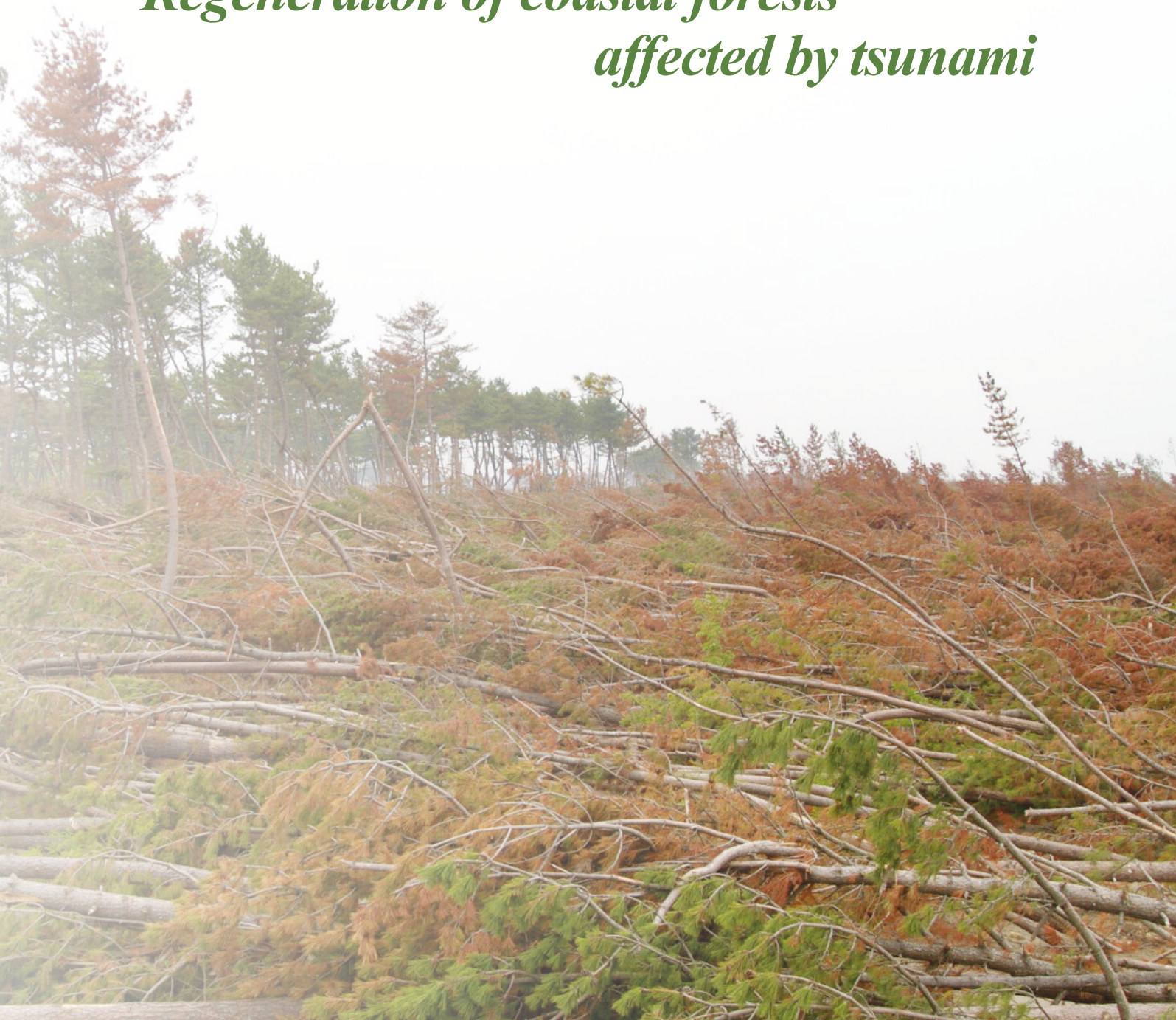


Regeneration of coastal forests affected by tsunami



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Tomoki Sakamoto

1. Introduction

On March 11, 2011, 14:46, a huge earthquake centered off the Sanriku coast occurred, resulting in a large tsunami and that led to the worst disaster of the postwar period on the Pacific coast in east Japan. Many lives and much property and social infrastructures were destroyed. Coastal forests were also considerably affected in a wide area between Aomori and Chiba Prefectures. In particular, forests located between Iwate and Fukushima Prefectures were severely damaged. The forests had served as a form of disaster prevention against wind, tide, and blown sand as well as provided landscape amenities and places for recreation until their multifaceted functions were entirely lost. Considering these lost functions, regeneration of these coastal forests is essential in the post-earthquake recovery process. It is desirable that these forests be regenerated not only for restoring them to their condition before the tsunami but also for improving them.

The Forestry and Forest Products Research Institute conducted “Fiscal 2011 Emergency Survey on Post-earthquake Recovery (Research on Reduction of Tsunami Damages by Coastal Disaster Protection Forests)” as a Forestry Agency-sponsored project, with the help of the Japanese Society of Coastal Forest. Leaving survey details to the survey report and publications by members of the Japanese Society of Coastal Forest, I review herein, as a member of the project, the damage this tsunami has caused to coastal forests and the ways by which coastal forests may have reduced tsunami damages. I also summarize characteristics of coastal forests as disaster prevention facilities, and finally, describe my thoughts on regeneration and recovery of coastal forests.

I thank the Conservation Division; Tohoku Regional Forest Office; Kanto Regional Forest Office of the Forestry Agency; Prefectures of Aomori, Iwate, Miyagi, Fukushima, Ibaraki, and Chiba; Japan Forest Technics Co.; Japan Conservation Engineers & Co., Ltd.; the Japanese Society of Coastal Forest; and many other entities for their support and cooperation in a series of surveys.



Photo 1

Catastrophically damaged coastal forest (Noda village, Iwate Prefecture)

The coastal forest was lost, leaving only a part. The coastal levee along the shoreline was also destroyed, leaving a part and concrete blocks, and other material entered the inland side. At right rear, there are many stumps with broken stem.

2. Tsunami Damages to Coastal Forests

2.1 Huge tsunami

The 2011 Great East Japan Earthquake (the 2011 Tohoku Pacific coast Earthquake) that caused the tsunami of present interest was a huge earthquake of magnitude 9.0, with its epicenter located off the Sanriku coast. The tsunami that attacked coastal areas in the Tohoku region was never encountered before and was far larger than what people could have imagined. The wave was particularly high in coastal areas in the Iwate Prefecture, wherein the ria coastline had developed; coastal levees were destroyed and forests were devastated in coastal areas affected by the huge tsunami (Photo 1). In the scenic Takatamatsubara in Rikuzentakata city, because of pre-existing ground subsidence, the tsunami damage was not limited to trees but included the land, which was largely washed out and had become a sea. The wave height in the Sendai Plain was not as high as that in the ria coastline, but some inundation heights exceeding 10 m were recorded*. In many places in the Sendai Plain, the tsunami affected coastal levees and scoured the land to create depressions on the inland side of the levees (Photo 2). The coastal levees themselves were also violently destroyed, presumably owing largely to the scouring (Photo 3).

*Based on preliminary estimates by the 2011 Tohoku Earthquake Tsunami Joint Survey Group (<http://www.coastal.jp/ttjt/>) (November 11, 2011).



Photo 2

Scouring behind a coastal levee (Iwanuma city, Miyagi Prefecture)

In the coastal forest shown at the upper left, constituent materials of the destroyed coastal levee were scattered and the seaward portion of the forest zone was pushed down.



Photo 3

Destroyed coastal levee and scouring behind it (Iwanuma city, Miyagi Prefecture)

The coastal levee was destroyed and the sea surface can be observed. The strip-shaped water surface on the right side is a depression considered to have been scoured by the tsunami that overflowed the levee. Concrete pieces at the front and white objects in the center are constituent materials of the damaged coastal levee.

A phenomenon similar to the scouring on the inland side of the coastal levees also occurred in an artificial sand dune (Photo 4). Furthermore, there were some places that had been coastal forests but became seas, presumably because the topsoil was washed away mainly by the backrush (Photo 5).



Photo 4

Artificial dune washed away (Misawa city, Aomori Prefecture)

There was an artificial sand dune in a depression vertically extending in the center. It is believed that the back of the artificial dune was sequentially eroded from the inland side by the tsunami that overflowed the artificial dune and was finally lost.



Photo 5

Washout of land (Sendai city, Miyagi Prefecture)

There appears to be a river, but the two sides of the coastal forest were linked before the tsunami. The coastal forest is considered to have been divided by scouring because of focused backrush.

2.2 Tsunami damages to coastal forests

Types and degrees of damages of coastal forests were diverse, considering that the tsunami reached a wide range of areas and its scale; terrain conditions; affected backrushes; size and type (tree species, tree height, breast-height diameter, clear stem height, and stand density) of coastal forests; topsoil conditions; and disaster prevention facilities, such as coastal levees, were different among locations. In the damage survey of coastal forests, the types of damage to trees were divided into stem breakage, uprooting, and leaning.



Photo 6

Stem breakage (Soma city, Fukushima Prefecture)

The broken stem remained connected to the stump in some cases or was washed away in other cases. The state of the breakage edge also is not uniform.

2.2.1 Stem breakage, uprooting, and leaning

“Stem breakage” refers to a broken stem (Photo 6). Although stems of some trees appeared to be just bent without being completely broken, cracking was confirmed inside the stems. Among trees with broken stems, the stem was completely separated from the stump in some trees or connected to the stump with bark or other tree parts. If only the stump was left without the stem being attached to it, it meant that the upper part (stem) had become driftwood.

“Uprooting” refers to a state wherein the stem tilted and the root mass was lifted. The degrees of uprooting widely varied, from the lodging state wherein the tree was fully turned over to the state wherein some roots appeared above the ground surface or roots were floating in the sediment layer.

Typical examples were observed on the inland side of the Teizan Canal in the Sendai Plain and lowlands such as Matsukawaura in Fukushima Prefecture (Sato et al., 2012; Tamura, 2012). For many uprooted trees, development of sinker roots (taproots and spindle roots) was not observed, and the roots revealed a thin board-like shape (Photo 7). Further, many places wherein uprooting occurred were swampy lowlands (Photo 8). These findings suggest that trees in these areas had no deep roots because of the high



Photo 7

Uprooting (Sendai city, Miyagi Prefecture)

Uprooting continuously occurred from the sea side to the land side, leaving a strip-shaped forest zone such as after line logging. Water remained even 13 days after the tsunami, and the place was like wetland.



Photo 8

Root system of driftwood (Soma city, Fukushima Prefecture)

Many driftwood with roots had board-shaped root systems and sinker roots had not been developed.



Photo 9

Coastal forest pushed down (Sendai city, Miyagi Prefecture)

Trees with stems broken at the base and those that underwent uprooting are mixed. Although the damage was devastating, trees were not necessarily washed away (thus did not become driftwood).

groundwater level and were readily pushed down by the tsunami with an additional effect of buoyant force from the tsunami rather than being pulled out by the tsunami. Root damage because of shaking by the earthquake and the loss of binding force of roots because of liquefaction are also believed to have facilitated uprooting (Committee on Regeneration of Coastal Disaster Prevention Forests related to the Great East Japan Earthquake, 2012).

“Leaning” is a state wherein the stem is inclined (Photo 9). Causes of leaning include stem breakage near the base and uprooting. If the cause could be identified, the event was classified into either of these causes. However, the cause could not be confirmed to be breakage or uprooting in some cases because the basal part was covered with sand brought by the tsunami or blown sand accumulated before the tsunami; these cases were classified as “leaning.” Some trees were found to undergo both uprooting and stem breakage.

The association between stem and root strength (resistance to uprooting) against the force exerted by the tsunami determines whether the tree undergoes stem breakage or uprooting. In brief, uprooting occurs if the root is weaker than the stem against the force of the tsunami, and stem breakage occurs if the resistance of the root is high.

Compared with trees with a root system having a board-like shape of less than 1 m



Photo 10

Stem breakage (Fudai village, Iwate Prefecture)

The breakage edge is complex, suggesting that breakage was not completed in a single strike.



Photo 11

Stem breakage (Rikuzentakata city, Iwate Prefecture)

In Takata-matsubara, coastal forests were often lost along with soil, but stem breakage was readily noticeable where the soil remained. Washed-out roots had well-developed sinking roots.

depth, those with a root system normally developed beyond a certain thickness were rarely uprooted or became driftwood with attached roots (described below). In contrast, stem breakage of trees with a relatively large diameter, leaving the stump, was observed in clusters (Photo 10 and Photo 11). It appeared that trees of a size beyond a certain level



Photo 12

Concrete blocks scattered in forest (Natori city, Miyagi Prefecture)

Constituent materials (such as concrete blocks) of coastal levees destroyed by the tsunami became drifting objects and entered coastal forests. Coastal forests were severely damaged not only by the tsunami itself but also by these concrete blocks.

with developed sinking roots underwent stem breakage before uprooting occurred, unless the ground was scoured.

It is noteworthy that uprooting and stem breakage occurred not only from the power of the tsunami itself but also from impacts by tsunami-driven objects. For example, concrete blocks from broken coastal levees did not stay in place but entered coastal forests on the inland side. These concrete blocks then directly strike coastal forests and pushed down or damaged trees therein (Photo 12). In Ichikawa-cho in Hachinohe city, the coastal forest was possibly pushed down by such objects like fishing boats drifting into the forest (Photo 13; Sakamoto et al., 2012).

“Driftwood” is a phenomenon wherein some part or the entire tree is moved from where it has grown to some other place. Some driftwood occurred with roots attached owing to uprooting (washout), and others occurred without roots owing to stem breakage. When such trees were found in the survey area, they were recorded as driftwood.

2.2.2 Survival/dieback

Although many coastal forests and trees constituting coastal forests were severely damaged, other coastal forests survived the tsunami. The Nagahama coastal forest in Ishinomaki city in Miyagi Prefecture is such an example (Photo 14). The area behind this coastal forest was flooded to approximately 4 m high, and many houses surrounding



Photo 13

Drifting objects transported into coastal forest (Hachinohe city, Aomori Prefecture): provided by the Agriculture, Forestry and Fisheries Department, Aomori Prefecture)

Fishing boats and various other drifting objects entered coastal forests. From a different point of view, coastal forests captured objects drifting because of the tsunami and prevented them from being transported inland.

the forest were washed away. Despite these serious damages in the surrounding area, the initial damage to the forest was limited to those at the front edge hit by constituent materials of coastal levees. Plausible reasons for the survival of the forest include that the forest was constituted of relatively large-diameter trees with mean breast-height diameter of 29 cm* and that the clear stem height was relatively high compared with the inundation height. Furthermore, compared with the inundation depth of 4 m in the forest, the mean clear stem height was as high as 13 m (Photo 15); therefore, the tsunami presumably passed between the trees and did not strike the tree crowns (foliage layer). As a result, the trees received wave power weaker than the resistance of the stem, and this could be the reason why this forest survived.

Among coastal forests that appeared to have survived immediately after the tsunami, some subsequently showed browning leaves and were debilitated (Nakamura et al., 2012). Such trees were located where near base areas had been scoured (Photo 16) or in relatively low places, wherein the water residence time was possibly longer. The possible cause of scouring is that the flow velocity increased in dunes inclining toward the inland

* 36 cm, if only canopy-constituting trees (trees higher than 20% in this coastal forest) were concerned.



Photo 14

Surviving coastal forest (Ishinomaki city, Miyagi Prefecture: March 12, 2011, provided by Aero Asahi Corporation)

Surrounding areas, including those behind the coastal forest, were flooded, and many houses were washed away to the east of the coastal forest (at right in photo); however, damage to the forest was limited. However, many trees died later.

side, intensifying the scouring force.

Debilitation of the surviving trees was also observed in the coastal areas in the Sendai Plain. Until 2 weeks after the disaster, a few isolated dead trees could be observed, but no cluster of dead trees was apparent in the coastal areas in the Sendai Plain. Moreover, even leaning trees had green leaves. However, when I revisited the Sendai Plain more than 2 months later, most leaning trees had brown leaves, and even some trees standing upright had browning leaves and seemed weakened.

The cause of debilitation in these trees is not necessarily clear, but many weakened trees were those with their roots partly exposed by scouring and those located in relatively low areas, wherein the flooding period was estimated to be longer than in the surrounding areas. For low height trees, it may be an additional factor that the stems and leaves were damaged by the passing tsunami with a large amount of sand; these trees may be more susceptible to briny wind injury.

Debilitation of the remaining trees has been confirmed in various regions, and the affected range and degree of damage to coastal forests may become wider and more severe than estimated immediately after the tsunami.



Photo 15

High clear stem height of surviving coastal forest (Ishinomaki city, Miyagi Prefecture)

Although the inundation depth was estimated to be nearly 4 m, it was believed that the tsunami passed between the stems and did not strike tree crowns (canopy layer), owing to the clear high stem height.



Photo 16

Scouring that occurred in surviving coastal forest (Ishinomaki city, Miyagi Prefecture)



Photo 17

Leaning of coastal forest caused by the tsunami (Misawa city, Aomori Prefecture)

Although the coastal forest leaned toward the inland, leaning terminated in the middle of the coastal forest, with a clear boundary.



Photo 18

Deposition of driftwood (Iwanuma city, Miyagi Prefecture)

Part of the coastal forest was uprooted and became driftwood but was captured by trees on the inland side that did not undergo uprooting or stem breakage (rear of photo).

3. Functions of Coastal Forests against Tsunami

Coastal forests, although they experienced a variety of damage, revealed tsunami damage-reducing functions in various places.

3.1 Diminishing wave power

The wave power-reducing function of a coastal forest is produced by the forest acting as a resistor against running water for reducing the flow velocity and wave power of a tsunami. By this function, it is expected that structure damage by the tsunami will be reduced and that the tsunami arrival is delayed so that additional time for evacuation is acquired. During evacuation, it is possible to escape death by a hairbreadth; even a difference of a few seconds may matter at the last minute.

Although these functions have been clearly demonstrated in numerical simulations, it is difficult to clearly demonstrate them in the field, considering that multiple factors are involved in tsunami damage. Examples of wave power reduction by coastal forests have also been reported in the Indian Ocean Tsunami in 2004, but there has been an objection that the presented data were insufficient. A rebuttal to the objection has been published but has not adequately addressed the issue (Sakamoto and Noguchi, 2009).

In the tsunami of present interest, in Aomori Prefecture, wherein the scale of the tsunami was smaller than in the area between Iwate and Fukushima Prefectures, there were

some places in which leaning of trees because of the tsunami was clearly confirmed to have stopped in the middle of a coastal forest (Photo 17). This fact suggests that the wave power was reduced while the tsunami was passing through the forest (Sato et al., 2012; Noguchi et al., 2012).

3.2 Capturing drifting objects

This is a function to stop the transportation of drifting objects by tsunami. It includes a function of preventing drifting objects such as ships and rubble from colliding with conservation targets, such as houses; function of preventing additional tsunami damages caused by houses and other objects that have become drifting objects; and function of preventing houses and other objects from flowing out to sea because of backrush. There is a certain level of uncertainty in these functions because drifting objects can pass between trees, but effects can be expected unless lodging or washout of the forest zone occurs.

Although drifting objects pass less readily through a wider forest zone, even a single tree can pose a barrier in some cases (Sakamoto et al., 2008), and there are important differences in these functions between places without and with trees. Unlike the wave power-reducing function, this function is easy to demonstrate, because floating objects are often left on site.

In this survey, a case wherein ships had been stopped by a coastal forest (Photo 13) and cases wherein concrete blocks from broken coastal levees and other drifting objects stayed in the forest although they had pushed down trees in the forest (Photo 2, Photo 3, Photo 12) were observed. Further, we observed a case wherein driftwood was trapped by the surviving trees (Photo 18).

For this function, it has been highlighted that debris captured by the forest zone may be driven again by backrush and may cause additional damage (Laso Bayas et al., 2011). However, in the case of large-scale tsunami wherein rubble that becomes drifting objects increases damage, places attacked by rubble associated with backrush are possible to have been already damaged seriously by the spilling wave. Between additional damage caused by rubble being pulled by backrush and damage avoided by capturing rubble, the latter is expected to be larger. Therefore, even if the possibility that rubble captured by the coastal forest is driven again by backrush reflects the actual situation, underestimating the function of trees to capture floating objects is not justified.

3.3 Regulation of land use

This is a function for regulating land use and preventing conservation targets from danger by occupying a certain amount of coastal area with coastal forests. In this function, coastal forests do not directly act against tsunami, but their disaster prevention effect is reliable and large and deserves positive evaluation.

For example, in areas affected by the tsunami of present interest, concrete masses from coastal levees were scattered in coastal forests (Photo 12). If buildings had been there, these concrete masses could have directly struck them.

Moreover, in Nagahama in Ishinomaki city (Photo 14), land development for housing was suppressed owing to the presence of coastal forest; thus, the forest prevented potential damage to houses that could have been built there and damaged by the tsunami had the coastal forest not been there. Furthermore, it has been evaluated that the coastal forest prevented potential additional damage from these houses that could have occurred if they had been washed away, broken into rubble, and driven inland by the tsunami (Okada et al., 2012).

3.4 Means to escape from tsunami

Counter-tsunami functions of a coastal forest include providing means of escaping from the tsunami, such as climbing, holding, and soft landing. Specifically, these are functions that allow people to climb trees higher than the inundation depth and wait for the tsunami to cease, allow people attacked by the tsunami to hold on to trees in order to avoid being washed away, or to rescue people who have been washed away by the tsunami. Although these are somewhat primitive to be called functions, it is a fact that many lives were saved by trees during the Indian Ocean Tsunami (Sakamoto and Noguchi, 2009).

In the case of the tsunami from the Great East Japan Earthquake, atmospheric temperature and water temperature were substantially lower than those in areas affected by the Indian Ocean Tsunami, and trees could not survive the tsunami in many locations because the scale was too large. Thus, benefits from this function might have been limited.

4. Characteristics of coastal forest as a disaster-preventing facility during tsunami

The basic disaster prevention plan issued by the Central Disaster Prevention Council (2008) in February 2008 recommends promoting afforestation for preventing mountain and avalanche disasters but does not include coastal forests as counter-tsunami measures. This omission presumably occurred because in Japan wherein advanced land use has progressed, it was difficult to assign locations for coastal forests, which are assumed to be invaded by tsunami, as disaster prevention facilities.

However, it is not realistic to construct coastal levees sufficient for resisting tsunamis of this scale, owing to both cost and undesirable effects such as those on landscapes. Furthermore, because the risk of overreliance on coastal levees has been widely recognized, comprehensive measures, including optimization of land use, will be considered in the future. In this process, coastal forest is likely to be recognized and actively incorporated for its characteristics as a multifaceted space responsible for the tsunami damage-reducing function. In this section, I describe characteristics of coastal forest as a disaster prevention facility.

4.1 Low degree of freedom

Coastal forests have a low degree of freedom compared with coastal levees. For example, if a coastal levee has been constructed with a 5-m projected tsunami height, but the projected tsunami height increases to 8 m, the coastal levee can be modified to increase the height. However, increasing the height of a coastal forest is almost infeasible. Tree height has a certain limit depending on the environmental conditions in the target area and can be reduced by pruning but cannot be arbitrarily increased. Moreover, because tree height, tree density, breast-height diameter, and clear stem height are interrelated, for increasing tree density, breast-height diameter cannot exceed a certain limit. Therefore, tree density must be reduced as the tree height increases for creating a coastal forest comprising large-diameter trees. Furthermore, the tree species that can grow are dependent on the environmental conditions of the target area. Thus, the nature of a coastal forest is limited once the location, wherein the coastal forest is to be created has been determined.

The width of the forest zone and ground level can be artificially altered. To enhance functions of a coastal forest depending on the projected scale of tsunami, it is necessary to increase the width of the forest zone and elevate the ground.

4.2 Incompleteness

A coastal levee can completely stop seawater intrusion unless the tsunami height exceeds the levee height. However, a coastal forest allows tsunami to pass through the forest zone even when the inundation depth does not exceed the tree height and thus cannot prevent flooding of the hinterland. Even small-scale tsunami pass through coastal forests.

However, a coastal forest acts as a barrier to seawater, reducing the wave power and delaying the arrival time. This function can be expected to work until the wave power exceeds the tolerance of trees and coastal forest lodges. Even after the coastal forest has fallen, the forest continues to resist flowing water, albeit to a lower degree. The larger the tsunami scale is, the less noticeable this function is. However, when the tsunami scale is larger, it would be reasonable to say that the wave power-reducing effect is still provided unless the forest trees become driftwood. In contrast, the function of a coastal levee is largely lost when the tsunami height exceeds the levee height. As counter-tsunami facilities, coastal forests and levees should be evaluated on different criteria.

4.3 Uncertainty

Many actual cases are available for illustrating functions of drifting object-blocking and climbing/holding/soft-landing. However, it is largely uncertain to what extent these functions can be expected to work. For the drifting object-blocking function, drifting objects can pass between tree stems and break or push down trees, depending on the object type, irrespective of the tsunami scale. For climbing/holding/soft-landing, the outcome largely depends on individual abilities and luck.

4.4 Time

A coastal forest cannot be created in a short time and requires longer than construction of a coastal levee. Although the required time depends on growth conditions, it is considered to take approximately 20 years until a coastal forest grows to the size required to execute its target functions.

In contrast, a longer life as a disaster-preventing facility can be expected compared with a coastal levee, which undergoes aging degradation. However, in the case of a pine forest, measures for preventing pine wilt disease (spread by pine weevil) are required for this advantage to be realized.

4.5 Evaluation under normal circumstances

Tsunami damage-mitigating functions of coastal forests involve many incomplete and uncertain parts compared with those of coastal levees, and construction of coastal forests also takes time. However, coastal forests are superior in terms of fewer adverse effects and multifaceted utility during normal times. Examples include functions of reducing blown sand damage, serving as a windbreak, reducing wave damage, providing a place for walking, and providing a landscape of white sand and green pines. Coastal forests should be considered helpful in serving as useful spaces for a much longer period than serving as disaster prevention facilities against tsunami.

5. Toward Recovery

The exact nature of coastal forests to be regenerated/recovered varies under the influence of land use plans in the overall recovery plan and thus cannot be defined at this time. Here, I try to highlight how regenerated/recovered coastal forests should look while dividing the process into several stages.

5.1 Regeneration of coastal forest to the pre-tsunami state

The first thing to do is regeneration of coastal forests. In regional reconstructions, it is necessary to restore the coastal forests for blown sand control and windbreak. This reforestation is intended to restore the conventional nature of coastal forests, centering on recovery of daily functions of the coastal forests, such as the blown sand defense and windbreak functions. It is noteworthy that wherever uprooting is believed to have occurred because of insufficient root system development because of a high groundwater level, measures, such as embankment, are necessary to ensure the availability of sufficient space for root spreading. The need for embankments in low wetlands has been highlighted at the time of the Chile earthquake tsunami in 1960 (Izumi et al., 1961).

Regeneration of the coastal forests is necessary regardless of the evaluation of their counter-tsunami functions. To enhance the counter-tsunami functions within the scope of regeneration, it may be effective to return residential areas built in coastal forests back to the coastal forests.

5.2 Healthy coastal forest

It is important that regenerated/recovered coastal forests comprise healthy trees because coastal forests in Japan are not necessarily in a healthy state; many of them are composed of black pine or red pine trees. Thus, countermeasures for pine wilt disease (spread by pine weevil) are essential but have not been adequately applied, and there are several almost completely devastated coastal forests. Moreover, in coastal pine forests, trees are generally planted at a high density of 10,000 trees/ha; thus, it is necessary to adequately manage tree numbers as the planted trees grow. However, in many coastal forests, delayed tree number adjustment has resulted in overcrowded forests, wherein the trees are thin and have long clear stem height relative to their total height.

A coastal forest can provide the blown sand defense function as long as the sandy soil is covered with trees. It can provide the windbreak function without problems if branches on the seaward forest edge are not withered and a desirable tree height is ensured on the leeward edge. Therefore, maintaining forests healthy is the priority and the stand structure is not specifically adjusted for functional enhancement. However, with the aim of tsunami resistance, the results of this survey suggest that a forest zone composed of large-diameter trees with a well-developed root system is desirable for reducing damages to the coastal forest itself. Thus, coastal forests composed of healthy trees are important for disaster prevention functions.

Concerning coastal forests as disaster prevention facilities, it is desirable to avoid trees turning into driftwood, which could increase damage inland. When trees can no longer withstand a tsunami, it is desirable that stem breakage should not lead to separation from the stump and that uprooting should result in lodging without roots being pulled out or cut off rather than driftwoods resulting from stem breakage and uprooting. If these aims are accomplished, the tsunami-derived force is substantially reduced, and trees are more likely to stay in their original locations. However, current knowledge is insufficient for defining how trees should be arranged and grown to achieve this goal. Our knowledge of associations between specific stand types and the wave power-reducing function of coastal forests has not advanced to a practical level allowing the design of stand types based on it. Thus, presently, a practical approach would be to prioritize establishment of healthy coastal forests and maintenance of existing coastal forests as healthy forests.

5.3 Functional enhancement

As discussed above, it is not practical to alter the tree height, breast-height diameter, clear stem height, or tree density of black and red pines for enhancing tsunami damage-

reducing functions, particularly the wave power-reducing function of healthy growing coastal forests. Practically, it is necessary to widen the forest zone to increase the wave power-reducing function. This function is expected to resist a tsunami of a greater magnitude as the width of the forest zone increases. In brief, the desired width of the forest zone varies with the projected tsunami scale and expected reducing effect.

A wider forest zone also helps secure a space to stop driftwood, if created, within the forest. A forest zone that is unlikely to become driftwood should be aimed as a disaster prevention facility, but it is equally important that the forest captures driftwood once it occurs. When the width of a forest zone is difficult to increase, it is desirable to consider creating another forest zone on the inland side to stop the washing out of trees from the coastal forest.

Cases wherein garden trees, hedges, or homestead woodlands reduced damages have also been reported after the Chile earthquake tsunami in 1960 (Izumi et al., 1961). Unlike in rural areas, establishing homestead woodlands is impractical in residential areas. Alternative approaches include establishing a row of trees with well-developed roots along the main road running parallel to the coast and increasing trees in public spaces such as parks. In particular, because the momentum of tsunami becomes weaker with distance from the coast, trees are likely to withstand the tsunami. The momentum of drifting objects is similarly reduced, and thus, an increased drifting object-capturing effect of trees can be expected.

If additional modifications to forest zones are to be considered, the functions may be enhanced by filling a lower space in a forest wherein trees have a large clear stem height as self-pruning of branches of forest trees is considered to be disadvantageous in terms of the wave power-reducing function. Specifically, a possible approach is to introduce evergreen broadleaf trees into the lower layer. When the drifting object-capturing function is specifically targeted, it is also effective to prune lower branches so that the clear stem height is high enough to reduce resistance and increase tolerance to tsunami.

A foredune is often used for constructing a coastal forest and can be expected to function like a coastal levee against tsunami. The levee crown of the foredune is managed to prevent break and recess formation, wherein wind and blown sand can focus; this measure also effectively works for tsunami. In reality, it is not possible to eliminate breaks because of roads and other structures; thus, means of managing breaks must be prepared. It is noteworthy that although the coastal forest is aimed at avoiding concentration of a tsunami and receiving a tsunami as evenly as possible, as described above, effective approaches on the inland side near conservation targets include forest zone and embankment arrangement for protecting conservation targets in a focused manner.

5.4 Ideal appearance

Appearance, particularly arrangement of regenerated/recovered coastal forests, is not necessarily possible to design from scratch because of interrelationships with other land uses and will often develop based on pre-tsunami conditions. Nevertheless, lastly, I have tried to outline how a regenerated/recovered coastal forest should ideally look.

If the tsunami damage-reducing effect of a coastal forest is intended to be substantially enhanced, it is required to construct the forest zone with an increased width and a raised ground level with an embankment.

If a high embankment can replace the function of a coastal levee, it would be possible to construct an area between the beach and coastal forest, similar to a natural coast, or to leave places with a high groundwater level on the inland side partly as wetlands without forming a coastal forest.

If a coastal levee is to be constructed to prepare for tsunamis, possible approaches include placing the coastal levee inside or on the inland side of the coastal forest, similar to those on Fudai beach and old Takata-matsubara, both in Iwate Prefecture. The coastal levee constructed on the inland side of the coastal forest can also be used as a road.

A reason why a few ships were captured by coastal forests despite many ships being carried onshore by the 2011 tsunami is presumably that land use was advanced and no coastal forests were present in many locations where ships were moored. In future reforestation, I hope that coastal forests are created in places where there was no previous forest band. Although this operation requires coordination with land use in the surrounding regions, it is desirable that new space be secured for coastal forests.

It is noteworthy that pine trees constituting coastal forests are not necessarily growing steadily. Trees that previously underwent main shaft (stem) death and have the main shaft derived from branches are common and even dominant trees are no exception. Such trees have a stem, wherein the dead main shaft is contained and thus are structurally weak at that part. Moreover, in this tsunami, stem breakage occurred often near the ground level, but breakage at high positions occurred more in large-diameter trees. The same thing may also occur when dead branches are considered. A measure that may practically be difficult to implement but may prevent stem breakage at a high position would be cutting off dead main shafts and branches, if such detailed work is affordable.

One can assume that a larger-diameter tree is more resistant to wave power. However, aged large-diameter trees are not necessarily highly resistant to wave power, considering that they may have a stem, wherein a dead stem or branches are incorporated and have decayed from that part. In this regard, a report on a storm tsunami that attacked prefectures of Kochi, Tokushima, Osaka, and Wakayama in September 1934 also states that black pine damage was least in trees with 30–60 cm diameter and that more breakage

and lodging occurred in trees with a greater diameter (Bureau of Forestry, Ministry of Agriculture and Forestry, 1935). Therefore, the forest zone should be renewed to maintain tolerance to tsunami.

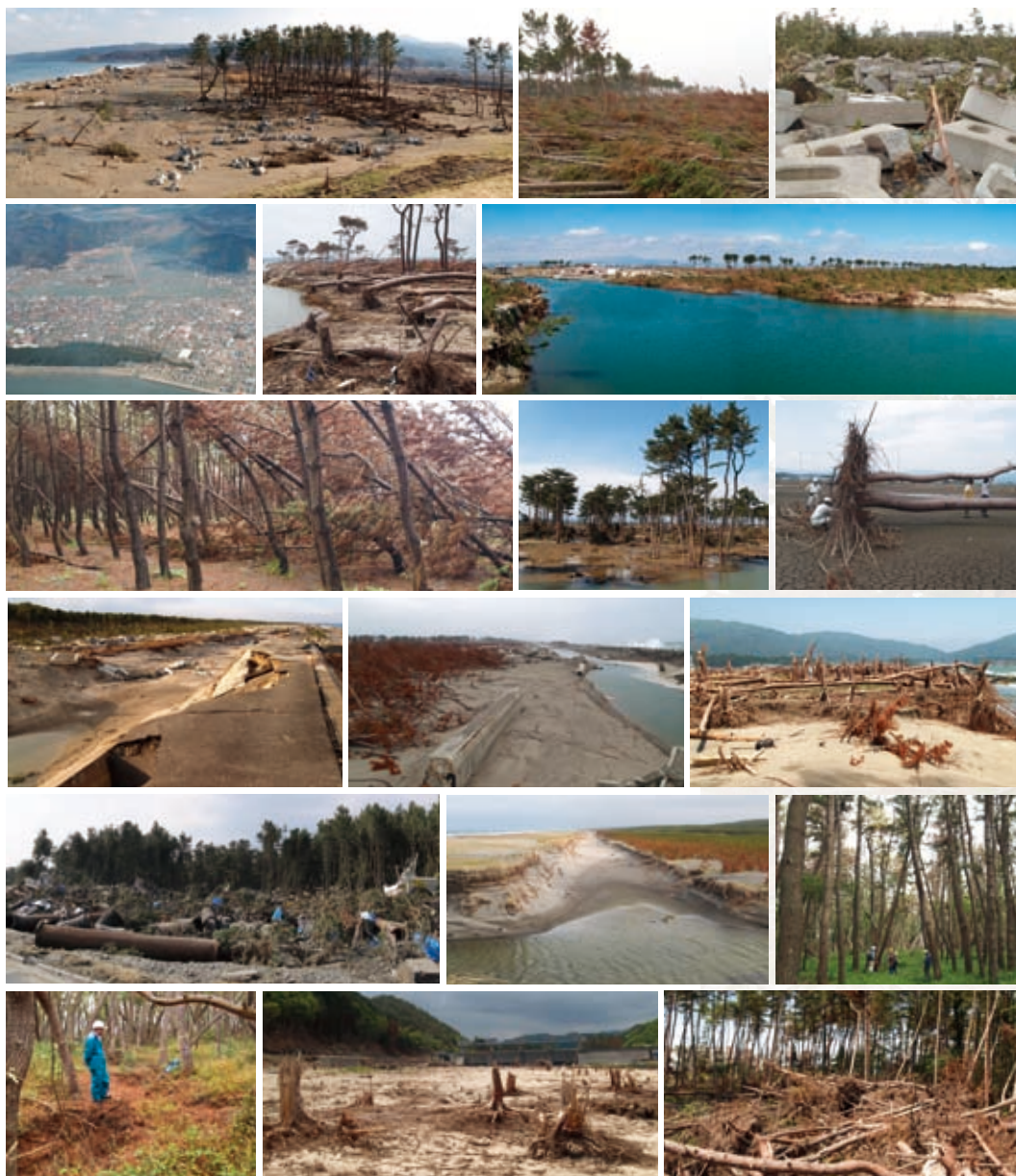
6. Conclusion

Coastal forests in many places were severely damaged by this tsunami. In regeneration of coastal forests, I want to take this opportunity to solve problems that coastal forests have faced pre-tsunami rather than engage in simple reforestation. In brief, I hope that a healthy stand type is established by appropriate tree number adjustment and that measures against pine wilt disease are properly conducted. It is noteworthy that seedlings are suspected to be unavailable in sufficient quantity because of the extremely large affected area. To address this concern, I propose to consider using seedling trees found in affected regions and reviewing the planting numbers. Further, functional strip roads must be available in coastal forests for detailed work and maintenance, and it is important to proceed with an image of the coastal forest to regenerate/recover from the stage of disposing damaged trees.

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