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Constructing a Multivariate Linear Model to Investigate the Wind Propagation Dynamics of Dandelion with Analytic Hierarchy Process

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Abstract: The dandelion, a plant native to Eurasia, has successfully dispersed to regions across the globe. This dispersal is facilitated by the wind, which carries dandelion seeds attached to the pappus or petals of the pappus over considerable distances. Nevertheless, the extensive distribution of the dandelion has garnered significant attention. While this plant currently poses no immediate harm, the issue of species invasion resulting from its presence has become a matter of concern. Consequently, it is imperative to conduct research on the dissemination of the dandelion and its potential ramifications on other species. In addressing the first problem, this article commences by progressing from a rudimentary to a more intricate examination. The study dissects the wind propagation dynamics of dandelion, scrutinizing both the vertical and horizontal dimensions. It is deduced that the dandelion rapidly attains a threshold velocity during the early stages of propagation, prompting the construction of a comprehensive kinematic model for dandelion seed dispersal by integrating the analyses of both directions. Subsequently, a logarithmic distribution-based seed wind propagation model is formulated, drawing upon the aforementioned kinematic model. Lastly, the article deliberates upon the consequential ramifications. For the second problem, a multivariate linear model is developed to consider various factors including plant characteristics, environmental hazards, and ecosystem resistance. The analytic hierarchy process is employed to discuss the weight of each influencing factor and quantitatively assess the invasion ability of Taraxacum mongolicin. Ultimately, the model is tested and the collected data is utilized to verify the validity of the model.

Keywords: Wind Seed Dispersal; Logarithmic Distribution; Monte Carlo Simulation; Biological Invasion Assessment; Analytic Hierarchy Process.

1. Introduction

1.1. Problem Background

Dandelion is a common wild plant with strong adaptability and high reproductive capacity, originating from the Eurasian continent. Due to the lightness and umbrella-like structure of dandelion seeds, as shown in Figure 1, their seeds can be carried by the wind, allowing them to spread rapidly in new ecological environments. This makes it an example of an invasive species and illustrates the concept of non-native species entering new ecosystems and posing a threat to existing ones. Invasive species have the potential to harm ecosystems, economies, and human health.

The rapid spread of dandelion has raised doubts about its growth and transmission patterns in different climates. This arouses the concern of ecologists and researchers about the transmission mode of dandelion. Only by understanding the transmission mode of dandelion in different climatic conditions, can we better understand its competitive relationship with other species and prevent and control it.

1.2. Restatement of the Problem

Given the background information and qualifications in the problem statement listed, we need to address the following questions:

Problem 1: Predicting Dandelion Spread

To predict the spread of dandelions under different climatic conditions and to understand their growth near open land, a mathematical model was created that considered the growth characteristics of dandelions and the effects of climate change in order to accurately predict the spread of dandelions near an open one-hectare plot over different time periods (1, 2, 3, 6, and 12 months).

Problem 2: Impact Factor of Invasive Species

- We need to develop a mathematical model to determine the "impact factors" of alien species. The model should incorporate a number of variables, including the characteristics of the invasive species, the degree of damage to the ecosystem, and the difficulty of management and control measures. We will use this model to calculate the impact of dandelion and compare it to two other plant species that are considered invasive in specific areas.

1.3. Our Work

We mainly established two models of invasion factors of dandelion powder and Du translation. After the model is built, we begin to collect data and make full use of the data in appropriate contexts. In addition, we used kinetic analysis and a handful of models for estimating invasion factors in the dispersion of dandelion. The details are as follows:

2. Assumptions and Justifications

1. **Assume that the height of the seed released by the dandelion remains constant.** It is necessary to neglect the differences in size and shape of dandelions to make assumptions about height in order to keep the model concise

when building a wind- blown seed dispersal model.

2. **Assume that the terminal descent rate of dandelion seeds follows a Gaussian distribution**. Likewise, this is necessary when considering models of seed dispersal un- der wind. In the general case, we can assume a Gaussian distribution to describe different situations.

3. **It is assumed that the diffusion of dandelion is a point source**, that is, all dandelion seeds can be regarded as diffusing from a point source.

4. **Assuming that the wind speed is normally distributed**, the parameters of the nor- mal distribution are different in different months.

5. **Assume that dandelion has absolute advantage in habitation and reproduction**, ignoring the inhibitory effect of other populations on them, that is, the organisms occupy an overwhelming advantage in the same type of population. Obviously, this assumption is necessary, and if this condition cannot be met, it is open to question whether the organisms under consideration can be identified as invasive species.

3. Notations

The key mathematical notations used in this paper are listed in Table 1.

Table 1. Notations used in this paper

Symbol	Description
H	vertical settlement height
F	settlement rate
F_x	vertical resistance experienced by the seed
v_y	vertical velocity of the seed
A_s	The monitoring scope of SSA drones
R_s	The radius of the monitoring scope of SSA drones
c_i	The coordinate of point i
z_i	The height above sea level of point i
s_f	The speed of wildfire spread
rg_r	The range of Radio Repeater droner
n	The number of Radio Repeater drones we need

4. The Population of a Honeybee Colony Model

Dandelions, renowned for their vibrant yellow blossoms, possess a captivating mechanism for seed dispersal. As these flowers mature, their distinctive "puffball" seed heads form, with each individual seed attached to a delicate parachute-like structure called a 'pappus.' When a gentle breeze sweeps across the landscape, these dandelion seeds effortlessly ascend, gracefully carried by the wind to new destinations. This ingenious adaptation enables dandelions to thrive and propagate, serving as a quintessential example of nature's remarkable engineering, deftly harnessing the wind's power.

Seed wind dispersal is a process in which seeds leave the plant body and move in the air until they stop on the ground. According to the principle of dynamics, when the air flows around the seed, the seed always receives the action of pressure and tangential force. These forces can be decomposed into two directions, namely, the force consistent with the direction of the incoming flow and the vertical lift force perpendicular to the direction of the incoming flow. If the plant is taken as a reference, the trajectory of seed dispersal is approximately a parabolic curve, and its movement in the horizontal and vertical directions is usually considered. Based on this, the analysis of seed propagation motion will be carried out in the plane rectangular coordinate system. In addition, due to the small size of the seed, the seed is assumed to be a particle in the analysis of seed dispersal movement, and the movement process of seed dispersal is analyzed according to the particle method.

4.1. Vertical Sedimentation Analysis of Seed Dispersal

For ease of analysis, we assume that the air is at rest in the vertical direction, and that the vertical settling velocity of the seeds isv_y the force analysis of the seeds is shown in Figure 1.

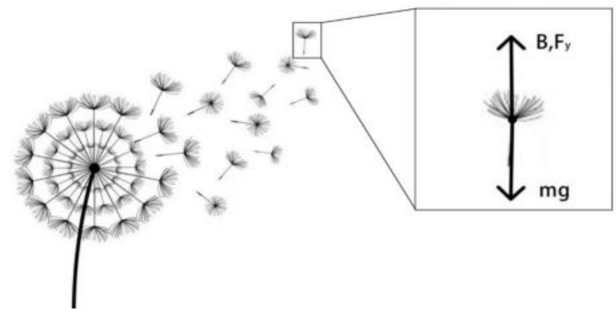


Figure 1. The force analysis of the seeds.

It can be concluded from the analysis, the resistance received is $F_x = C_d A_{py}, \frac{\rho v^2 y}{2} = k_y v_y$, the buoyancy force received is B, the gravity is mg,the seed dispersal motion displacement is y,time is t, the acceleration is a_y , then the equation of motion for seed settling in the vertical direction is:

$$m\frac{d^2y}{dt^2} = m\frac{dv_y}{dt} = mg + B + F_y = mg - B - k_y{v_y}^2 \quad (1)$$

The acceleration equation in the vertical subsidence motion of the seed is:

$$a_y = \frac{dv_y}{dt} = \frac{mg - B - k_y{v_y}^2}{m} \quad (2)$$

We set t = 0, $v_y = 0$,then the seed settling acceleration has a maximum value of$a_y = g - \frac{B}{m}$.When v_y gradually increasing, $a_y \to 0$, $v_y \to v_{ymax}$.

We set $a_y = \frac{dv_y}{dt} = 0$,

$${v_{ymax}}^2 = \frac{mg - B}{k_y} \quad (3)$$

Transformed that, we get:

$$\frac{dv_y}{dt} = \frac{k_y\left({v_{ymax}}^2 - {v_y}^2\right)}{m} \quad (4)$$

Carry out indefinite integral:

$$\frac{1}{2v_{ymax}} ln\frac{v_{ymax} + v_y}{v_{ymax} - v_y} = \frac{k_y}{m} \#5 \quad (5)$$

nder the initial conditions oft = 0, $v_y = 0$, the constant C = 0 is substituted into the equation and transformed into:

$$v_y = v_{ymax} \times \frac{exp\left(\frac{2v_{ymax}k_yt}{m}\right) - 1}{exp\left(\frac{2v_{ymax}k_yt}{m}\right) + 1} \quad (6)$$

Equation (6) reflects that the instantaneous velocity of seed settlement approaches the maximum settlement velocity with time.

When $t = \frac{m}{v_{ymax}k_y}$,then

$$v_y = v_{ymax} \times 0.7619 \quad (7)$$

When t ≫ $\frac{m}{v_{ymax}k_y}$,then

$$v_y \approx v_{ymax} \quad (8)$$

4.2. Dynamic Analysis of Horizontal Displacement of Seed

Taking the plant body as a reference system, the horizontal movement speed of the seeds in the air is v_p, and the wind speed is v_a; Taking the air as a reference, the seed relative to the wind speed is v_x, that is, $v_x = v_a - v_p$, and let t = 0, t = 0, $v_x = v_0$, then relative to the plant reference, the horizontal movement speed of the seed is $v_p = v_a - v_x$. The resistance of the seed in the horizontal direction is

$$F_x = C_d A_{py} \frac{\rho v^2{}_y}{2} = k_y v_y \quad (9)$$

In the reference frame relative to air, the equation of motion for the horizontal propagation of the seed is

$$m\frac{d^2x}{dt^2} = m\frac{dv_p}{dt} = F_x = k_x v_x{}^2 \quad (10)$$

The acceleration equation in that horizontal direction is

$$a_x = \frac{dv_p}{dt} = \frac{k_x(v_a - v_p)^2}{m} \quad (11)$$

When $a_x = 0$, $v_x \rightarrow 0$, which means that the horizontal propagation velocity of the seed is close to the air velocity.

$$\frac{1}{(v_a - v_p)^2} = \frac{k_x}{m} dt + C \quad (12)$$

At the initial condition t = 0, $v_a - v_p = v_0$, then $C = \frac{1}{v_0}$, and the equation (12) is obtained

$$v_p = v_a - \frac{1}{\frac{k_x t}{m} + \frac{1}{v_0}} = v_a - \frac{v_0 t}{m + k_x v_0 t} \quad (13)$$

Equation (13) reflects that as time goes on, the speed of the seed relative to the air becomes smaller and smaller, and the speed of the seed relative to the plant body is

$$v_p = v_a - v_x = v_a - \frac{v_0 m}{m + k_x v_0 t} \quad (14)$$

Compared with the resistance coefficient, the seed mass m is generally very small

$$\frac{v_0 t}{m + k_x v_0 t} \approx \frac{k_x v_0 t}{k_x v_0 t} = 1 \quad (15)$$

$$v_x = v_a - v_p = \frac{v_0 m}{m + k_x v_0 t} \approx 0 \quad (16)$$

Then,

$$v_p = v_a - v_x \approx v_a \quad (17)$$

4.3. Simplification of the Equation of Motion for Seed Wind Propagation

The relaxation time of seeds propagating by wind is very short in both horizontal and vertical directions. Equation (8) shows that the seed settling velocity can reach the v_{ymax} in a short time after release, and equation (17) shows that the horizontal propagation velocity after seed release is also consistent with the wind speed in a short time. In order to simplify the analysis of the model, suppose the seed horizontal propagation distance is X, the seed sinking height is H, the seed sinking velocity at time t is $v_y \approx v_{ymax}$, and the horizontal motion ve- locity is $v_p \approx v_a$, then the seed propagation motion equation can be simplified as

$$\begin{cases} \frac{dx}{dt} = v_a \\ \frac{dh}{dt} = v_{ymax} \end{cases} \quad (18)$$

The variation of this equation is

$$dx = \frac{v_a}{v_{ymax}} dh \quad (19)$$

Further integral transformed

$$x = \frac{h \times v_a}{v_{ymax}} \quad (20)$$

Equation (20) is the basic formula for analyzing the seed propagation distance. According to this formula, the horizontal propagation distance of seeds can be determined under the con- dition of known wind speed.

4.4. Wind Distribution Model in Which the Wind Speed Follows a Lognormal Distribution

Let $\psi = \ln\xi$, where ξ is a wind speed random variable with probability density h (X) and distribution function H (X), then

$$\xi = e^{\psi} \quad (21)$$

From the definition of the probability distribution function, we get

$$F(y) = P(\xi \le y) = P(e^{\psi} \le y) = P(\psi \le lny) = \int_0^{lny} h(x)dx \quad (22)$$

Calculation method of density function according to probability distribution of random variable function

$$f(y) = h(lny) \times \frac{1}{y} \quad (23)$$

The random variable ψ follows a normal function, i.e., the probability density function of ψ is

$$h(x) = \frac{1}{\sigma_x\sqrt{2\pi}} \exp\left[-\left(\frac{x-\mu_x}{\sqrt{2}\sigma_{lny}}\right)^2\right] \quad (24)$$

According to the characteristics of the random variable function, the probability density function of wind speed is

$$f(x) = \frac{1}{y\sigma_{lny}\sqrt{2\pi}} \exp\left[-\left(\frac{lny-\mu_{lny}}{\sqrt{2}\sigma_{lny}}\right)^2\right] \quad (25)$$

Where σ_x is the standard deviation of the random variable ψ, μ_x is the mean of the ran- dom variable ψ.

Logarithmically transforming both sides of equation (25) at the same times

$$lnf(y) = \ln\left(\frac{1}{\sigma_{lny}\sqrt{2\pi}}\right) - \left(\frac{lny - \mu_{lny}}{\sqrt{2}\sigma_{lny}}\right)^2 \quad (26)$$

According to the maximum and minimum conditions of the function, the first derivative with respect to y is calculated for both sides of the equation (26) at the same time, and the left side of the equation is 0, and the equation is solved.

$$y = \frac{\exp(\mu_{lny})}{\exp(\sigma^2{}_{lny})} \quad (27)$$

This equation reflects the maximum value of the probability density of wind speed.

Substitute the mathematical expectation E (y) of the wind speed in Equation (25) to obtain the average distance of seed propagation

$$\lambda_m = \frac{E(y)H}{F} \quad (28)$$

In this model, the parameters of wind speed distribution σ_{lny}, μ_{lny} can be calculated. The parameter H is the height of settlement and F is the velocity of settlement.

4.5. Data Collection and Model Substitution

We are currently estimating the dispersal of a dandelion plant near a one-hectare clearing during the "fluffy ball" phase for one month, two months, three months, six months and twelve months, taking into account different climatic conditions. It can be seen from the analysis that the influence of different climatic conditions is reflected in the wind speed and the height of seed settlement. At the same time, the impact on climate is also reflected in the number and growth trend of dandelion seeds after maturity. According to the data, the growth period of dandelion is different under different climatic conditions, as shown in Table 2.

Table 2. The growth period of dandelion is affected by climate.

Climatic conditions	Dandelion growth period
Temperate zone	4-6 months
Subtropical	About 7 months.
Tropical	Up to 8 months

Table 3. The standard deviation of wind speed and average wind speed in different months in a region

Month	Average wind speed	Wind direction	Rainfall
1	3.21	NE	45
2	4.02	N	50
3	2.95	E	53
4	3.25	SE	59
5	3.79	SW	60
6	4.21	W	75
7	3.76	S	54
8	3.02	NW	46
9	4.18	NNE	39
10	3.95	NNW	45
11	1.94	SSW	55
12	2.15	SSE	62

At present, we assume that the starting time is January, and the data in the table 3 are the standard deviation of wind speed and average wind speed in different months in a certain area. The unit of wind speed is meters per second, the monthly precipitation is expressed in millimeters, and the compass direction is used to record the wind direction, such as SSE, NNE and N. Using these data as the basis of the model, the simulated distribution of dandelion seeds in the next few months can be calculated and analyzed.

Monte Carlo method, also known as statistical simulation method, is a random simulation method. Considering the randomness of seeds in the process of propagation, random numbers or pseudo-random numbers are used to simulate and predict the sub-model. Based on the data collected above, considering the factors such as the flowering period of seeds, the dandelion in the "fluffy ball" stage is placed in the center of a hectare of land. Monte Carlo is used to simulate the spread of seeds. At the same time, the spread is limited according to the different climatic conditions of each month. The total simulation results are shown in the following figure 2.

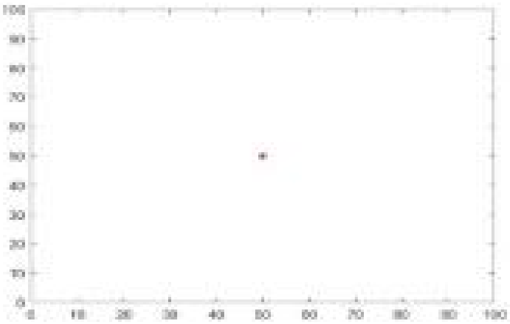
Due to the characteristics of dandelion seeds, their wind direction is greatly affected. The receipts collected show that the wind speed in January was NE. According to the forecast chart, most of the seeds were distributed in the southeast direction of the central point in January, which conformed to the wind speed restriction. At the same time, six months later, the first batch of seeds basically bloomed and produced new seeds for the second round of transmission, resulting in a comprehensive coverage of the area after 12 months.

5. Assessment of Invasiveness

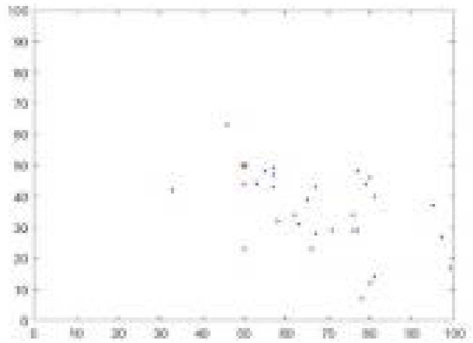
5.1. Analytical Examination

Biological invasions entail the rapid proliferation of non-indigenous species in novel eco- systems, presenting substantial threats to indigenous flora and fauna, ecological equilibrium, and human economic concerns. The emergence of these invasive species is often facilitated by factors such as international trade, tourism, and climate fluctuations, enabling them to over- come geographical barriers and flourish in unfamiliar environments.

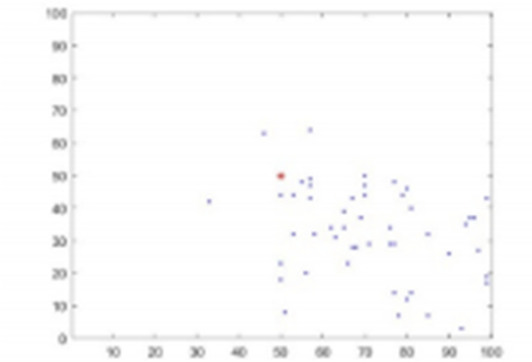
In light of comprehensive considerations and a thorough review of pertinent literature, our approach involves the establishment of a species hazard assessment model grounded in the Analytic Hierarchy Process (AHP).



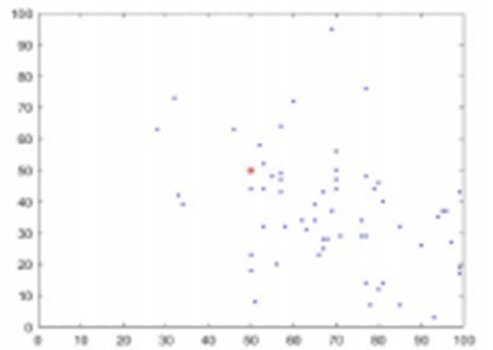
0 months



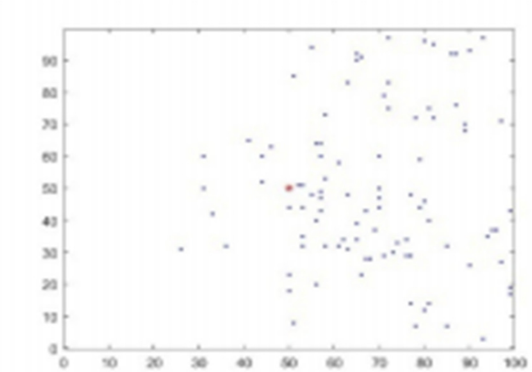
1 months



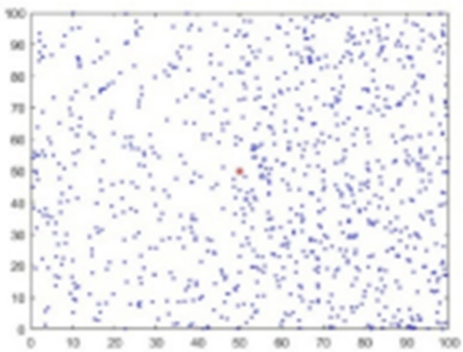
2 months



3 months



6 months



12 months

Figure 2. Prediction results

The selection of indicators was informed by consultations with experts in botany, who identified eight biological traits pertaining to reproduction and dispersal as critical risk factors. These factors, serving as pivotal parameters, encompass the quantity of seeds per fruit, annual seed production per square meter, seed viability, long-distance dispersal capability, vegetative reproduction potential, seed germination requirements, susceptibility to dissemination through human activities, and the impact of natural and anthropogenic disturbances. In addition to these biological characteristics, our evaluation incorporates the extent of ecological harm inflicted by the organism, the intensity of its natural adversaries within the invaded system, and the extent of human harvesting activities.

5.2. Linear Model

Within this section, our objective is to ascertain the impact factor of dandelions and scru-tinize the interconnections among diverse indicators and the said impact factor. To fulfill this aim, we utilize a linear model as the principal analytical instrument. The rationale for adopting a linear model and the advantages it confers within the scope of our investigation are explicated below.

For the formulation of the risk assessment mathematical model, eight biological traits as- sociated with reproduction and dispersal were identified as critical risk factors based on the expertise of botany professionals. These parameters, as outlined in reference [4], encompass the following: Number of seeds per fruit (SF), Annual seed production per square meter (ASR), Viability of seeds (measured in months) (VIA), Long-distance dispersal strength (LDD), Veg- etative reproduction strength (VRS), Seed germination requirement level (SGL), Potential to be disseminated through human activities (HA), and the Role of natural and man-made dis- turbances (NMD).By conducting a weighted analysis of the aforementioned influencing factors and establishing an appropriate evaluation model, the final scores will be obtained for the in- fluencing factors, which will serve as important criteria for evaluation. The diagram of the model is shown in Figure 3.

$$ImpactFactor = \beta_0 + \beta_1 \times SF + \beta_2 \times ASR + +\beta3 \times VIA + \beta4 \times LDD + \beta5 \times VRS + \beta6 \times SGL + \beta7 \times HA + \beta8 \times NMD \quad (29)$$

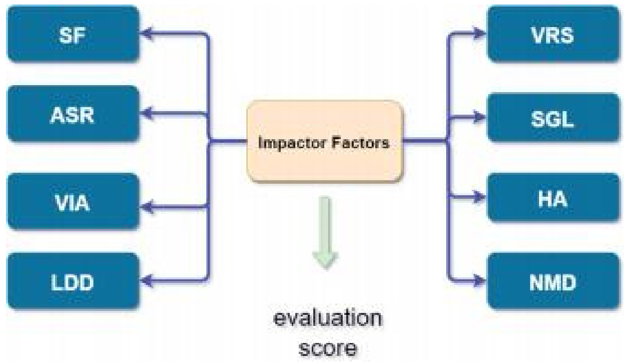


Figure 3. Diagram of Genetic Factor Evaluation Model

In the context of our model, β0 denotes the intercept, while β1 to β8 serve as coefficients, each representing the respective weights or contributions of individual indicators to the overall impact factor. It is imperative to emphasize that these coefficients necessitate estimation through data-driven methodologies.

5.3. Analytic Hierarchy Process

The establishment of the hierarchy in the Analytic Hierarchy Process (AHP) involves the identification of the primary decision objective, which is subsequently decomposed into a hi- erarchical structure comprising criteria, sub-criteria, and alternatives. The top-level criterion encapsulates the overarching objective, while the lower-level criteria delineate the constituent factors contributing to the attainment of that objective.

Subsequently, pairwise comparisons are undertaken to assess the criteria or factors in terms of their importance or contribution to the overall objective. This process entails compar- ing each criterion to every other criterion, gauging their relative significance. The comparative evaluation is facilitated through the utilization of a scale, such as numerical ratings or verbal judgments, to delineate the hierarchy of importance among the criteria.

Table 4. Saaty's Scale for Pairwise Comparisons

Intensity of Importance	Explanation
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance

Subsequently, the pairwise comparison judgments are documented in a matrix format, where the rows and columns correspond to the criteria undergoing comparison. Typically, this matrix is populated with values or judgments signifying the relative importance derived from the pairwise comparisons.

Table 5. The pairwise comparison judgments are documented in a matrix format

	SF	ASR	VIA	LDD	VRS	SGL	HA	NMD
SF	1	3	5	3	5	5	3	3
ASR	1/3	1	3	1/3	3	3	1/3	1
VIA	1/5	1/3	1	1/5	1/3	1/3	1/5	1/3
LDD	1/3	3	5	1	3	3	1	3
VRS	1/5	1/3	1/3	1/3	1	1	1/3	1/3
HA	1/3	3	5	1	3	3	1	3
NMD	1/3	1	3	1/3	3	3	1/3	1

Following the acquisition of the comparison matrix, the subsequent phase involves assessing its consistency through the computation of the Consistency Index (CI). Saaty has furnished a formula for determining the CI based on the matrix:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Here, λmax denotes the maximum eigenvalue of the matrix, and n represents the order of the matrix, corresponding to the number of criteria.

Table 6. Eigenvalue

Indicator	Eigenvalue
SF	1.31
ASR	0.93
VIA	0.61
LDD	0.49
VRS	0.38
SGL	0.78
HA	1.02
NMD	0.69

5.4. Problem Solving

By inputting the collected data of different types of plants into the invasion factor evaluation model we have established, the evaluation indicators of each species are obtained as shown in Table 7. At the same time, for better visualization, all the scores are plotted as a bar graph, as shown in Figure 4 and Figure 5.

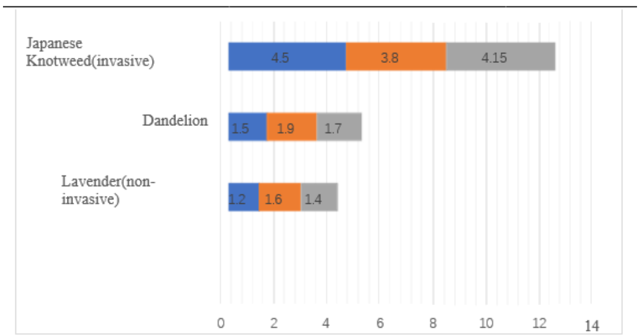


Figure 4. Evaluation scores of impact factors for different species

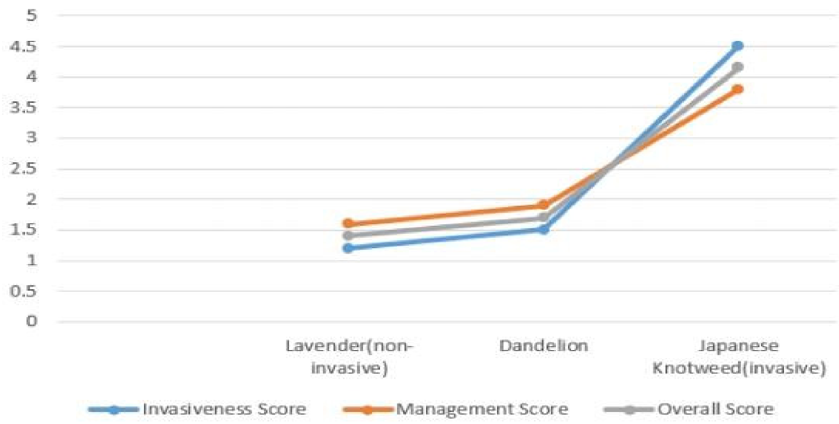


Figure 5. Line graph of evaluation scores for different species

Table 7. Score Table for Plants

Plant	Invasiveness Score	Management Score	Overall Score
Lavender(noninvasive)	1.3	1.7	1.5
Dandelion	1.6	1.9	1.8
Japanese Knot- weed(invasive)	4.7	3.9	4.5

Utilizing a program to solve the established model, we generate a rate table for the afore- mentioned plants. Subsequent analysis of the results may lead to the consideration of dandeli- ons as non-invasive based on the obtained outcomes.

Biological invasions refer to the rapid spread of non-native species in new ecosystems, posing threats to local species, ecological balance, and human economic interests. These inva- sive species often originate from other regions and, due to factors like international trade, tour- ism, and climate change, manage to traverse geographical barriers and thrive in new environ- ments.

Biological invasions have profound impacts on ecosystems. They introduce new compet- itors, predators, diseases, or parasites, endangering the survival of native species. Invasive spe- cies can disrupt ecosystem structures and functions, leading to loss of biodiversity and affecting soil quality, water resources, and air quality. Furthermore, invasions can affect agriculture, forestry, fisheries, and livestock, negatively impacting human economies and food security.

In conclusion, evaluating the significance of a biological invasion requires a comprehensive assessment of its potential threats to ecosystems, local species, human economies, and social interests, enabling appropriate preventive and management measures to be taken.

6. Model Evaluation

6.1. Strengths

When establishing a dandelion wind seed dispersal model, we considered both vertical and horizontal movement directions in the kinematic model. We incorporated a probabilistic distribution model to make the model more flexible and realistic.

We performed a rationality check on the biological invasion factor assessment model using available data. By comparing the model's calculated results with actual data, we have established the reliability and truthfulness of this model.

6.2. Weaknesses

In the discussion on the impact of environmental factors on dandelion growth conditions, we only considered the influence of wind speed and temperature. Insufficient consideration of influencing factors may lead to inaccuracies in the model's predictions.

In the biological invasion factor assessment model, the timeliness of validation data may result in inadequate verification of the model, requiring additional verification to enhance reliability.

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