EFFECTIVENESS OF EXISTING CASUARINA EQUISETIFOLIA FORESTS IN MITIGATING TSUNAMI DAMAGE

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Abstract

Field surveys were conducted on the eastern coastline of Sri Lanka to investigate which vegetation species are effective against a tsunami and to evaluate the effectiveness of existing *Casuarina equisetifolia* forests in tsunami mitigation. Open gaps in *C. equisetifolia* forests were identified as a disadvantage, and introduction of a new vegetation belt in front of the existing *C. equisetifolia* forest is proposed to reduce the disadvantages of the open gap. A numerical model based on two-dimensional nonlinear long-wave equations was applied to explain the present situation of open gaps in *C. equisetifolia* forests, and to evaluate the effectiveness of combined vegetation system. The results of the numerical simulation for existing conditions of *C. equisetifolia* forests revealed that the tsunami force ratio (R = tsunami force with vegetation/tsunami force without vegetation) was 1.4 at the gap exit. The species selected for the front vegetation layers were *Pandanus odoratissimus*. A numerical simulation of the modified system revealed that R was reduced to 0.7 in the combined *P. odoratissimus* and *C. equisetifolia* system. The optimal width of *P. odoratissimus* (W_1) calculated from the numerical simulation was W_1=10 m. Establishment of a new front vegetation layer except for open gaps that are essential, such as access roads to the beach, is proposed.

Keywords: Coastal forests, tsunami mitigation, drag force, open gap

1. Introduction

The Indian Ocean tsunami on 26 December 2004 caused destruction of life, property, and massive damage to the coastal ecosystem. The damage occurred mainly in Indonesia, Sri Lanka, Thailand, and India, with innumerable injured and hundreds of thousands of destroyed facilities and life (Kathiresan and Rajendran, 2005). Sri Lanka had never experienced damage on such a large scale. About two-thirds of Sri Lanka, especially the western, southern, and eastern coast lines, were severely damaged (Wijetunge, 2005). These damages have highlighted the urgent need to develop methods to mitigate tsunamis and other natural disasters in coastal regions. Coastal forests can function as an alternative solution for mitigating tsunami damage because establishment of a hard infrastructure for tsunami mitigation is not economical especially for developing countries.

Planted *Casuarina equisetifolia* forests were observed in many investigated sites for tsunami mitigation during the field survey. The disadvantages of coastal forests were also revealed. These include open gaps in a forest due to, for example, a road, river, gap between two forests, or difference in elevation. A gap in the coastal zone is reported to increase risks and potential damage because the water flow through the gaps is accelerated as it moves into the constriction. Many previous researchers have examined the shortcomings of open gaps by field investigations (Mascarenhas and Jayakumar, 2008; Fernando et al., 2008), numerical simulations (Tanimoto et al., 2008; Nandasena et al., 2008; Thuy et al., 2009, 2010), and laboratory experiments (Fernando et al., 2008; Thuy et al., 2009, 2010). However, none of the above studies discussed the disadvantages of open gaps in existing *C. equisetifolia* forests by analyzing the variation of maximum tsunami force.

Therefore, the objectives of the present study were to study the (1) disadvantages of open gaps, and (2) effectiveness of modified vegetation systems for reducing the disadvantages of existing *C. equisetifolia* forests.

2. Materials and methods

2.1 Site description

Field surveys of coastal vegetation were conducted on the eastern coastline of Sri Lanka. The vegetation was observed along the coastal belt from Kalmunai to Passekudah including eleven locations (about 72 km, 24-27 May 2010) and from Passekudah to Kokkilai including nineteen locations (about 160 km, 14-18 December 2010) (Figure 1). The areas were mainly covered with *C. equisetifolia* forests that established under the various projects intended to protect people, the infrastructure and the environment from future tsunami hazards. The tree and forests characteristics, such as tree height (H), trunk diameter at breast height, tree density, forests length (L), forests width (W), the spacing between the trees in the shore (l_1) and cross-shore directions (l_2), and the distance from the forest to the sea were measured during the field survey. In addition, the tsunami water depth and flow velocity were obtained from the available data.

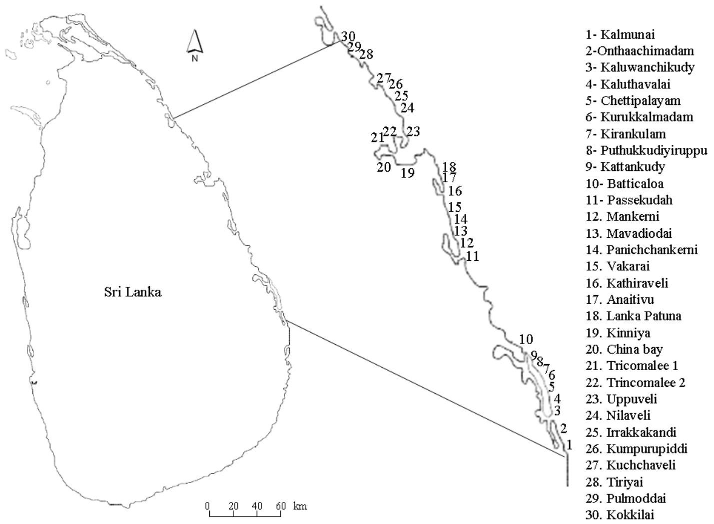

Figure 1: The locations of the investigation sites

2.2 Estimation of drag force coefficient using tree characteristics

The physical characteristics of coastal vegetation were considered by means of drag force of trees along a width of *W* (m) and a length of vegetation of 1 (m). The following equation shows the cumulative drag force acting on the forest (Tanaka et al., 2007).

$$\begin{aligned} D_{\text{cum}} &= n' * (\text{drag force on one tree}) \\ &= n' * \int \frac{1}{2} C_{di} \rho u_i^2 \, \mathrm{d}A_i \\ &= \frac{n'}{2} * (\alpha\beta C_d) * \rho U^2 * (h' \frac{d'}{100}) \\ &= \frac{1}{2} * \frac{d' n' \alpha\beta}{100} * C_d \rho U^2 h' \end{aligned} \quad (1)$$

where D_{cum} is the cumulative drag force of trees with a width of *W* (m) and a length of 1(m), n' is the number of trees in a vegetation width of *W* (m) and length of 1 (m), d' is the reference tree trunk diameter at 1.2 m above the ground (cm), α and β are additional coefficients representing the effects of branches and leaves, respectively, on the drag force C_d is the drag coefficient, ρ is the density of salt water (kg/m^3), *U* is the depth-average velocity (m/s), and h' is the tsunami depth (m). Coefficients α and β were chosen according to the average tree height.

Equations 2, 3, and 4 define the vertical vegetation structure, $C_{d\text{-}all}$, effective vegetation thickness, dN_{all} (cm/ (vegetation width x 1 m^2)), and vegetation thickness per unit area, dN_u (cm/unit vegetation area m^2), as follows (Tanaka et al., 2007).

$$C_{d-all} = \alpha\beta * C_d \quad (2)$$

$$dN_{all} = \alpha\beta * d' n' \quad (3)$$

$$dN_u = \frac{dN_{all}}{l^2 n'} = \frac{\alpha\beta d'}{l^2} \quad (4)$$

where l is the average space between the trees (m). Equations 2, 3, and 4 are related to the drag force in Equation 1. C_{d-all} describes the characteristics of the tree itself, dN_{all} describes the characteristics including the effects of the tree structure $\alpha\beta$ in the W (m) x 1 (m) vegetation, and dN_u describes the characteristics of a unit vegetation area.

2.3 Numerical simulation analysis

A numerical simulation was carried out to investigate the effects of an open gap, such as a road, in *C. equisetifolia* forests on tsunami mitigation. The present situation of a sample forest was investigated using the numerical simulation, and the disadvantages associated with the open gaps were identified. Then, the existing conditions of *C. equisetifolia* forests were modified by introducing a front vegetation layer to reduce the disadvantages. Finally, a numerical simulation was conducted to determine the effectiveness of the modified system.

2.4 Governing equations

The governing equations were two-dimensional nonlinear long-wave equations. The governing equations used for the numerical simulation were the continuity equation (5), the momentum equation in X and Y directions (6) and (7), and the equation for drag force (8).

$$\frac{\partial \zeta}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = 0 \tag{5}$$

$$\begin{aligned}&\frac{\partial Q_x}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q_x{}^2}{d}\right) + \frac{\partial}{\partial y}\left(\frac{Q_x Q_y}{d}\right) + gd\frac{\partial \zeta}{\partial x} + \frac{\rho g n^2}{\rho d^{7/3}} Q_x \sqrt{Q_x{}^2 + Q_y{}^2} + \frac{1}{2\rho}\frac{\rho \gamma C_{D-all} b_{ref}}{d} Q_x \sqrt{Q_x{}^2 + Q_y{}^2} \\ &-2\frac{\partial}{\partial x}\left(\upsilon_e \frac{\partial Q_x}{\partial x}\right) - \frac{\partial}{\partial y}\left(\upsilon_e \frac{\partial Q_x}{\partial y}\right) - \frac{\partial}{\partial y}\left(\upsilon_e \frac{\partial Q_y}{\partial x}\right) = 0\end{aligned} \tag{6}$$

$$\begin{aligned}&\frac{\partial Q_y}{\partial t} + \frac{\partial}{\partial y}\left(\frac{Q_y{}^2}{d}\right) + \frac{\partial}{\partial x}\left(\frac{Q_x Q_y}{d}\right) + gd\frac{\partial \zeta}{\partial y} + \frac{\rho g n^2}{\rho d^{7/3}} Q_y \sqrt{Q_x{}^2 + Q_y{}^2} + \frac{1}{2\rho}\frac{\rho \gamma C_{D-all} b_{ref}}{d} Q_y \sqrt{Q_x{}^2 + Q_y{}^2} \\ &-2\frac{\partial}{\partial y}\left(\upsilon_e \frac{\partial Q_y}{\partial y}\right) - \frac{\partial}{\partial x}\left(\upsilon_e \frac{\partial Q_y}{\partial x}\right) - \frac{\partial}{\partial x}\left(\upsilon_e \frac{\partial Q_x}{\partial y}\right) = 0\end{aligned} \tag{7}$$

$$F = \frac{1}{2} C_{d-all} \rho U^2 A \tag{8}$$

where Q_x and Q_y are the discharge flux in x and y directions respectively, t is the time, d the total water depth ($d = h+\zeta$), h the local still water depth, ζ the water surface elevation, g the gravitational acceleration, ρ the density of salt water, n the Manning roughness coefficient, γ the tree density (number of trees/m^2), F the drag force on trees, A the projected area of trees facing the tsunami, and U the depth-average velocity. To evaluate the tsunami reduction by a coastal forest, the variations of tsunami force behind the forest was examined with input data including, the topography, tsunami conditions, and different tree and forest characteristics. The topographical condition used for the tsunami numerical simulation is shown in Fig. 2.

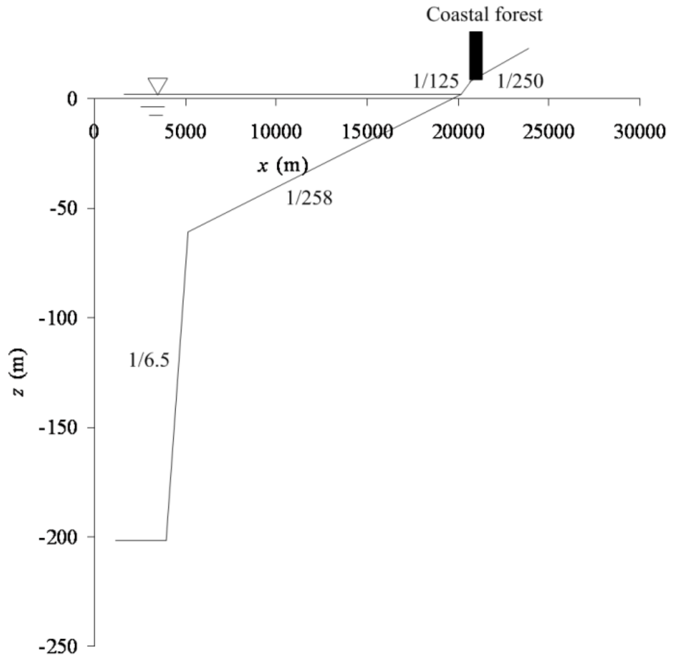

Figure 2. The topographical conditions used for the numerical simulation

2.5 Conditions of numerical simulation for existing and modified forest conditions

A numerical simulation was carried out on a *C. equisetifolia* forest at the Batticaloa site (length = 600 m and width = 60 m) to identify the disadvantages of open gaps. The existing condition of *C. equisetifolia* forests was modified to decrease the disadvantages of the open gaps. It also aimed to improve the effectiveness of the present *C. equisetifolia* forests. The modification was done by establishing a vegetation layer in front of the existing *C. equisetifolia* forest. Fig. 3 (b) shows a schematic view of the front vegetation layer. Variations of the tsunami force ratio (R) were assessed at the middle of the open gap exit (point B in Fig. 3 (b) in determining W_1).

$$\text{Tsunami force ratio } (R) = \frac{\text{Force with vegetation}}{\text{Force without vegetation}}$$

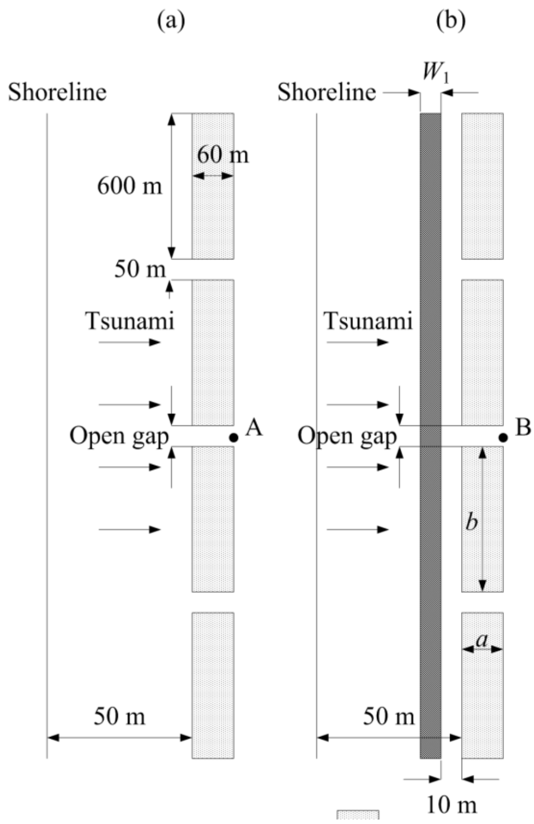

Figure 3. Schematic views of (a) exiting condition, (b) modified system

3. Results and discussions

3.1 Present situation and problems associated with planted C. equisetifolia forests

C. equisetifolia forests at investigated sites were established by various organizations including NGOs and government institutes before and after the Indian Ocean tsunami in 2004. Most of the forests established before the Indian Ocean tsunami in 2004 failed to protect people and infrastructures behind the forests. Therefore, it can be assumed that such planting projects were carried out without considering the scientific guidelines as well as socioeconomic criteria. The forests that were established after 2004 tsunami also failed to take similar characteristics (i.e., forest density, forest length and width, open gap width, etc.) of matured forests into account, and hence, it can be assumed that the newly established forests also will not be effective against future tsunami events. The demerits of coastal forests, such as an open gap in a forest (i.e., a road, a river, a gap between two forests, etc.), were identified in many of the investigated *C. equisetifolia* forests. Mascarenhas and Jayakumar (2008) reported that roads perpendicular to the beach in a coastal forest served as pathways for a tsunami to travel inland in many places in Tamil Nadu, India, during the Indian Ocean tsunami in 2004. The presence of an open gap in a forest could intensify the force of the tsunami waves by channeling them into the gap (Tanimoto et al., 2008; Tanaka, 2009; Thuy et al., 2009). Fig. 4 (a) and (b) show examples of open gaps in a *C. equisetifolia* forest in investigated areas.

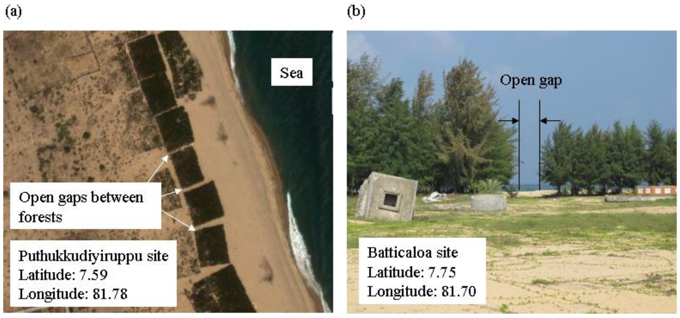

Figure 4. Examples of an open gap at investigated sites

A numerical simulation was carried out to identify the disadvantages of an open gap in an existing *C. equisetifolia* forest. The model was run for the without-vegetation condition first and then for the *C. equisetifolia* forest condition (Fig. 3(a)). Fig. 5(a) and (b) show the *x*-*y* distribution of the maximum tsunami force (F_{max}) (N) for a no-vegetation condition and behind the forest for with-vegetation condition, respectively.

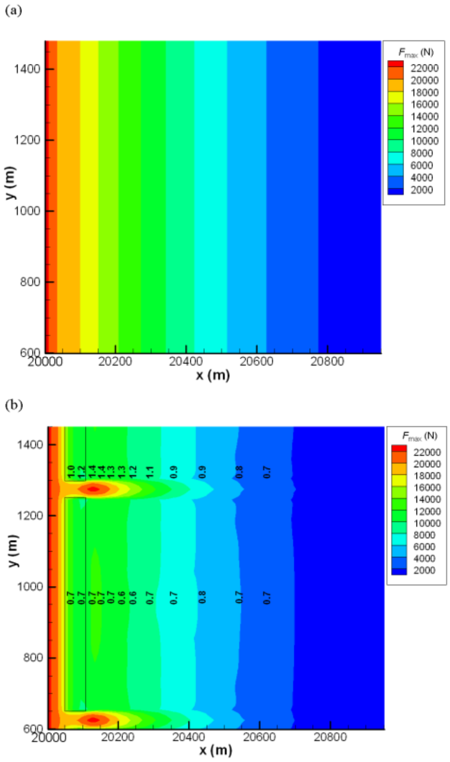

Figure 5. x-y distribution of the maximum tsunami force for (a) no-vegetation condition, (a) behind the forest for with-vegetation condition

The potential tsunami force is defined as the total drag force on a virtual high column with the unit width and unit drag coefficient. The location of the shoreline was along the *y*-axis of both figures (*x* = 20000), and the difference between the values of the *x*-axis and the shoreline (*x* = 20000) shows the distance from the shoreline to the inland. The situation at the gap and gap exit was critical. The maximum tsunami force varied from 18,000 to 20,000 N inside the gap, and it increased to about 22,000 N at the gap exit (between 100–150 m from the shoreline). The variation of *R* at the gap exit and along the center line of the forest is shown in Fig. 5(b). The values of *R* along the gap exit were greater than the values of *R* at parallel locations along the center line of the forest. The highest value of *R* was 1.4, and it was seen at the exit of the gap (point A in Fig 3(a)). Therefore, the results of Fig. 5 reveal that the presence of an open gap in a coastal forest amplified the tsunami force even more than the no-vegetation condition. A similar result was found by Thuy et al. (2009) where the maximum velocity at the gap exit was 1.7 times than the maximum velocity without a coastal forest in their simulation condition. These results emphasize the importance of developing methods to minimize the tsunami force at the gap exit, at least to the no-vegetation condition. In the present study, we propose a new vegetation layer at the front of the existing *C. equisetifolia* forest to minimize the amplification of tsunami force through the open gap. In the improved planting condition, *Pandanus odoratissimus* as the front line could be used to reduce the disadvantages of open gaps. The optimum widths of *P. odoratissimus* (W_1) were estimated by the numerical simulation as described below.

3.2 Selection of effective widths of *P. odoratissimus*

The present situation of planted *C. equisetifolia* forests was improved by introducing a front vegetation layer to reduce the disadvantages of open gaps. The results of the numerical simulations conducted to determine the optimum value of W_1 is shown in Fig. 6.

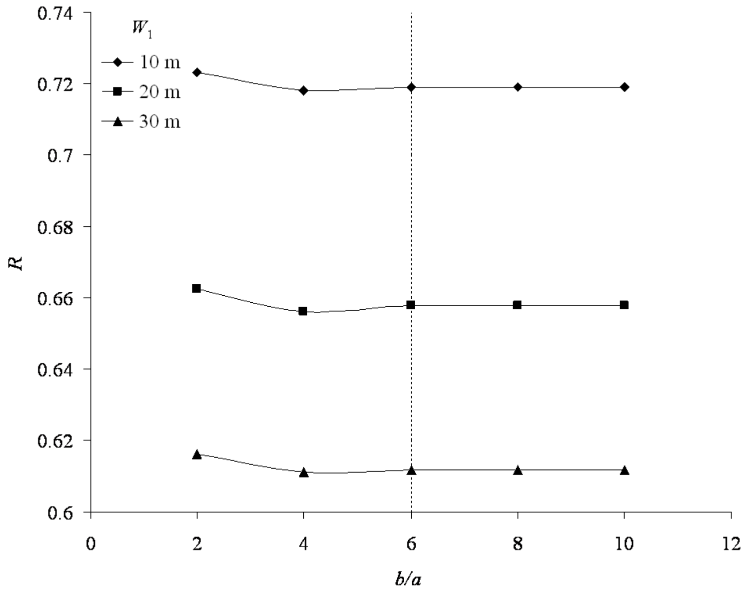

Figure 6. Variation of R for different W_1 values

The figures describe the variation of *R* with *b/a* (*b*=forest length along a shoreline, *a*=forest width to streamwise direction) for different values of W_1 (W_1 = 10, 20, and 30 m). The *R* in Fig. 6 was gradually decreased to *b*/*a*=6 because increasing the *b*/*a* creates a longer effective forest length perpendicular to the tsunami direction. The *R* at the gap exit of the existing condition was 1.4, but it was reduced to around 0.6–0.7 by introducing *P. odoratissimus* as the front vegetation layer. The selection criterion for the optimum value of W_1 was that *R* should be less than one. According to Fig. 6, *R* was less than one in all the cases, and it might be decreased further if the width of *P. odoratissimus* (W_1) was increased still further. Nevertheless, the establishment of a thick *P. odoratissimus* layer as the front line would not be effective from economical and social points of views. An economic point includes high cost spend for establishment of a thick vegetation layer and the social points include illegal settlement and illegal activities within the shelterbelt. Consequently, W_1=10 m was selected for proposed front vegetation layer. The density of *P. odoratissimus* was selected to equal the average tree density of existing *P. odoratissimus* forests (0.4 trees/m^2) at the investigated sites. Many of the open gaps of the existing *C. equisetifolia* forests serve no purpose, but some of them are access roads to the beach. Therefore, the proposed modification should exclude the open gaps that serve essential purposes.

3.3 Effectiveness of combined vegetation system on tsunami mitigation

The protective functions of combined vegetation systems have been studied in detail by many researchers using field investigations (Tanaka et al., 2007, 2010), numerical simulations (Tanaka et al., 2009), and laboratory experiments (Tanaka et al., 2009). All the above studies reported that a combined system can play an effective role in mitigating tsunami damage. Tanaka et al. (2007) conducted a field investigation in Sri Lanka after the Indian Ocean tsunami in 2004 and found that *P. odoratissimus* and *C. equisetifolia* were mixed for a distance of about 20 m at the Kalutara site. The tsunami height 60 m inland from the coast was 0.6 m, and the houses located within this area were not as heavily damaged because the tsunami height was low compared to its original value. In Sri Lanka, there are many newly established coastal vegetation planting projects for tsunami disaster mitigation. Tanaka et al. (2010) investigated the effectiveness of these new establishments on the southern and western coastlines of Sri Lanka and found that many of them consisted of combined vegetation projects.

4. Conclusions

Field surveys were conducted on the eastern coastline of Sri Lanka to investigate the present condition and effectiveness of existing coastal vegetation barriers against a tsunami. The conditions of existing *C. equisetifolia* forests were analyzed, and it was found that the open gaps in the forests created risk zones, especially at the gap exits. A numerical simulation was conducted to investigate the present condition with regards to open gaps in the forests, and it was found that the maximum tsunami force was amplified greatly by open gaps. R was calculated as 1.4 at the gap exit in comparison with the no-vegetation condition. This study proposed introducing a vegetation layer in front of the *C. equisetifolia* forest to reduce the disadvantages. *P. odoratissimus* was selected as the front vegetation layer. The results of a numerical simulation carried out to determine the combined effects of *C. equisetifolia* and *P. odoratissimus* demonstrated that the R at the gap exit was 0.6–0.7, which is a substantial reduction from 1.4. Therefore, *P. odoratissimus* as the front vegetation layer was proposed to improve the present situation of the *C. equisetifolia* forest. The results of a numerical simulation conducted to determine the optimal width of *P. odoratissimus* (W_1) gaps revealed that the best W_1=10 m considering economical and social points of views. The modification should be made except in the open gaps that are used for essential purposes such as roads to access the beach.

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