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

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Abstract

The genus *Opuntia* (prickly pear cactus) has become an increasingly problematic invasive species in various parts of the world, including China. This review evaluates the potential distribution and invasion risk of *Opuntia* under climate change scenarios, focusing on its ecological impacts, current management strategies, and recommendations for future control efforts. We explore the biological characteristics that facilitate its spread, the species' current distribution in China, and the environmental factors influencing its expansion. Management approaches, including mechanical, chemical, and biological control methods, are critically assessed, with integrated pest management (IPM) emerging as a promising strategy. Challenges such as non-target effects of biological controls, limited effectiveness of mechanical and chemical methods, and ecological concerns are discussed. Proactive prevention strategies, including early detection, public awareness, and biosecurity measures, are essential for mitigating future invasions. The review highlights the need for ongoing research to better understand the dynamics of *Opuntia* invasions and the development of more effective, region-specific management practices. Future directions should focus on improving early-warning systems, enhancing stakeholder engagement, and fostering adaptive management strategies to address the growing threat posed by *Opuntia* in China's ecosystems and agricultural sectors.

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

I. Introduction

The genus *Opuntia*, commonly known as prickly pear cactus, is a widely distributed group of succulent plants native to the Americas. These plants have gained significant attention due to their potential for commercial cultivation as a source of food, fodder, and various other products. (Martins et al., 2023; Stintzing & Carle, 2005) . However, the introduction of *Opuntia* species to regions outside their native range has also led to concerns about their potential invasiveness and the impact on local ecosystems. (Bakewell-Stone, 2023). The genus *Opuntia*, part of the Cactaceae family, comprises over 200 species, with *Opuntia ficus-indica* Mill. being the most widely cultivated and commercially significant species (Stintzing & Carle, 2005). These plants are distinguished by their flat, paddle-like cladodes (stem segments) and the presence of spines, which vary in size and density (Reyes-Agüero et al., 2006). *Opuntia* species are highly adaptable to diverse environmental conditions, including drought, high temperatures, and poor soil, which contribute to their resilience and success in both native and introduced ranges. Climate change is anticipated to further influence the distribution patterns and invasion potential of these plants (Bakewell-Stone, 2023; Jorge et al., 2023)

Prickly pear cacti are defined by their distinctive cladodes, which serve as the primary photosynthetic organs and enable water storage in their fleshy tissues, allowing them to survive in arid and semi-arid environments. These adaptations make *Opuntia* species particularly suited to extreme environmental conditions (Eggli & Nyffeler, 2009)

Beyond their resilience, *Opuntia* holds significant importance in agriculture, ecology, and culture. They are cultivated for their edible fruits, pads (cladodes), and seeds, which serve as sources of food, fodder, and other products. Ecologically, they play vital roles in arid and semi-arid ecosystems by providing food and habitat for various wildlife. Culturally, the prickly pear cactus has symbolic and traditional significance, especially in Latin America, where it is deeply integrated into local customs and traditions (Ciriminna et al., 2019; Mayer & Cushman, 2019; Yahia, 2012).

The genus *Opuntia*, commonly known as prickly pear cactus, exhibits a broad distribution, encompassing both its native range in the Americas and regions where it has been introduced. This includes an overview of its historical and current distribution patterns, as well as projections for future changes under climate change scenarios (JON P. REBMAN1AND DONALD J. PINKAVA, 2001; Jorge et al., 2023).

Historically, *Opuntia* species are native to the Americas, with the greatest diversity found in Mexico and the southwestern United States. Over time, these species have been introduced to other regions, including Africa, Europe, Asia, and Australia, primarily for agricultural and ornamental purposes (Bakewell-Stone, 2023; Chávez-Moreno et al., 2013). Currently, *Opuntia* species are present on every continent except Antarctica, with established populations in numerous countries. Their distribution is influenced by factors such as climatic conditions, soil characteristics, and human activities, including both intentional introductions and unintentional spread. Mapping efforts have provided valuable insights into their current distribution patterns (Erre et al., 2009; Yahia, 2012). Looking ahead, climate change is expected to significantly affect the future distribution of *Opuntia*. Modeling approaches predict shifts in suitable habitats for various species under different climate scenarios, helping identify regions that may become more or less conducive to *Opuntia* growth and invasion in the coming decades (Fuller et al., 2010; Ureta et al., 2018).

The comprehensive assessment of invasion risks for the genus *Opuntia* requires a thorough analysis of the factors contributing to their invasive potential, including biological characteristics, ecological interactions, and the influence of human activities (Jorge et al., 2023; Stintzing & Carle, 2005). *Opuntia* species exhibit several biological traits that enhance their invasiveness, such as rapid vegetative growth, efficient seed dispersal mechanisms, tolerance to various environmental stressors, and the ability to outcompete native plant species, allowing them to colonize and dominate disturbed habitats (CABI, 2019b). Ecologically, *Opuntia* invasions can significantly impact local ecosystems by altering habitat structure and species composition and disrupting native plant-animal interactions, such as pollination and seed dispersal networks. Additionally, their introduction can facilitate the establishment of other invasive species through habitat modifications (Essl & Kobler, 2009). Human-mediated activities, including intentional introductions for agricultural, horticultural, and ornamental purposes, as well as unintentional dispersal through contaminated products and vehicles, have been major contributors to the spread of *Opuntia*. The lack of effective management and control measures in some areas further exacerbates invasion risks (Bakewell-Stone, 2023).

Opuntia species exhibit several biological characteristics that enhance their invasive potential, including rapid vegetative growth and propagation through cladode fragmentation (Essl & Kobler, 2009; Reyes-Agüero et al., 2006), efficient seed dispersal mechanisms often facilitated by animals, and a high tolerance to diverse environmental conditions such as drought and poor soils. These species can outcompete native plants and colonize disturbed habitats (Bakewell-Stone, 2023; Essl & Kobler, 2009). Ecologically, *Opuntia* invasions can significantly alter habitat structure and species composition in natural and semi-natural ecosystems, disrupt native plant-animal interactions such as pollination and seed dispersal networks, and facilitate the establishment of other invasive species through habitat modifications (Belayneh, 2018; Weber, 2004). Human activities also play a critical role in their spread, including intentional introductions for agricultural, horticultural, and ornamental purposes, unintentional dispersal via contaminated agricultural products, machinery, and vehicles, and inadequate management and control measures in some regions (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*

Suggestion: Avoid excessive details about individual studies unless directly relevant to the current argument.

Move the detailed biological characteristics that facilitate invasion described in the introduction to this section. Some points about Opuntia's invasiveness are repeated across multiple paragraphs. Consolidating these ideas will help improve readability and avoid redundancy.

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. These species are known to disturb natural ecosystems in a variety of ways, including through mutualism disruption and allelopathy. Controlling these species requires a multifaceted approach that considers ecological, chemical, and technological aspects.

Numerous studies on invasion and control have focused on *Opuntia* species, including *Opuntia stricta*, *Opuntia ficus-indica*, *Opuntia monacantha*, and *Opuntia humifusa*, because of their widespread influence as invasive species. Since their introduction, these cacti have proliferated all over the world, often avoiding domestication and becoming invasive in regions such as the Mediterranean, Africa, and Australia. Due to variations in local abiotic circumstances, invader abundance, and native community characteristics and composition, the effects of a biological invasion on native communities are anticipated to be unequal throughout invaded regions. Exploiting the known mechanisms that drive the success of invasive species is one technique to increase predictive capacity regarding the impact of an invasive species given changeable conditions. Allelopathic characteristics, which can be poisonous to plants directly or indirectly through upsetting root symbionts like mycorrhizal fungus, are commonly seen in invasive species. It is anticipated that plants that depend on mycorrhizas will be impacted by the indirect method, which disrupts mutualism, but non-mycorrhizal plant species will not be impacted (Roche et al., 2023).

A mixed planting experiment with native Lactuca indica and four invasive species revealed that the native plant's response depends on the invasive species' identity and diversity. The study found that the native plant's total biomass increases at low invasive plant richness and decreases at high density. The leaf nitrogen concentration of the native plant increases with invasive plant richness, indicating a greater influence from invasive plant identity (Kama et al., 2023).

Exotic invasive flora is gaining traction due to human mobility, international commerce, and climate change. They alter ecosystems by emitting secondary metabolites, such as root exudates and volatile organic compounds (VOCs). These compounds have been extensively researched and are known to enhance invasiveness. However, their ecological impacts remain poorly understood. A systematic review of literature from 2012-2022 found that invasive species have greater chemical diversity and distinct chemical behavior in native versus invaded regions. Factors influencing VOC emissions include herbivory, soil microbes, temperature increases, and carbon dioxide levels. Invasive plants may exhibit reduced variability in VOC emissions due to environmental changes (Clavijo McCormick et al., 2023). Invasive alien species pose significant threats to biodiversity and ecosystem services. To manage them, understanding their distribution and proliferation mechanisms is crucial. Unmanned aerial vehicle (UAV) surveillance is an effective method for collecting data. A study assessed the efficacy of six RGB indices for identifying invasive plant species using UAV imagery. Results showed that TGI and SSI indices were most accurate for common milkweed cover area, while if index was most appropriate for blanket flower cover area. These methodologies enable efficient, rapid, and economical data processing for conservation professionals (Bakacsy et al., 2023). Although the emphasis is on the invasive characteristics of *Opuntia* species, it is crucial to acknowledge the possible advantages they may provide, including their application in arid land agriculture and as a food source. 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,*	Distribution and Naturalization	(Bagrikova & Perminova, 2022)

		O.phaeacantha, *O.polyacantha,* *O.tortispina,* *O.tunoidea*		
	Mexico	15% of *Opuntia species* *O.ficus-indica* *O.albicarpa* *O.megacantha* *O.xoconostle,* *O.robusta* *O.streptacantha* *O.vulgaris,* *O.microdasys,* *O.dillenii O.dejecta* *O.hyptiacantha,*	Genetic Diversity and Taxonomy, Implications for Biodiversity and Agriculture 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*	(Caruso et al., 2010) (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* *O.bonaerensis*	Initial performance evaluation of *Opuntia spp.* Conservation and Biogeographic History	(Santos et al., 2023) (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	*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	Decline in Invasion Risk in Southern Africa, Genetic Diversity and Adaptation,	(Omer et al., 2024)

		Opuntia fcus-indica (L.) Mill	Economic Contribution Demographic Insights Lack of Awareness Socio-Economic Factors Gender Dynamics Uses of Prickly Pear Policy Implications Global Studies on *Opuntia ficus-indica*	(Modise et al., 2024) (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	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 Biological Properties and Applications 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,*	Challenges in Management	(Humphries et al., 2022)

		O.monacantha		
	------------------	*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

The section about *Opuntia* being native to the Americas and having spread globally appears a couple of times, almost verbatim. It would be helpful to consolidate the information to avoid repetition.

Historical Distribution

The genus *Opuntia*, commonly known as prickly pear cactus, is native to the Americas, with a distribution ranging from Canada to Chile (Bakewell-Stone, 2023; Jorge et al., 2023). The native range of *Opuntia* includes desert, semi-desert, and dry, subtropical regions, where the plants have adapted to thrive in arid and semi-arid environments. *Opuntia* species have been widely introduced and cultivated in many parts of the world, including Africa, Europe, Asia, and Australia, often for use as a fruit crop, livestock feed, or ornamental purposes (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).

The wide distribution and successful introduction of *Opuntia* in many parts of the world can be attributed to several factors, including its ability to propagate vegetatively, the dispersal of its fruits and seeds by animals, and its adaptability to diverse environmental conditions, including drought tolerance and the capacity to grow in nutrient-poor soils (Bakewell-Stone, 2023; Reyes-Agüero et al., 2006). *Opuntia* is native to the Americas, with a distribution ranging from Canada to Chile. The genus is well-adapted to desert, semi-desert, and dry, subtropical regions, where it has evolved to thrive in arid and semi-arid environments (Yahia, 2012). Over time, *Opuntia* species have been widely introduced and cultivated in many parts of the world, including Africa, Europe, Asia, and Australia, often for use as a fruit crop, livestock feed, or ornamental purposes.

In some cases, introduced *Opuntia* populations have become naturalized and invasive in these new regions, posing a threat to native ecosystems. This can be attributed to the genus' ability to propagate vegetatively, the dispersal of its fruits and seeds by animals, and its adaptability to diverse environmental conditions, including drought tolerance and the capacity to grow in nutrient-poor soils (Parker et al., 2013; Rojas-Sandoval & Acevedo-Rodríguez, 2014).

Current Distribution

Opuntia species are currently found in a variety of regions around the world, with the genus being most widespread in the Americas, where it is native. Outside of its native range, *Opuntia* has been introduced and naturalized in many parts of the world, including Africa, Europe, Asia, and Australia (Bakewell-Stone, 2023; CABI, 2019a; Yahia, 2012).

In China, *Opuntia* species have been introduced and cultivated, primarily for their edible fruits and as a fodder crop. However, some introduced populations have become invasive, particularly in the southern and central regions of the country. Other regions, such as parts of Europe and Africa, have also reported the naturalization and invasive spread of *Opuntia* species, which can have significant impacts on local ecosystems and biodiversity (Jorge et al., 2023; Tesfay & Kreyling, 2021; Witt et al., 2020). Ongoing monitoring and surveillance efforts are necessary to track the spread and distribution of *Opuntia* species in China and other regions, as their potential for invasion and impact on native ecosystems can be significant.

Mapping of existing populations in China and globally

Opuntia species are currently found in a variety of regions around the world, with the genus being most widespread in the Americas, where it is native. Outside of its native range*, Opuntia* has been introduced and naturalized in many parts of the world, 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.

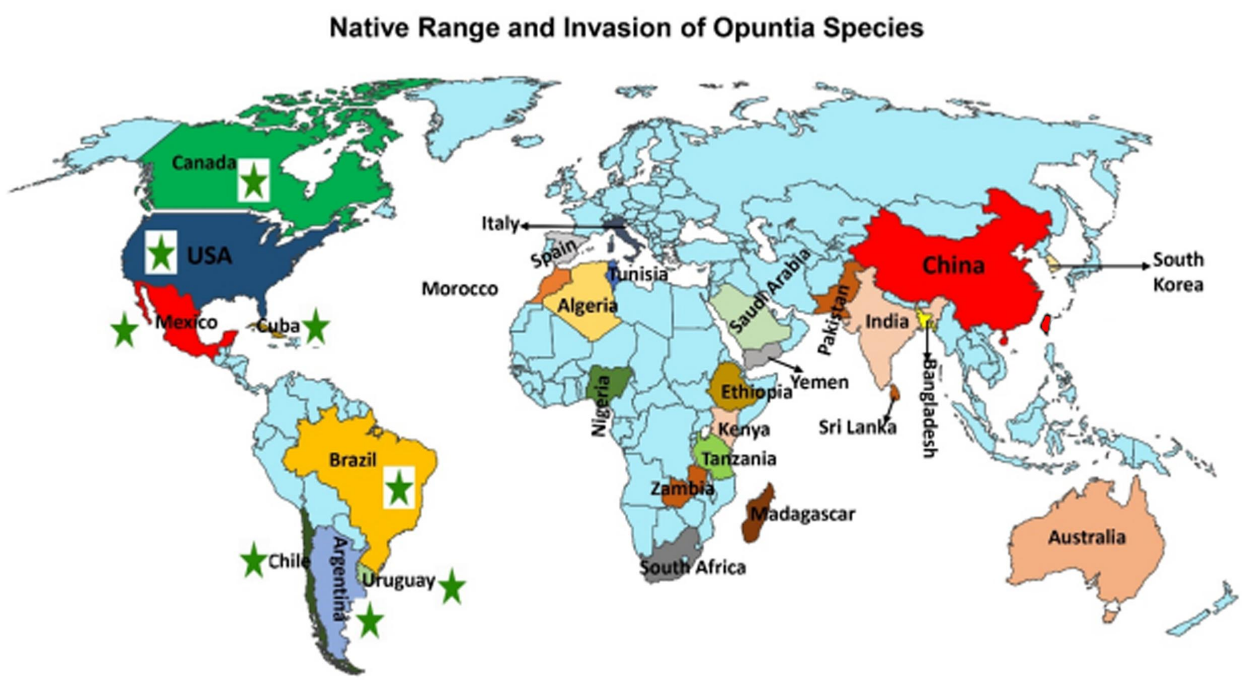

Figure 1. The map depicting the native range (marked with green stars) and the global invasion of Opuntia species.

In China, *Opuntia* species have been introduced and cultivated, primarily for their edible fruits and as a fodder crop. Ongoing monitoring and surveillance efforts are necessary to track the spread and distribution of *Opuntia* species in China and other regions, as their potential for invasion and impact on native ecosystems can be significant. Figure 2 shows the map of *Opuntia* Invasion in Chinese Provinces.

Figure 2. The map of Opuntia Invasion in Chinese Provinces

Factors influencing the current distribution

The current distribution of *Opuntia* species is shaped by several factors, including historical introductions and cultivation for purposes such as fruit production, livestock feed, and ornamental uses. Their adaptability to diverse environmental conditions, including drought tolerance and the ability to thrive in nutrient-poor soils, has further facilitated their establishment in a wide range of habitats. Additionally, *Opuntia* species exhibit effective vegetative propagation and seed dispersal mechanisms, often aided by animals, enabling them to spread and establish populations in new regions (Dudai, 2012; Missiakô Kindomihou, 2020).

To mitigate the potential impacts of *Opuntia* on native ecosystems, continued monitoring and management efforts are essential in regions where these species have been introduced.

Projected Distribution under Climate Change Scenarios

Climate change is expected to have significant impacts on the potential distribution of *Opuntia* species, both in their native ranges and in areas where they have been introduced.

Warming temperatures and changes in precipitation patterns are likely to alter the suitability of habitats for *Opuntia*, potentially leading to range expansions in some regions and contractions in others.

Regions that are currently unsuitable for *Opuntia* may become more suitable, leading to the potential for new introductions and invasions. Conversely, areas that are currently suitable may become less so, potentially leading to the decline or extirpation of existing populations (Langille et al., 2017; Strum et al., 2015; Yadav et al., 2018).

Various modeling approaches, such as species distribution modeling and climate-based risk assessment, are used to project the potential distribution of *Opuntia* species under different climate change scenarios. These models incorporate factors like temperature, precipitation, and other climatic variables, alongside information on the species ecological requirements and current distribution, to estimate areas that may become suitable or unsuitable for *Opuntia* in the future (Erre et al., 2009; Mtengwana et al., 2021; Ureta et al., 2018).

Based on climate change projections, the distribution of *Opuntia* species is expected to shift in the coming decades. Regions currently unsuitable may become more suitable, potentially facilitating the introduction and establishment of *Opuntia* in new areas. Conversely, some areas currently suitable may become less so, leading to the decline or extirpation of existing populations. Given *Opuntia's* history of invasiveness in many parts of the world, caution is essential when considering its 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 substantial changes, primarily driven by human activities that have altered the global atmosphere and environment. Since the late 19th century, global average temperatures have risen by approximately 1.1°C, a trend that is projected to continue (Jorge et al., 2023). Precipitation patterns have also shifted, with some regions experiencing more intense rainfall while others face prolonged droughts. These changes in temperature and precipitation have far-reaching implications for ecosystems, biodiversity, and human communities worldwide (Jorge et al., 2023; Rajpoot et al., 2020)Key climate change factors influencing the distribution and invasion potential of *Opuntia* include rising atmospheric carbon dioxide concentrations, global temperature changes, and alterations in precipitation patterns. Atmospheric carbon dioxide levels have increased by over 40% since the Industrial Revolution, directly affecting plant growth, including the photosynthetic efficiency and water-use capabilities of *Opuntia* species (Langille et al., 2017). Elevated CO_2 levels may enhance the growth and productivity of *Opuntia*, potentially increasing its competitive ability and invasiveness; however, specific responses to elevated CO_2 remain poorly understood and require further research (Skendžić et al., 2021; Ziska et al., 2018).

Rising global temperatures are expected to significantly influence *Opuntia* distribution. Warmer temperatures may allow *Opuntia* to expand into higher latitudes and elevations previously limited by colder conditions. However, increased frequency and intensity of heatwaves and droughts may negatively impact certain *Opuntia* populations in some regions. The Earth's average surface temperature has already increased by approximately 1.1°C, with most of this warming occurring in recent decades, and projections indicate continued warming depending on future greenhouse gas emissions (Jorge et al., 2023; Langille et al., 2017; Sharma & Prabhakar, 2014).

Alterations in precipitation patterns also play a critical role in shaping Opuntia's distribution and invasion potential. Changes in precipitation regimes, such as prolonged droughts or intense rainfall events, may affect habitat suitability for *Opuntia*, enabling expansion into previously unsuitable areas while reducing suitability in others. Increased water availability in some regions and decreased availability in others could significantly influence *Opuntia* dispersal and establishment (Skendžić et al., 2021).

Future climate change scenarios, including those outlined by the Intergovernmental Panel on Climate Change's Representative Concentration Pathways, provide valuable projections for assessing potential shifts in *Opuntia* distribution and invasion risks across different regions. These insights will inform strategies for managing the impacts of climate change on *Opuntia* populations (Gong et al., 2020; Langille et al., 2017; Skendžić et al., 2021; Ziska et al., 2018)

Future Projections

Climate change models and scenarios, such as the Representative Concentration Pathways developed by the Intergovernmental Panel on Climate Change, provide projections for future climate conditions. These models suggest that the magnitude and rate of climate change are likely to increase in the coming decades, with significant implications for the distribution and invasion potential of many plant species, including *Opuntia*.

Evidence suggests that climate change can significantly alter the abundance and distribution of invasive species, including the genus *Opuntia* (Skendžić et al., 2021). Changes in key environmental factors, such as temperature and precipitation, can influence a species' ability to survive and thrive in new regions, potentially leading to increased invasion risks Regional climate models relevant to China and other areas:

Various climate change scenarios, such as the Representative Concentration Pathways, provide projections for future temperature and precipitation patterns in different regions. These models suggest that the magnitude and rate of climate change are likely to increase in the coming decades, with significant implications for the distribution and invasion potential of many plant species, including *Opuntia*.

For example, climate models predict that the potential distribution of *Opuntia* may expand in northern latitudes, where warmer temperatures and milder winters could allow the species to establish and spread. 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).

The introduction and spread of invasive *Opuntia* species can have significant impacts on native ecosystems, including competition with native plants, alteration of fire regimes, and changes in habitat structure and resources.

The potential for increased distribution and abundance of *Opuntia* under climate change scenarios could threaten the biodiversity of regions where it is introduced, as the species can outcompete and displace native plant communities (Bakewell-Stone, 2023).

V. Invasion Risk Assessment

Definition and Importance of Invasion Risk Assessment

Invasion risk assessment is a critical tool for evaluating the potential for a non-native species to become invasive in a new region.

It involves systematically evaluating factors that can influence the likelihood of a species successfully establishing, spreading, and causing harmful impacts in an area 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

Several key factors contribute to the invasion risk of *Opuntia* species. Climate suitability plays a significant role, as *Opuntia* can adapt to a wide range of climatic conditions, including varying temperature and precipitation regimes. Additionally, their efficient reproductive and dispersal mechanisms, such as vegetative propagation and animal-mediated seed dispersal, facilitate their spread and establishment in new areas (Bakewell-Stone, 2023; O'Loughlin et al., 2019)The competitive abilities of *Opuntia,* including their tolerance of drought, nutrient-poor soils, and ability to outcompete native vegetation, further enhance their invasive potential (Bakewell-Stone, 2023). The lack of natural enemies, such as predators, pathogens, or herbivores, in introduced regions also contributes to their invasive success. Moreover, propagule pressure, defined by the frequency and magnitude of introduction events and the number of individuals introduced, influences the likelihood of their establishment (Essl & Kobler, 2009).

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. By outcompeting and displacing native vegetation, *Opuntia* can alter ecosystem structure and composition. Understanding these characteristics and invasion pathways is critical for developing effective risk assessment frameworks for *Opuntia* species.

Ecological Interactions

The invasion of *Opuntia* species can have profound impacts on ecosystems and human activities. *Opuntia* invasions often alter the structure and composition of native plant communities, outcompeting and displacing native species.

These invasions can also affect soil properties and nutrient cycling, leading to changes in ecosystem functioning. Interactions with native fauna, such as herbivores and pollinators, are also disrupted by the presence of *Opuntia.* Understanding these ecological interactions is crucial for assessing the impacts of *Opuntia* invasions and developing effective management strategies.

The ecological impacts of *Opuntia* invasions are significant, as the species can outcompete native plants and alter ecosystem structure and function, resulting in negative consequences for biodiversity and ecosystem services (Essl & Kobler, 2009). *Opuntia* thrives in nutrient-poor, disturbed habitats, giving it a competitive advantage over native species (Essl & Kobler, 2009). Its efficient dispersal mechanisms, including animal-mediated seed dispersal and vegetative propagation, further facilitate its spread into new (Jorge et al., 2023; Weber, 2004).

Additionally, *Opuntia* invasions pose economic challenges. These include reduced agricultural productivity, increased costs for management and control, and decreased property values. Invasion risk assessment is a critical tool for evaluating the potential for non-native *Opuntia* species to become invasive in new regions, enabling proactive measures to mitigate their ecological and economic impacts.

Human Activities and Spread

The introduction and spread of *Opuntia* species in new regions have been significantly influenced by various human activities. One major factor is commercial cultivation, where *Opuntia* has been widely introduced as a crop for fruit, fodder, and other agricultural purposes, leading to its establishment in numerous regions worldwide (Bakewell-Stone, 2023; Ciriminna et al., 2019; Mohamed–Yasseen et al., 1996). Additionally, *Opuntia* species are often cultivated for their aesthetic appeal as ornamental plants, which can result in their escape and naturalization in the wild. Beyond intentional cultivation, *Opuntia* has also been utilized for agricultural applications such as food crops and animal fodder, further promoting its spread (Bakewell-Stone, 2023). Human-mediated pathways have played a key role in the inadvertent spread of *Opuntia*. The transportation of livestock, machinery, and goods has facilitated the unintentional movement of *Opuntia* fruits and seeds, while vehicles and machinery have been particularly effective in dispersing these species into new areas (CABI, 2019a, 2019b). Traffic and transportation activities, such as the movement of goods and livestock, further contribute to the species' dispersal. Human-driven pathways, whether intentional or accidental, have been critical in the global spread of *Opuntia*. To address this issue, a comprehensive assessment of these factors is essential, alongside consideration of their ecological and socio-economic impacts. Such evaluations can inform effective decision-making and management strategies, enabling the prevention of new introductions, the control of existing populations, and the mitigation of negative impacts on native ecosystems and human activities.

Assessment Methodologies

To assess the invasion risk and potential distribution patterns of *Opuntia* species under climate change scenarios, a combination of methodological approaches can be employed. These include both qualitative and quantitative strategies. Qualitative risk assessments rely on expert-based evaluations of *Opuntia's* characteristics and invasion history, while quantitative approaches utilize tools such as species distribution modeling and climate niche modeling to predict potential invasion patterns (Essl & Kobler, 2009; Jorge et al., 2023).

Case studies from regions where *Opuntia* is present or has the potential to invade, such as China, provide valuable insights into the species' behavior, impacts, and likelihood of further spread. Key aspects to consider 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 effectiveness of existing management strategies effectiveness (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.

A multi-faceted approach is essential to evaluate *Opuntia's* potential invasion risks comprehensively. This includes combining qualitative and quantitative assessment methods with regional case studies, while also considering the species' current distribution, habitat preferences, and ecological and socio-economic impacts. Such an integrated framework is crucial for developing effective strategies to mitigate the risks associated with *Opuntia* invasions in the context of a changing climate (Bakewell-Stone, 2023; Jorge et al., 2023; O'Loughlin et al., 2019; Ziska et al., 2018).

Risk Assessment Results

Opuntia species possess significant invasive potential, posing ecological, economic, and management challenges that require comprehensive risk assessments and proactive mitigation strategies. Key findings from risk assessments highlight that *Opuntia* species have a high likelihood of further expansion and invasion, particularly under climate change scenarios. 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 significant economic consequences, such as reduced agricultural productivity, increased management costs, and decreased property values (Bakewell-Stone, 2023; O'Loughlin et al., 2019). Additionally, the spread of *Opuntia* can disrupt native ecosystems, altering the structure and composition of flora and fauna.

Effective management strategies are critical to mitigate these risks. Early detection, rapid response, and the integration of mechanical, chemical, and biological control methods have proven effective in managing *Opuntia* invasions. Proactive and integrated approaches, including containment and targeted control measures, are essential to prevent and mitigate the negative impacts of *Opuntia* invasions in China and other regions. The widespread human-mediated introduction and cultivation of *Opuntia* for commercial and ornamental purposes have significantly contributed to its global spread, emphasizing the need for improved regulation and risk management strategies.

By comprehensively assessing the potential distribution patterns, invasion risks, and impacts of *Opuntia* under climate change scenarios, policymakers, and land managers can develop more informed strategies for preventing and mitigating the consequences of its invasions. A multifaceted approach, incorporating both qualitative and quantitative methods and analyzing regional case studies, is essential for understanding the species' invasive potential and devising effective management solutions (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). Furthermore, areas with a high degree of human-mediated disturbance, such as agricultural lands, urban areas, and transportation corridors, can facilitate the establishment and spread of *Opuntia* (Jorge et al., 2023).

Opuntia species thrive in regions with a high proportion of suitable habitats, such as nutrient-poor, semi-arid, and disturbed environments, which align closely with their ecological requirements (O'Loughlin et al., 2019). Identifying these high-risk areas is essential for prioritizing prevention and management efforts, as well as implementing early detection and rapid response mechanisms to mitigate potential invasions. *Opuntia ficus-indica* has a well-documented history of invasiveness in various regions, including the Mediterranean and drylands, where it has caused significant ecological and socio-economic impacts on native ecosystems and human activities.

The factors driving *Opuntia's* invasive potential and distribution patterns under climate change scenarios are diverse. Key contributors include its adaptability to a wide range of climatic conditions, including drought tolerance and the ability to thrive in nutrient-poor, disturbed environments (Bakewell-Stone, 2023). Its prolific vegetative reproduction through fragmentation, coupled with efficient seed dispersal mechanisms often facilitated by animals, enables rapid establishment and long-distance spread. Additionally, human-mediated introductions for agricultural, ornamental, and other purposes have facilitated its expansion. Historical patterns of invasion further show that *Opuntia* often establishes successfully in regions with climatic conditions similar to its native range.

To comprehensively assess the invasion risk and potential distribution patterns of *Opuntia* in China and other parts of the world, an integrated, multidimensional approach is necessary. This includes qualitative analyses of historical invasion patterns, ecological requirements, and human-mediated introductions, alongside quantitative modeling of climatic suitability and habitat preferences (Erre et al., 2009; Essl & Kobler, 2009). Such assessments can identify areas at high risk of invasion and guide targeted prevention and management strategies.

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).

By integrating qualitative and quantitative methods, policymakers and land managers can develop informed, effective strategies to manage the risks associated with *Opuntia* invasions and protect vulnerable ecosystems.

Potential economic and ecological impacts

The invasion of *Opuntia* species can result in profound economic and ecological consequences, significantly disrupting native ecosystems and human activities. A primary concern is the displacement and competition with native plant species, leading to reduced biodiversity and alterations in ecosystem structure and function (Bakewell-Stone, 2023; Essl & Kobler, 2009; Jorge et al., 2023; O'Loughlin et al., 2019). The proliferation of *Opuntia* in farmlands and pastures also reduces agricultural productivity and livestock grazing capacity, causing economic losses for farmers and herders. Moreover, the formation of dense, impenetrable thickets restricts movement for humans and animals, limits access to resources, and disrupts infrastructure (Belayneh, 2018).

Another significant concern is the heightened risk of fire due to *Opuntia's* flammability and its capacity to alter fuel loads. Invaded regions face an increased likelihood of fire outbreaks and more severe fire regimes, threatening both natural habitats and human settlements. In addition, the sharp spines and glochids of *Opuntia* pose human health and safety risks, leading to injuries and infections, while the invasive species can also negatively affect tourism and recreational activities in affected areas.

The ecological impacts extend to disruptions in ecosystem services and nutrient cycling processes in invaded areas (Belayneh, 2018). This includes the degradation of natural habitats, reduced agricultural yields, and impacts on livestock productivity. Furthermore, the costs associated with controlling and eradicating *Opuntia* infestations—including mechanical, chemical, and biological control methods—add an economic burden. Indirect costs arise from reduced agricultural productivity, habitat degradation, and adverse effects on infrastructure and human well-being.

The severity of these impacts varies depending on the specific region, ecosystem, and socio-economic context, emphasizing the importance of proactive management strategies to prevent and mitigate *Opuntia* invasions. Identifying high-risk areas, particularly under climate change scenarios, is critical for prioritizing prevention and implementing early detection and rapid response measures. Quantifying the economic and ecological impacts of *Opuntia* invasions is essential for informing risk management strategies, guiding resource allocation, and addressing the challenges posed by this invasive species (Bakewell-Stone, 2023; Belayneh, 2018; Jorge et al., 2023).

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

While *Opuntia* has been widely introduced and cultivated globally, the genus has also become invasive in many parts of the world, causing significant ecological and economic impacts.

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.

The invasion of *Opuntia* in various regions has led to the development and implementation of diverse management strategies. Biological control methods, such as the use of natural enemies like the cochineal insect and the prickly pear moth, have demonstrated some success in managing *Opuntia* populations. Additionally, integrated approaches that combine mechanical, chemical, and biological control methods have proven effective in addressing *Opuntia* invasions.

These global case studies offer valuable insights and lessons that can guide the development of tailored management strategies for potential *Opuntia* invasions in China. By learning from these experiences, stakeholders can implement more informed and effective approaches to mitigate the impacts of *Opuntia* on ecosystems and human activities (Bakewell-Stone, 2023; Essl & Kobler, 2009; Jorge et al., 2023; Yahia, 2012).

1. Invasion in Mediterranean and Developing Countries

Because the Mediterranean region is identified as a worldwide invasion hotspot, the invasion of alien species in the Mediterranean and developing nations poses major ecological and financial problems. 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.

In addition, *Opuntia* stricta's invading character has grown to be a major issue in many nations, especially in the Mediterranean basin where it has just been identified as a pest. Originally widespread in many areas, particularly in Africa and Asia where it has not yet been documented as a pest, this species has avoided domestication. *Opuntia stricta* has been observed in various North African countries as well as Spain, underscoring its ability to upset indigenous ecosystems (Pasiecznik & Rojas-Sandoval, 2007). Although effective biological control initiatives have helped stop its spread in certain places, the potential for further introduction is still a major concern, especially 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). Though invasive, *Opuntia* spp. can also be a good source of feed for cattle, especially in semi-arid areas (Sipango et al., 2022).

3. Invasion in China and Regional Impacts

China has a long history of *Opuntia* cultivation, particularly O. ficus-indica, for various agricultural and horticultural purposes. While *Opuntia* has been widely introduced and naturalized in many regions of China, the potential distribution patterns and invasion risk under climate change scenarios have not been extensively studied.

Some preliminary research suggests that China's diverse climatic conditions, from temperate to subtropical and arid regions, could provide suitable habitats for the proliferation of *Opuntia* species (Jorge et al., 2023).

The increasing frequency and intensity of extreme weather events, such as droughts and heat waves, associated with climate change may further exacerbate the invasion risk by favoring the establishment and spread of *Opuntia*.

These factors highlight the need for a comprehensive assessment of the potential distribution and invasion risk of *Opuntia* in China, as well as the development of effective management strategies to mitigate the environmental and economic impacts of potential invasions.

The degree of naturalization and invasion by *Opuntia* species in China varies significantly across regions, reflecting the diverse climatic conditions and ecosystems within the country. In arid and semi-arid areas of northwestern China, such as the Xinjiang Uygur Autonomous Region, *Opuntia* has been reported to spread extensively, often outcompeting native vegetation (Bakewell-Stone, 2023; Essl & Kobler, 2009). Similarly, degraded grasslands and rangelands in Inner Mongolia and other northern provinces have experienced the formation of dense, impenetrable thickets of *Opuntia*, disrupting livestock grazing and limiting access to essential resources.

Coastal regions and islands, including Hainan and Taiwan Province, have also been significantly impacted. Here, *Opuntia* has invaded and transformed coastal habitats, altering ecosystem dynamics. Subtropical regions in southern China, such as Guangdong and Guangxi provinces, present additional concerns, as *Opuntia* thrives in these climates and poses a potential threat to local ecosystems (Jorge et al., 2023; Yahia, 2012).

These regional case studies highlight the susceptibility of various ecosystems in China to *Opuntia* invasions. They emphasize the need for a comprehensive, nationwide assessment to guide management strategies. Balancing the potential benefits of cultivating *Opuntia* with the risks of invasion is essential for minimizing ecological and socio-economic impacts while maximizing its utility.

4. Management Strategies Employed in China

regions in southern China, including Guangdong and Guangxi provinces, where *Opuntia* has been observed to form dense thickets and disrupt local ecosystems. These regional case studies demonstrate the diverse climatic conditions and ecosystems in China that are susceptible to *Opuntia* invasions, underscoring the need for a comprehensive, nationwide assessment to guide management efforts (Essl & Kobler, 2009; Jorge et al., 2023). Several strategies have been employed to manage *Opuntia* invasions in China, with varying levels of success. Mechanical control methods, such as manual removal and cutting, have been implemented to address small-scale infestations. However, these approaches are labor-intensive and often fail to prevent regrowth from plant fragments left behind. Chemical control using herbicides has also been explored, but its effectiveness is limited, and the use of chemicals poses risks of unintended environmental consequences.

In temperate regions of northern China, *Opuntia* may find suitable climatic conditions for establishment and spread, particularly under climate change scenarios. The environmental and economic impacts of potential *Opuntia* invasions in these areas demand urgent attention and the development of effective management strategies.

Integrating sustainable approaches, such as biological control, targeted grazing, and cultivar selection, could provide more viable long-term solutions for managing *Opuntia* (Bakewell-Stone, 2023; Essl & Kobler, 2009; Jorge et al., 2023; Yahia, 2012). These regional case studies underscore the diverse climatic conditions and ecosystems in China that are susceptible to *Opuntia* invasions. They highlight the need for a comprehensive, nationwide assessment to inform and guide management efforts effectively.

5. Successful Management Scenarios and Lessons Learned

In addition to the successful management examples, experiences from other countries can also provide valuable lessons for addressing potential *Opuntia* invasions in China. One important lesson is the need for proactive prevention and early detection. Many invasive species, including *Opuntia*, are much more effectively managed when detected and addressed early before they have had the opportunity to become widely established and cause significant ecological and economic damage. Another key lesson is the importance of stakeholder engagement and cross-sectoral collaboration. Effectively managing *Opuntia* invasions often requires the participation and coordination of various stakeholders, including government agencies, agricultural and forestry sectors, and local communities. Integrating these lessons into the development of management strategies for potential *Opuntia* invasions in China can help ensure more sustainable and effective outcomes.

While *Opuntia* invasions have posed significant challenges in many regions, there have also been examples of successful management efforts that can provide insights for China. For instance, in Australia, the introduction of the cochineal insect as a biological control agent has been credited with significantly reducing the abundance of invasive *Opuntia* species in many areas (Bakewell-Stone, 2023). Similarly, in parts of Africa, the integration of mechanical, chemical, and biological control methods, along with the promotion of alternative, non-invasive cultivars, has helped mitigate the impacts of *Opuntia* invasions (Jorge et al., 2023). These examples demonstrate that a multi-pronged approach, tailored to the local conditions and challenges, can be effective in managing *Opuntia* invasions.

Opuntia has a history of being an invasive species in many parts of the world, with caution recommended when introducing the plant to new areas. In the Mediterranean region, for example, the invasion of *Opuntia* species has been shown to change habitat structure and species composition, although dense and extensive stands are limited to a few species (Essl & Kobler, 2009).

Similarly, in some developing countries where *Opuntia* was introduced for agricultural purposes, the plant has become invasive, leading to environmental problems and challenging efforts to control its spread.

As a case in point, the introduction of *Opuntia ficus-indica*, one of the most widespread and commercially important cactus species, has resulted in significant environmental issues in areas where it has become invasive.

In Portugal, O. ficus-indica is even listed as a regulated invasive alien plant, demonstrating the recognition of its potential for causing ecological harm (Bakewell-Stone, 2023). These case studies highlight the need for a nuanced approach to the management of *Opuntia*, balancing its potential benefits with the risks of invasions.

In conclusion, the potential distribution patterns and invasion risk of Genus *Opuntia* in China and other parts of the world under climate change scenarios warrant urgent attention and the development of effective management strategies (Bakewell-Stone, 2023; Prior et al., 2018; Pyšek & Richardson, 2010; Venette et al., 2021). By learning from successful management examples and lessons from other countries, China can develop a comprehensive, multi-pronged approach to address the challenges posed by *Opuntia* invasions and mitigate their environmental and economic impacts.

VII. Management Approaches for Controlling *Opuntia* Invasions

Current Management Practices

Several strategies have been employed to manage *Opuntia* invasions in China, yielding varying degrees of success. Mechanical control methods, such as manual removal and cutting, have been utilized to address small-scale infestations; however, these approaches are labor-intensive and often fail to prevent regrowth from remaining plant fragments (Bakewell-Stone, 2023). Chemical control using herbicides has also been explored, but its effectiveness is limited, and the use of chemicals can lead to unintended environmental consequences.

Grazing by livestock, such as goats, has shown some success in reducing *Opuntia* populations, but this method is not suitable for all environments, and overgrazing can result in additional ecological issues. Biological control, using natural enemies like the cochineal insect and the prickly pear moth, has demonstrated promising results in certain regions. However, the adoption of biological control in China has been limited due to concerns about potential non-target effects and conflicts with the commercial cultivation of *Opuntia* (Bakewell-Stone, 2023).

Overall, the current management practices in China have achieved only limited success in controlling *Opuntia* invasions, emphasizing the need for a comprehensive, nationwide assessment to guide future management efforts (Prior et al., 2018; Strek, 2014). Integrated approaches that combine mechanical, chemical, and biological control methods have proven more effective in some areas. However, the effectiveness of these strategies remains variable, underscoring the need for more coordinated and extensive efforts to address the growing potential for *Opuntia* invasions in China.

Prevention Strategies for Future Invasions

Prevention strategies are critical for managing the establishment and spread of *Opuntia* invasions. Early detection and rapid response play a vital role in addressing infestations before they become unmanageable. Implementing robust monitoring and surveillance systems, along with developing early warning mechanisms, can facilitate the timely identification of *Opuntia*. Strengthening border biosecurity measures, such as inspections and quarantine protocols, is essential to prevent the introduction of *Opuntia* and other invasive species into China. Public awareness and community engagement are equally important, as they encourage the identification and reporting of *Opuntia* sightings, aiding early detection and prevention efforts. Promoting the use of non-invasive *Opuntia* cultivars and discouraging the planting of known invasive species further reduces the risk of spread. Additionally, educational campaigns can empower local communities to actively participate in these initiatives. Proactive prevention strategies, combining these efforts, are crucial for effectively managing *Opuntia* invasions and protecting China's ecosystems and agricultural systems from their potential impacts (Bakewell-Stone, 2023; Capozzo et al., 2021; Jorge et al., 2023).

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

Control and eradication efforts are essential for managing areas where *Opuntia* invasions have already become established. A combination of control methods may be required for effective management. Mechanical control methods, such as manual removal, cutting, and burning, can be effective for small-scale infestations but often require repeated efforts to prevent regrowth from plant fragments. Chemical control, using approved herbicides, can also be useful; however, the long-term environmental effects must be carefully considered. Biological control, employing natural enemies like the cochineal insect and the prickly pear moth, has shown promise in some regions, though its adoption has been limited due to concerns over non-target effects and conflicts with commercial cultivation. Integrated management approaches that combine mechanical, chemical, and biological control methods have proven more effective in certain areas. Regular monitoring and evaluation of the effectiveness of these control efforts are crucial to refine and adapt management strategies over time. Collaborating with international experts and learning from successful management experiences in other countries can further enhance control and eradication strategies in China. By integrating lessons from the global management of *Opuntia* invasions, China can develop more effective and sustainable strategies to address this challenge (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. Integrated pest management approaches should combine prevention, early detection, and control strategies to manage *Opuntia* invasions effectively. These strategies should integrate mechanical, chemical, and biological control methods, tailored to the specific environmental and economic conditions of different regions in China. Additionally, fostering the abundance and diversity of beneficial species, such as natural enemies, decomposers, and pollinators, can play a crucial role in an integrated pest management approach (Anderson et al., 2019). From a policy perspective, it is essential to develop and enforce comprehensive policies and regulations to prevent the introduction and spread of *Opuntia* and other invasive species. Engaging relevant stakeholders, including land managers, farmers, conservation organizations, and local communities, is vital to ensure the effective implementation and adaptation of management strategies. Providing incentives and support for landowners and land managers to adopt best practices for managing *Opuntia* invasions can further enhance these efforts (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. While some control methods have been attempted, the effectiveness has been variable, and more research and investment are needed to develop and implement integrated pest management strategies. By adopting a multi-faceted approach that combines prevention, early detection, and control measures, China can better protect its ecosystems and agricultural systems from the potential impacts of *Opuntia* invasions.

Summary of Key Findings

Climate change is expected to alter the geographic ranges and impacts of invasive species, such as *Opuntia*, in China and globally. Various management strategies, including mechanical, chemical, and biological control methods, have been employed to manage *Opuntia* invasions with varying degrees of success. Integrated pest management approaches, which combine multiple control strategies, have shown greater promise in addressing *Opuntia* invasions in other regions. Early detection and rapid response are essential for preventing the establishment and spread of these invasions. Strengthening biosecurity measures, promoting public awareness, and fostering stakeholder engagement are key components of effective prevention and management strategies. Proactive prevention and early detection are critical for managing *Opuntia* invasions in China effectively. Continued research and investment in integrated pest management strategies are necessary to address the potential threats posed by *Opuntia* under climate change scenarios.

Implications for Biodiversity and Ecosystem Health

The invasion of *Opuntia* species poses significant risks to biodiversity and ecosystem health, particularly in regions with high levels of endemism and ecological sensitivity. *Opuntia* invasions can outcompete native plant species, alter ecosystem structure and function, and disrupt ecological processes such as nutrient cycling and the activities of pollinators and other beneficial organisms. Addressing *Opuntia* invasions is essential for preserving the unique biodiversity and ecological integrity of China's natural ecosystems

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. Targeted research is needed to fill gaps in knowledge about the biological and ecological characteristics of *Opuntia* species, their potential distribution patterns, and the interplay between climate change and invasion dynamics. Additionally, investigating the long-term impacts of *Opuntia* invasions on biodiversity, ecosystem functions, and ecosystem services, particularly in sensitive or protected areas, is essential. Comprehensive and long-term monitoring programs should be implemented to track the distribution, abundance, and impacts of *Opuntia* invasions across different regions of China. These programs should include regular evaluations of the effectiveness of control measures and adapt management strategies accordingly, integrating new research findings and best practices from other regions.

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