyšek & Richardson, 2010; Venette et al., 2021). Learning from other nations and successful management models can help China create a thorough, multi-pronged strategy to handle *Opuntia* invasions and minimize their environmental and financial consequences.

VII. Management Approaches for Controlling *Opuntia* Invasions

Current Management Practices

Opuntia invasions in China have been controlled using several approaches, with varied degrees of success. Small-scale infestations have been addressed with mechanical management techniques including hand removal and cutting; but, these procedures are labor-intensive and frequently unable to stop regrowth from surviving plant pieces (Bakewell-Stone, 2023). Although chemical control with herbicides has also been investigated, its efficacy is limited and the use of chemicals can result in unanticipated environmental effects.

Although grazing livestock, such as goats, has shown some efficacy in lowering *Opuntia* numbers, this approach is not appropriate for every habitat and overgrazing can cause other environmental problems. In some areas, biological control—using natural enemies like the cochineal insect and the prickly pear moth—has shown encouraging effects. But given worries about possible non-target consequences and difficulties with commercial *Opuntia* farming, China has adopted biological control only sparingly (Bakewell-Stone, 2023).

Emphasizing the need for a thorough, national assessment to direct future management efforts, the present management policies in China have had limited success in managing *Opuntia* invasions (Prior et al., 2018; Strek, 2014). In some cases, integrated systems combining mechanical, chemical, and biological control techniques have shown better success. Still, the success of these tactics varies, which emphasizes the need for more coordinated and large-scale initiatives to handle the increasing possibility of *Opuntia* invasions in China.

Prevention Strategies for Future Invasions

Managing *Opuntia* invaders' establishment and spread depends on prevention plans. Addressing infestations before they become uncontrollable depends mostly on early identification and quick reaction. Establishing early warning systems and strong monitoring and surveillance systems helps to enable prompt *Opuntia* detection. Preventing the arrival of *Opuntia* and other invading species into China depends on strengthening border biosecurity policies including inspections and quarantine procedures. Since they help to identify and document *Opuntia* sightings, therefore supporting early detection and prevention initiatives, public awareness and community involvement are equally vital. Encouragement of the adoption of non-invasive *Opuntia* cultivars and discouragement of known invasive species help to further lower the risk of distribution. Moreover, educational programs can enable nearby populations to take part actively in these projects. Combining these initiatives, proactive preventative plans are essential for properly controlling *Opuntia* invasions and shielding China's agricultural systems from their possible consequences (Bakewell-Stone, 2023; Capozzo et al., 2021; Jorge et al., 2023).

Integrated Pest Management and Its Role in Mitigating *Opuntia* Invasions

Managing places where *Opuntia* invasions have already become entrenched depends on control and eradication initiatives. Good management could call for a mix of control strategies. Small-scale infestations can benefit from mechanical control techniques including physical removal, cutting, and burning; yet, sometimes repeated attempts are needed to stop regrowth from plant fragments. Chemical control—using licensed herbicides—can also be beneficial; nevertheless, long-term environmental consequences have to be carefully examined. In some areas, biological

control—using natural enemies like the cochineal bug and the prickly pear moth—has shown potential; but its use has been restricted because of issues over non-target effects and problems with commercial farming. In some fields integrated management strategies combining mechanical, chemical, and biological control techniques have shown greater success. Refining and changing management techniques over time depends on regular monitoring and evaluation of the success of these control initiatives. Further improving control and eradication plans in China is cooperation with outside professionals and learning from effective management practices abroad. By combining knowledge from the worldwide management of *Opuntia* invasions, China can create more sustainable and efficient plans to handle this problem (Bakewell-Stone, 2023; Binny et al., 2021; Funk et al., 2014; Pyšek & Richardson, 2010).

Recommendations for Future Management

Based on the review of potential distribution patterns and invasion risk assessment of the genus *Opuntia* in China and other parts of the world, the following recommendations are proposed for future management. To properly control *Opuntia* invasions, integrated pest management techniques should incorporate early identification, preventive, and control tactics. These approaches should include mechanical, chemical, and biological control techniques, catered to the particular environmental and financial situation of every area of China. Furthermore very important in an integrated pest control strategy is encouraging the abundance and variety of helpful species including pollinators, decomposers, and natural enemies (Anderson et al., 2019). From a policy standpoint, it is imperative to create and implement thorough laws and rules to stop Opuntia and other invading species from being introduced and proliferated. Effective use and adaption of management systems depend on including pertinent stakeholders including land managers, farmers, conservation groups, and residents. Further improving these initiatives is giving landowners and land managers incentives and helping to implement best practices for controlling *Opuntia* invasions (Amede et al., 2007; Stanturf et al., 2009).

VIII. Conclusion

The potential distribution and invasion risk of Genus *Opuntia* in China and other parts of the world under climate change scenarios is a significant concern that requires comprehensive and coordinated management efforts. Although various control techniques have been tried, their efficacy has been erratic; so, more study and money are required to create and apply integrated pest management plans. China can better safeguard its ecosystems and agricultural systems from the possible effects of *Opuntia* invasions by using a multifarious strategy combining preventive, early identification, and control actions.

Summary of Key Findings

Globally and in China, climate change is predicted to modify the geographic ranges and effects of invading species including *Opuntia*. Mechanical, chemical, and biological control techniques among other management approaches have been used to control *Opuntia* invasions to varied degrees of success. *Opuntia* invasions in other areas have shown more potential for integrated pest management techniques, which mix several control tactics. Preventing the start and spread of these invasions depends on early identification and fast reaction. Key elements of good prevention and management plans are strengthening biosecurity policies, raising public awareness, and encouraging participation of stakeholders. Management of *Opuntia* invasions in China depends critically on early detection and proactive prevention. To handle the potential hazards *Opuntia* presents under climate change scenarios, ongoing study and funding in integrated pest management techniques are required.

Implications for Biodiversity and Ecosystem Health

Particularly in areas with great degrees of endemism and ecological sensitivity, the invasion of *Opuntia* species seriously jeopardizes biodiversity and ecosystem integrity. Native plant species can be outcompeted by *Opuntia* invasions, change the structure and function of ecosystems, and disturb ecological processes including nitrogen cycling pollinator activity and other positive organism activity. Maintaining China's natural habitats' special biodiversity and ecological integrity depends on addressing *Opuntia* invasion.

Future Research Directions

To better understand and address the potential distribution patterns and invasion risk of the genus *Opuntia* in China under climate change scenarios, several future research directions are proposed. Filling in knowledge regarding the biological and ecological traits of *Opuntia* species, their possible distribution patterns, and the interaction between climate change and invasion dynamics requires targeted study. Especially in sensitive or protected areas, it is imperative to look at the long-term effects of *Opuntia* invasions on biodiversity, ecological functions, and ecosystem services. Programs for thorough and long-term observation should be started to track the range, quantity, and effects of *Opuntia* invasions over several parts of China. These initiatives should combine fresh research results and best practices from other areas with regular assessments of the success of control measures and modification of management tactics.

Author Contributions

Conceptualization ZQ; Literature Search, SLG; KL; Writing-original draft preparation SLG; Writing-review

& editing, SLG; KL; and ZG;

Conflicts of Interest

The authors have no conflicts of interest to declare relevant to this article's content.

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