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Climate-Driven Diffusion and Adaptive Management of Forest Invasive Species

Yiran Tu

Wuhan Kaiming Middle School, Wuhan, China
rustcytoplasm@gmail.com

Abstract. The two linked ecological crises of the Anthropocene for forest ecosystems are climate change and biological invasion. This review presents the synthesis of how climate change promotes the spread of invasive alien species (IAS) in boreal and temperate forests that have been cold-climate controlled environments in the past. The combined effect of these stressors is explained by the Fluctuating Resource Availability Theory; ecosystem vulnerability is directly related to the reduced availability of resources resulting from severe weather and tree loss. These "resource pulses" help the invasive species spread rapidly after disturbance. Canadian goldenrod is an invasive species that can adapt to changes in the environment quickly, produce allelopathic chemicals to inhibit other plants. Invaders have replaced native plants, formed a monoculture, changed the carbon cycle and reduced biodiversity. In the event of a severe forest degradation, it will be a carbon source. Economic damage is about $1.4 trillion in lost GDP worldwide each year, and health risks come from allergens released by expanded allergenic pollen of weed populations in some colonised areas, affecting up to 12% of the population. Early detection via predictive distribution models for climate-informed risk zoning; integrated control combining mechanical, chemical and biological methods, emphasizing sustainable biological control; and post-invasion forest restoration focused on ecosystem resilience. The most economical method for preventing both deliberate and accidental introduction is still in use. Under prolonged warming in the future, ecosystems will continue to degrade without the concerted efforts of countries to reduce emissions and control invasive alien species.

Keywords: Climate change, invasive plant species, forest restoration

1. Introduction

The Anthropocene, the current geological epoch, is marked by two major ecological crises triggered by human activities: ongoing climate change and global biodiversity loss driven by biological invasions. Climate change remodels the physical environment of the planet, while invasive alien species (IAS) reshape the internal biological structure and functional operation of ecosystems from the inside out. Exploring how climate warming promotes the proliferation and spread of invasive species is no longer just a theoretical research topic. Instead, it has become a fundamental basis for us to carry out targeted ecosystem management and biodiversity protection work.

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The synergistic relationship between climate change and biological invasion can be well explained by the Theory of Fluctuating Resource Availability. The core view of this theory is that the degree to which an ecosystem is vulnerable to biological invasion is closely tied to unused resources within the ecosystem. Climate change frequently triggers extreme environmental disturbances, including severe droughts, extreme floods and altered wildfire patterns. These disturbances greatly reduce the resistance and stability of native biological communities. Meanwhile, they produce surplus resources in the ecosystem, which invasive species can quickly occupy and utilize relying on their unique evolutionary advantages .

Canadian goldenrod (*Solidago canadensis*) is a typical representative of such invasive species. It was originally introduced as an ornamental plant but has successfully invaded most regions of Eurasia and Asia. Its strong invasive ability mainly stems from two key traits. First, it has excellent phenotypic plasticity, enabling it to adapt to warming local environments much faster and better than native species. Second, it produces allelopathic phytochemicals that can interfere with the soil microbial community of native ecosystems, inhibiting the growth and reproduction of local organisms [1].

As the world is getting warmer every year, the suitable places for invasive species such as Canadian goldenrod and invasive bamboos are expanding steadily [2]. Rising temperatures and an increase in these invasive plants are reducing the carbon sink strength of temperate forests and altering the biogeochemical cycle [3]. At this time, it may be no longer carbon-absorbing but rather a source of carbon [4].

Given that the Earth has been getting hotter and hotter recently, people need to learn how to live in this new climate. Combine early species monitoring and climate-based risk regionalisation, and introduce an innovative bioeconomy approach to develop value-added utilization pathways for invasive plant biomass. The above multi-dimensional management mode will help protect the structure and ecological stability of the forest ecosystem [5]. Climate change has spread invasive species in the forest more rapidly, particularly in the formerly cold boreal and temperate regions. The intruders are using the bad weather and damage to trees as a cover to build a camp in a disturbed area. Canadian goldenrod is a fast-growing species that emits chemicals to disrupt the community of native plants. Therefore, there will be a decrease in biodiversity, changes to nutrient cycles and reduced carbon sink capacity. There are economic and public health costs caused by allergenic pollen in the area. Therefore, in the face of climate change, early warning and adaptation strategies will be introduced to improve the ecological service capacity of forests.

2. Climate change and biological invasions in forest ecosystems

2.1. Global climate change trends and implications for temperate forests

Boreal forests are the world's largest terrestrial biome and extend over a wide range of high latitudes in North America, Europe and Asia. These cold forests are rich in carbon and store it in the soil and plants to help moderate the climate of the entire world [6]. Boreal forests are also extremely old, with many types of life that have developed to live in a harsh climate for a long time. Due to the long-standing cold climate in the area, non-native invasive plant species that require warm environments have not been able to establish and proliferate [6].

However, boreal forests have warmed more rapidly and severely than any other forest biome around the world [7]. Research has shown that temperatures in the northern part of boreal forests are rising at a much faster rate than in other biomes recently. A rise in temperature will gradually reduce the favourable weather conditions for the Boreal Forest ecosystem in the past. Therefore, invasive

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plants are now able to expand their range to the north and higher-altitude areas where they could not survive before [6, 8]. The northern range of the suitable temperature for survival has shifted, and new areas for invasion have emerged.

Recently, due to climate change around the world, there have been many serious extreme-weather events such as heat waves, local cold waves, and droughts. For example, the Pacific Northwest saw a record-high temperature in 2021 and thus many trees died in a large area. These severe events have led to widespread tree deaths in some boreal and temperate forest areas, and the risks of combined drought and heatwaves are rising in Europe. Extreme weather events have been occurring more frequently due to a warming world climate system.

Trees in cold-temperate and boreal forests are not well adapted to both very cold and very hot conditions. These trees have evolved in relatively stable cold areas and do not have the physiological ability to cope with rapid changes in temperature. In a dry year, the tree will not produce photosynthetic carbon and will therefore decline in size. This will reduce their all-weather durability and health [9]. The trees have been damaged, and thus can no longer control the spread of the invasive species. Therefore, the situation for native trees has worsened further, and they are now more susceptible to disease and have died in large numbers.

2.2. Climate-driven range shifts of invasive plant species: latitudinal and altitudinal expansion

At the same time, with global warming, some invasive plant species that could not survive in the severe cold of the North have begun to spread. Many invasive plants have a wider temperature tolerance range or better survival ability than native species such as *Solanum rostratum*, and they have a higher net photosynthetic rate than the natives [10]. As the native trees are weak and more susceptible to changes in the environment, invasive species have been able to proliferate in the wild and are now widespread in the region. Year after year, there has been a reduction in resources, and the original plants have been damaged accordingly.

These foreign plants have replaced the native trees in the boreal forest and are thriving here. They are competing for light, water, nutrients and growing space in an aggressive manner, and thus have displaced the native plants in the understory. Invasive plants are also replacing native plants in some parts of the environment by filling the ecological positions of the native species. Some invasive species are also allelopathic, that is to say, they produce chemical substances in the environment to inhibit the growth of other plants. Finally, the above reasons will reduce the diversity of the area and reduce the stability of boreal forests.

Based on the Fluctuating Resources Availability Hypothesis proposed by Davis in 2000 [11], extensive tree deaths lead to an increase in unused resources in the ecosystem. When the trees die, all the resources they had used in the ecosystem will be returned to the environment and become available for other organisms in that ecosystem. The above abundant resource opportunities are referred to as "resource pulses". Resource pulses are relatively long-lasting, and thus the opportunity for opportunistic species to colonise disturbed areas has been extended.

Therefore, it will have the following positive effects on the invasive species. Invasive species such as *Ageratina Adenophora* and *Solidago canadensis* have not had natural enemies in the places they were introduced, and native species have had natural enemies there. The local area of the invasive plant can be controlled by some herbivores and other plants. After establishing in the new areas, these controlling forces are often gone. Weeds are generally in areas that are prone to rapid proliferation of non-native plants. Many produce many seeds that can be carried over long distances by wind or water. Some spread vegetatively by roots or stems and thus have a large population.

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2.3. History of the global spread and present distribution

The Vulnerability to invasive species of the boreal forest varies in different areas. Some areas are exposed to different types of invasive pests and plants at varying degrees. A number of hot spots in the north-central area have been encroached upon to some extent. Spatial Patterns of vulnerability are influenced by local climate conditions, soil features, and the history of human activity. Based on the above trends, prioritise monitoring and prevention efforts.

Climate models will show that the boreal region remains warmer in the future of the 21st century. This warming will probably continue to expand the area for new invasive species. Compound extreme weather events, such as drought and heatwaves occurring simultaneously, will be more frequent, leading to increased tree mortality and resource pulses. Otherwise, there will be an increase in degradation of the boreal forest ecosystem and a reduction in biodiversity and carbon-sink capacity.

3. Mechanisms for success of climate-driven invasion

3.1. Competitive advantage and spread mechanism

A resource pulse offers an opportunity for invasion, and other biological traits that help invaders exploit this window more effectively than native species are also involved. All of them - climate change and extreme weather events, invasive alien species, etc. - are modifying the environment in the boreal forest.

Some of the invasive species are also more heat-tolerant than the native species. As the North gradually warms up, the original plants have adapted to cold temperatures can no longer live comfortably. Most of the introduced species are warm-weather plants or animals that have already adapted to high temperatures. This pre-adaptation helps them continue to grow and reproduce normally in the face of stress to the native species.

Based on the studies mentioned above, the invasive species *S. rostratum*and its native species *S. nigrum* have different levels of photosynthesis under nitrogen deficiency stress [10]. The invasive species had a larger ratio of roots to shoots and thus obtained soil resources more efficiently. Some invasive species are also relatively stable in the microbial community of their rhizosphere and can obtain nutrients more readily.

Due to the reduced resource availability in the area where trees have died, these plants are relatively strong and can grow well. Resources for dead trees release aid the invaders in gaining a relative advantage in phenotypic plasticity and other attributes over native plants.

3.2. Phenotypic plasticity and adaptation to warming

Ageratinaadenophora is a typical example of an invasive species with strong phenotypic plasticity in China and other places, and it is now considered a major invasive species. According to the above research, when other native plants cannot grow in the dry season, this kind of plants is still able to increase in size to some extent. *A. adenophora* changes the ratio of biomass allocation with temperature; it produces more underground structures at low temperatures and develops above-ground growth in high temperatures. The above is one of the strengths of resource optimisation in various circumstances.

Adaptability is also referred to as phenotypic plasticity. The same gene can be expressed in various ways as a result of different environments; this is called phenotypic plasticity [12].

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Therefore, changes in the growth shape and leaves of a plant are due to factors such as its environment or other reasons. A more plastic phenotype can acquire resources from a competitive environment more efficiently than the previous set of adaptations. Most studies have shown that invasive species are generally more phenotypically plastic than native species.

3.3. Climatic niche dynamics: conservatism, shift and expansion in native and invaded ranges

In light of the above changes, some improvements will be made to management. Currently, many studies have failed to consider an entire-ecosystem perspective and have thus caused other issues in the control of individual invasive species. Ecological system thinking should be used, and the removal of one invasive species may release other invasive species that are more widespread. When management takes remedial action, there is a delay; resources for responding to the disruption may be unavailable for a long time.

After a tree dies, resources are made available to the surrounding plants and, along with these new strengths, the spread of the plants may be promoted. Resource pulses in dead trees provide places for invaders to hide, and some of the features of these invaders enable them to use these places more advantageously than native plants. Climate Change and Extreme Weather are likely to spread invasive species more broadly in boreal forest ecosystems.

According to the predictions of climate models, the boreal region will also warm up in the 21st century. This warming will probably continue to increase the area of possible invasive species. Compound extreme weather events, such as the occurrence of drought and heatwave simultaneously, will be more frequent, leading to more tree deaths and resource pulses. Without intervention, it will be gradually damaged by a series of factors and will no longer be a good place for life and carbon storage.

4. Ecological and socioeconomic impacts of invasive species in forests

4.1. Biodiversity loss and alteration of community structure

Invasive species are a reason for the changes in biodiversity and damage to the environment worldwide at present. Invasive plants introduce artificial disruption to the balance of the ecosystem and are thus outcompeted by native species. Given the above advantages, invasive species are competing for the same resources of light, water and nutrients to outcompete the native species. Allelochemicals are released in the environment through leaching, root exudation, volatilisation and decomposition of dead organic matter, negatively affecting surrounding plants' growth and reproduction, for example, by reducing root length, inhibiting seed germination and growth of seedlings, and so on, thereby increasing the resource availability for themselves [1].

However, it is not very effective against naturally occurring neighbouring species that have evolved over time [13]. These native species have co-evolved with their ecosystems and developed defence mechanisms over a long period of time. In the event of an abundant invasive species, they will form a dense monoculture that displaces the original multi-species plant community. Many of the world's top 100 worst invasive alien species are threatening native plant communities in oceanic islands and forest ecosystems.

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4.2. Disruption of biogeochemical cycles and ecosystem functioning

Invasive species can harm all parts of nature that are affected by them or from which they are derived. Some invasive plants release allelochemicals to inhibit the germination and growth of native plants, and also reduce rhizobium nodulation and mycorrhizal symbiosis. Therefore, there will be a decrease in soil fertility and changes in the composition of the microbial community.

Although invasive plants have employed biological means such as allelopathy to outcompete other plants in nature, most of their initial dissemination has been caused by people. Most of the establishment and spread of invasive species are the result of human activities, either deliberately or unintentionally [14]. Phyllostachys*bambusoides* and *Phyllostachys edulis* were first imported to Japan as commercial varieties. In the 1970s, the bamboo industry declined; consequently, these plant plantations were no longer maintained and began to spread as weeds due to their excellent growth vigour. As a result of global warming today, it is spreading to higher latitudes [2].

4.3. Economic effects on forestry and health risks for people

Due to the above reasons, invasive plants have brought about serious damage to the economy and society around the world. A 2025 study indicated that approximately US$1.4 trillion in annual economic losses around the world have been caused by invasive alien species. The above species have caused harm to the forestry and livestock industries through land occupation and resource competition. *Solanum elaeagnifolium* has caused damage to agricultural and forest products and reduced the productivity of agricultural and forestry systems through its spread. At the same time, [15] invasive plant species have also caused harm to human health in an indirect and direct manner.

Some studies show that some invasive species are harmful to local plants and contribute to air pollution and a health emergency for the public. Most of the causes of hay fever and allergic rhinitis are pollen from the plant *Ambrosia artemisiifolia*. Other research has also found some asthma, other respiratory diseases and skin diseases that are associated with it. There are now many large populations of ragweed around the world that pose health risks to the public. Up to 12% of the people are sensitive to ragweed pollen in highly affected areas.

Economic costs of invasive species include damage to crops, pastures and forests in production; there are also environmental damage and control expenses. The amount of the economic loss around the world over the past 50 years has reached about US$1.288 trillion. Many forests around the world have suffered serious harm to their biodiversity and ecological functions due to harmful invasions by non-native plants and animals.

5. Adaptive integrated management strategies

5.1. Early detection and climate-informed risk zoning

Due to the damage to the environment and economy and people caused by the spread of weeds in the face of climate change, some remedial measures need to be taken urgently. Promptly build an early warning and prevention system. For example, set up a centre for the identification and early warning of invasive species, publish a list of species of concern, and implement tiered management of priority invasive species as key measures. Preventing harm from an invasive species in the future by reducing the number of deliberate or accidental introductions early on is relatively economical.

MaxEnt (Maximum Entropy) species distribution models are based on the principle of maximum entropy and are used in this paper. Models of species distribution points and analysis of climate and

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environment can be used to predict the future places where invasive species will occur [4]. Based on the above results, measures to prevent the spread of invasive alien species will be implemented. It is also a prediction model and therefore has some defects and errors. Be cautious in early detection and identification; otherwise, by the time of spread, both the eradication process and expenses will be high [11].

5.2. Integrated control methods: mechanical, chemical and biological approaches

Currently, all of the above control measures for invasive alien species are being employed. The first small-scale invasions were often mechanically operated and employed manual removal, mowing and burning. However, this way has some defects: although it will achieve good results in the short run, the danger will not be completely eliminated and it will be expensive. *Solanum elaeagnifolium* is a weed that can reproduce by producing adventitious roots on stem fragments and is difficult to eliminate mechanically.

The first type of chemical control is a herbicide, such as Metsulfuron-methyl or Amidosulfuron; however, it can also harm the water system, the air and the ground. Otherwise, it will harm the environment and life forms.

The best and most basic way is biological control; therefore, a natural enemy for the invasive species is introduced. This way will not harm the non-target species and is relatively environmentally friendly. Biological control will be used in conjunction with all other kinds of weed control to modify changes in the function of rangelands and pastures through changes in ecosystems, rather than focusing on specific weeds or using only one type of method. However, it is still a problem that the introduced species themselves may spread and cause new problems. Therefore, before the biological control operation, the control organisms must be assessed for risk.

5.3. Forest management and improvement of ecosystem resilience

Reduce the spread of weeds and, at the same time, reduce the harm caused by weeds to the forest. Passive natural recovery can be allowed to occur by relying on the existing seed bank for community succession, or active human-assisted restoration can be carried out to improve soil quality and actively plant native species with early-succession advantages [16, 17]. The goal of invasive plant management should be to reclaim or restore degraded weed-infested rangeland communities so that they are less susceptible to re-invasion by invasive plants and can meet land-use objectives.

Forest management of plant invasion needs to identify the invasive plant and how far it has spread, how likely it is to spread further, and then develop a control plan. At the beginning of a species' invasion, both its identity and distribution are often unknown, so suitable control measures may need to be taken before large-scale efforts are launched. Rapidly respond to the problems and manage them well to reduce the spread.

6. Conclusion

Climate change and the dispersal of diseases have damaged forests across the globe extensively. Warming in the last century has extended the northern and upper-altitude range of invasive species, and frequently occurring extreme weather events have reduced tree populations and created resources that favour opportunistic invaders. Forest ecosystems will have less biodiversity and carbon-sequestration capacity without intervention.

The Reasons for the success of the invasion are as follows: phenotypic plasticity, stronger competition with other plants for resources in the ecosystem, allelopathic inhibition of native plants, and a deficiency in natural enemies of pests in the invaded area. Invasive species are out of place in the ecosystem, change nutrient and energy cycles, and alter soil composition.

Adaptive Management should be rational and spatially explicit. A new early warning device will be added and the risk predicted ahead of time. Integrated control strategies for biological control aim to reduce off-target effects, and post-eradication restoration may be carried out passively by nature or actively by humans. Only through joint overseas efforts will the health of the forest ecosystem be preserved at this time.

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