



Soil hardness regulates the root penetration by trees planted on anthropogenic growing bases in coastal forests in Japan: new endeavors to reforest the coastal disaster prevention forests with high resilience for tsunami

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Received: 2 January 2020 / Accepted: 22 September 2020 / Published online: 2 October 2020
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Abstract

Purpose To restore the disaster resilience of coastal forests in tsunami-prone areas, growing bases have been artificially constructed with embanking before afforestation to increase the effective soil depth and allow deeper root system development. The aim of the present study was to describe and record the soil features of these anthropogenic growing bases and root development within them to provide guidance on their construction and comprehensively evaluate their potential for disaster resilience.

Materials and methods Soil surveys including root excavation were conducted on anthropogenic growing bases in coastal forests including seaside parks in the Kanto and Tohoku regions of Japan. All of the soils assessed were classified as “Spolic (Subaquatic)” or “Urbic” Technosols because they contained artefacts with large amounts of industrial soil materials in their profiles. Soil samples were taken from each horizon in the soil profiles using 400-ml and/or 100-ml cylinders, and the undisturbed cylinder samples were then analyzed to determine the bulk density, water permeability, and porosity of the soils at each site. The vertical distribution of soil hardness in the anthropogenic growing bases was also measured using a dynamic cone penetrometer.

Results and discussion Some of the growing bases were generally soft with high water permeability, indicating that soil improvements such as deep tillage were quite effective for building suitable growing bases. Notably, some vestiges of pedogenic processes would be partly recognized throughout the soil profile of an old growing base after construction. However, some embankments had serious issues in the growing base soil, including thick and continuous planar consolidated pan layers with quite low permeability and vestiges of strong gleyzation in their profiles. These poor soil conditions inhibited plant growth, particularly of the below ground roots, and remained in the growing bases for a long time.

Responsible editor: Kye-Hoon John Kim

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s11368-020-02788-9>) contains supplementary material, which is available to authorized users.

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Conclusions The study indicated quantitatively that (1) the physical properties of anthropogenic soils constructed using heavy machinery could be maintained for several decades, and (2) compaction should be avoided during soil preparation to avoid soil hardening, water stagnation, and hindrance of root penetration. Although these findings unfortunately lack quantitative consideration of the requirements for stabilizing embankments, they reinforce awareness of the difficulty of constructing anthropogenic soils to foster the growth of trees and provide sufficient strength for embanked foundations. This topic requires further study.

Keywords Coastal disaster · Coastal forest · Man-made growing base · Disaster resilience · Technosols · Tsunami

1 Introduction

Disaster prevention forests are grown on artificially constructed soils (e.g., Technosols) as part of the recovery work following a natural disaster and are increasing in area globally. One of the most conspicuous examples is probably coastal disaster prevention forests that occur along the shores of the Pacific Ocean eastern and northern Japan, which were greatly damaged by the tsunami that followed the Great East Japan Earthquake in March 2011. There is considerable evidence that coastal forests can reduce the force, depth, and velocity of tsunamis, reducing damage to property and loss of life (Forbes and Broadhead 2007), based on observations from tsunamis in Chile (Izumi et al. 1961), the Indian Ocean (Danielsen et al. 2005, Kathiresan and Rajendran 2005), and Japan (Sakamoto 2015). Therefore, the restoration of coastal forests with high resilience for tsunami is extremely important not only for Japan but also for the many other countries that are at risk from tsunamis in the future.

The tsunami that occurred in March 2011 greatly damaged ca. 3600 ha of coastal forests in eastern and northern Japan (Forest Agency of Japan 2019), and recovery work in these damaged forests is ongoing, with completion expected by the end of fiscal year (FY) 2020. This work is being conducted by the Forest Agency of Japan (FAJ) and prefectural governments to ensure the conservation of functions in coastal areas while considering various disaster prevention functions that comprise not only windbreak and tide protection effects but also tsunami damage reduction through the mitigation of wave energy. According to the report “Fiscal 2011 Emergency Survey on Post-Earthquake Recovery” (Forestry & Forest Products Research Institute 2012), most of the tsunami-damaged trees that were uprooted and washed away stood in the lowlands near the shoreline where the ground water level was relatively high, and so had shallower penetrating depths of their root systems than surviving trees. Similarly, Watanabe et al. (2014) reported that many trees that grew in places with a ground water depth of less than 1.0 m were uprooted and washed away regardless of their size and that the distance from the ground surface to ground water surface corresponded with the penetrating depths of the root systems of uprooted trees. Consequently, they proposed that the embanking layer should be made ≥ 1.0 -m thick (Watanabe et al. 2014). Then, the Ad Hoc Committee on Regeneration of Coastal Disaster

Prevention Forests related to the Great East Japan Earthquake (2012), which was established by FAJ, strongly recommended the constructing of embankments by piling soil to increase the effective soil depth and thus provide a growing base for restoration of tsunami-damaged forests. These deeper soils would allow deeper root systems to develop, suppressing the tree uprooting, reducing flooding risk, and consequently reforesting the area with tsunami-resilient coastal forests.

As this recovery work proceeded, it was found that while the planted trees grew well in some areas allowing the work to be completed on schedule, trees in other areas were unable to take root and grow sufficiently, indicating that soil improvement was required. Embanking was generally carried out with sandy soil materials brought from adjacent hills and/or recycled soil materials from tsunami debris using heavy machinery, backhoes, and bulldozers (Murakami 2015; Ono et al. 2018). It has previously been shown that the mechanical stresses that result from the bulldozing and the wheeling of heavy machinery can cause issues with over compaction and water stagnation on the soils in projects related to agriculture and forestry as well as park development and urban greening (e.g., Yabashi and Konko, 1985, 1987; Lipiec and Hatano 2003; Horn 2015), leading to concern that these soils would hinder plant growth, particularly of the roots (Hasegawa 1985; Lipiec and Hatano 2003). Similarly, anthropogenic soils on embankments in restored coastal forests in the Sendai Bay area and Sanriku district that were constructed during the early stage of recovery work in tsunami-damaged forests generally comprised quite hard, densely packed, and consolidated soil layers with low water permeability as a result of tread pressure from heavy machinery during embankment construction (Ono et al. 2016; Shinomiya et al. 2016; Iwate Prefectural Forestry Technology Center 2017). However, some successful recovery work has also been carried out. For example, trees that were planted on anthropogenic soils in green areas of several artificial islands constructed from 1972 in Tokyo Bay have grown well and some pedogenic processes have also been observed in the soils beneath this well-developed vegetation (Matsudaira 2019). Furthermore, work carried out by Chiba Prefectural Office since the 1990s has successfully established a growing base in damp lowlands of coastal sand dunes by performing landfilling before planting tree seedlings in coastal forests (Nohara and Takahashi 2007).

The aims of the present study were to (1) describe, record, and compare the soil physical properties and the root system development of planted trees in different-aged anthropogenic growing bases with embankments that have been constructed in coastal disaster prevention forests and seaside greenery parks; (2) evaluate the potential effects of heavy machinery on soil properties and how long these persist for; and (3) highlight the critical values of soil physical properties that affect the root development of planted trees in anthropogenic growing bases.

2 Materials and methods

2.1 Study sites

Soil surveys were conducted on anthropogenic growing bases in five stands in coastal forests with piled-up soils (Miyagi (MG), Iwate 1 and 2 (IT1 and IT2), Chiba 1 and 2 (CB1 and CB2)) and two seaside parks on artificial islands in Tokyo Bay (Tokyo 1 and 2 (TK1 and TK2)) (Fig. 1). Detailed descriptions of each site (e.g., location, planting tree species, piling-up soil materials, and stand ages) are summarized in Table 1. Sites MG, CB1, and TK2 were suspected to be unsuitable as forest growing bases, whereas the remaining sites (IT1, IT2, CB2, and TK1) had good soils for plant growth.

2.2 Soil surveys, sampling, and physical property analyses

Soil surveys were conducted at each site according to the Guidelines for Soil Description (FAO 2006). Before digging a soil pit, the representation of the surveyed soil profiles in

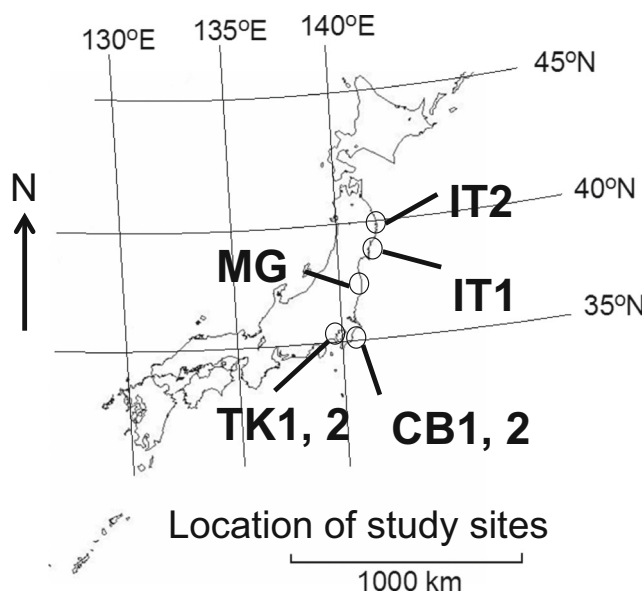


Fig. 1 Locations of the study sites

terms of the pedological condition of each site was confirmed through a multipoint exploratory survey using a hand auger according to Boone et al. (1999). The soils at each site were classified according to the World Reference Base for Soil Resources (WRB) 2014 (IUSS Working Group WRB 2015, Table 1). Soil samples were taken from each horizon in each profile using 400-ml core cylinders (DIK-1506; Daiki Rika Kogyo Co., Ltd. Saitama, Japan) or 100-ml core cylinders (DIK-1801; Daiki Rika Kogyo Co., Ltd.) where the large size was not suitable.

The undisturbed cylinder samples were analyzed to determine the bulk density, water permeability, and porosity of the soil, according to Kawada and Kojima (1976), as indicators of the soil compaction intensity and the hindrance of soil permeability by heavy machinery. Water permeability was measured as the saturated hydraulic conductivity of each horizon in a constant water level-type permeability test (soil permeability test apparatus, Mashimo type; Fujiwara Scientific Co., Ltd., Tokyo, Japan). Porosity was measured using the porous plate method (soil pF measuring porous plate, Mashimo type; Fujiwara Scientific Co., Ltd.). The bulk density and volumetric distributions of three phases (solid, liquid, and gas) in the soil were measured and calculated according to Marshall et al. (1999).

2.3 Measuring the vertical distribution of soil hardness (softness) in embankments

To determine the vertical distribution of soil hardness in the embankments at each site, transect lines (length: 2–10 m) were established at all sites except TK1 and the vertical distribution of soil hardness was measured at a depth of 1.0–2.5 m at intervals of 0.2–0.5 m along these lines using a handy dynamic cone penetrometer (SH-type; Daitou Techno Green, Inc., Tokyo, Japan; Fig. 2). At site TK1, the soil hardness was measured at three points around a soil survey pit due to time constraints. The detailed measurement conditions for each line are summarized in Table 1. Soil hardness was measured as the “softness” (i.e., S -value, cm drop^{-1}), according to Hasegawa (2008), which describes the soil penetration resistance based on the depth (cm) to which a cone (diameter: 20 mm) penetrates the soil per stroke when a 2-kg mass rammer is dropped from a height of 0.5 m. Thus, low “softness” indicates hard soil.

Soil hardness is generally used to assess the effect of soil compaction on root growth (i.e., soil penetrability) (Bengough and Mullins 1990; Lipiec and Hatano 2003). Bengough and Mullins (1990) previously reported that root elongation ceased at a root penetration resistance of ca. 1 MPa, while Lipiec and Hatano (2003) showed that the critical values of cone resistance that cause a reduction of root growth range from 1 to 1.7 MPa, while values that stop root growth range from 3 to 4 MPa. S -value can be converted into a physical

Table 1 Summary of the soil and stand characteristics at each study site

Site ID (site name)	Latitude, longitude, altitude	Planting tree species*	Piling-up soil material	Thickness of piling-up soils	Completion of coastal forest construction	Soil improvement treatment	Number of the survey line (length), interval distances among the points of the penetration test	Date of penetration test	Stand age at the soil survey	Soil classification at the soil survey (IUSS Working Group WRB 2015)
MG (Arahama)	38° 13' 29" N, 140° 59' 15" E, 4 m	<i>Pinus thunbergii</i>	Upper layer: sandy soils purchased from source pit in the adjacent hills to the north of Sendai City, original soil layer: sandy soils	0.8–2.0 m	FY 2013	Non-treated	Three transect lines (2.0 m), 0.10-m interval	Apr. 28, 2014	0 year	Spolic Reductic Technosol (Arenic, Densic, Transportic)
IT1 (Rikuzen-Takata)	39° 00' 25" N, 141° 38' 11" E, 3 m	<i>P. thunbergii</i> , <i>Pinus densiflora</i>	Loamy soils originated from granite in the adjacent hills in Rikuzen-Takata City	> 2.0 m	FY 2016	Deep tillage (2.0 m in depth), sloping the roof of the berm surface (2%)	Four transect lines (3.0 m), 0.25-m interval	May 10, 2017	0 year	Spolic Technosol (Loamic, Transportic)
IT2 (Noda)	40° 06' 14" N, 141° 49' 31" E, 3 m	<i>P. thunbergii</i>	Soils generated by construction of Hachinohe-Kuji Expressway	1.2–2.5 m	FY 2017	Low compaction in berm, sloping the roof of the berm surface (2%)	One transect line (3.5 m), 0.50-m interval	Oct. 16, 2018	1 year	Spolic Technosol (Loamic, Transportic)
CBI (Matsugaya)	35° 33' 52" N, 140° 28' 49" E, 2.5 m	<i>P. thunbergii</i> , <i>Morella rubra</i> , <i>Quercus phillyreoides</i>	Construction-generated soils and dredged soils	> 1.2 m	FY 2008	Non-treated	One transect line (2.0 m), 0.10-m interval	Feb. 17, 2015	7 years	Spolic Technosol (Siltic, Densic, Gleyic, Transportic)
CB2 (Futsu)	35° 18' 40" N, 139° 47' 57" E, 4 m	<i>Machilus thunbergii</i> , <i>P. thunbergii</i> , <i>Mallotus japonicus</i>	Upper layer: purchased sandy soils, original soil layer: sandy soils	0.8–1.1 m	FY 1988	Unknown	Two transect lines (10.0 m), 1.0-m interval	Dec. 4, 2018	30 years	Spolic Subaquatic Technosol (Arenic, Transportic)
TK1 (Tokyo Port Wild Bird Park)	35° 35' 00" N, 139° 45' 46" E, 10 m	<i>Celtis sinensis</i> , <i>Pittosporum tobira</i> , <i>P. thunbergii</i>	Upper layer: construction-generated soils containing some wastes, bottom layer: dredged soils	> 1.0 m	FY 1979	Unknown	Only three points for the penetration test around soil survey pit	July 29, 2019	40 years	Urbic Technosol (Siltic, Endodensic)
TK2 (Uminomori Park)	35° 26' 25" N, 139° 48' 16" E, 27 m	<i>P. thunbergii</i> , <i>Castanopsis sieboldii</i> , <i>M. thunbergii</i> , <i>Cerasus speciosa</i>	Upper layer: construction-generated soils (mainly originated from Kanto loam layer), bottom layer: dredged soils	> 0.7 m	FY 2014	Non-treated	One transect line (2.0 m), 0.25-m interval	June 22, 2017	3 years	Spolic Technosol (Loamic, Densic)

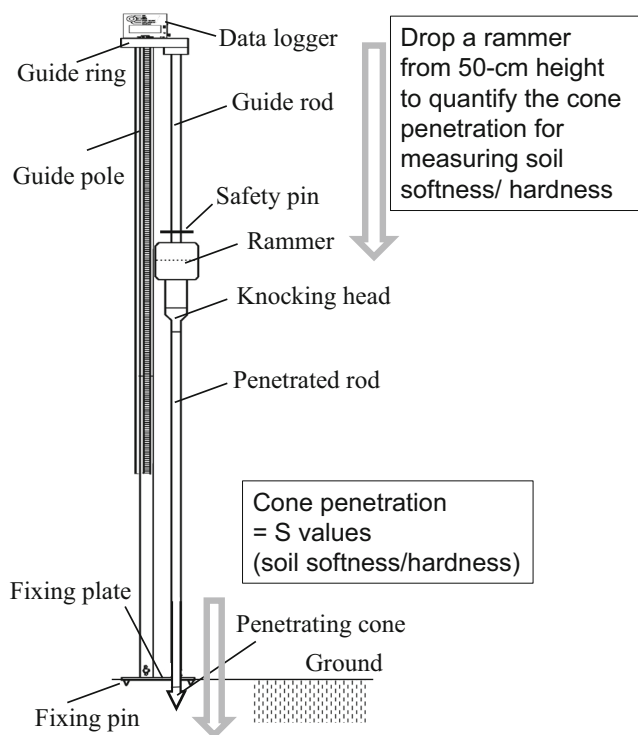


Fig. 2 Diagram of an SH-type handy dynamic cone penetrometer (Daitou Techno Green Inc., Tokyo, Japan)

parameter of the soil (i.e., penetrometer (cone) resistance (kgf cm^{-2})) according to the report of Nishimura et al. (1987), which refers to the Dutch formula written by Sanglerat (1972). This allows the *S*-values of 1.0, 0.7, and 0.5 cm drop^{-1} obtained in the present study to be roughly converted to 16.8, 23.5, and 32.4 kgf cm^{-2} , or 1.65, 2.30, and 3.18 MPa, respectively. In the field of revegetation technology in Japan, the relationship between the soil hardness of the growing base and the deep-rooting properties is placed in five categories based on the Research Committee of the Japanese Institute of Landscape Architecture (2000) (Table 2). To visually evaluate the vertical distribution of the *S*-values, the results of each soil penetration test were

presented as a contour diagram using the graphical software OriginPro 8.5J (OriginLab Corp 2010, Northampton, MA, USA). Watanabe et al. (2014) proposed that the embanking layer should be made $\geq 1.0\text{-m}$ thick to facilitate restoration of the coastal forest and provide strong resilience against tsunami. Thus, the quality of the soil as a growing base (i.e., whether the soil conditions promote tree growth) was assessed by the observed depths of penetration of roots in soil profiles and by the vertical distributions of soil hardness based on the criteria of the Research Committee of the Japanese Institute of Landscape Architecture (2000).

3 Results

3.1 Anthropogenic soils in coastal forests restored following the 2011 tsunami

Sites MG, IT1, and IT2 are located in tsunami-hit areas along the Pacific coastline of northeastern Japan (Fig. 1) and so had already been reforested through public restoration work to create coastal disaster prevention forests with embankments to ensure good root growth in the planted trees.

Table S1 shows the soil morphological features of the anthropogenic embankments. The piled-up soil layers were quite thick at all sites, ranging from a thickness of 0.8 to 2.5 m (Table 1). All of the embankments were constructed from pit sand that had been transported from hill areas adjacent to the respective sites, resulting in the texture of the soils generally being sand (S), loamy sand (LS), or sandy loam (SL). However, the C8 horizon at site IT1 was silty clay loam (SiCL). At site MG, there was a very thick wood chip layer (Oi horizon; 11 cm thick) that comprised tsunami-damaged pine timbers and branches. There were also occasional pools of water on the ground surface at site MG after rain (data not shown), resulting in the soil of the C1 horizon directly beneath the chip layers being quite wet due to the retention of stagnant water. Consequently, soil gleyzation was recognized in the C1 horizon, in which there was a positive reaction to α , α' -

Table 2 Soil hardness (“softness”) criteria of the Research Committee of the Japanese Institute of Landscape Architecture (2000)

“Softness” cm drop^{-1}	Propriety of deep-rooting	Description of soil hardness	Judgment of the quality as a growing base
< 0.7	Very hard to have spreading roots in most plants	Consolidated	××
> 0.7, ≤ 1.0	Anxious for a lowering of root development in most plants	Hard	×
> 1.0, ≤ 1.5	Anxious for a lowering of root development in some plants	Compact	△
> 1.5, ≤ 4.0	No problem for root development in plants (suitable condition)	Soft	○
> 4.0	No problem for root development in plants, but anxious for receiving drought damage and/or lowering bearing capacity of roots	Too soft	△

If the soil layer with “softness” < 1.0 cm drop^{-1} is consecutive 10 cm in thickness, or that with “softness” < 0.7 cm drop^{-1} is consecutive 5 cm in thickness, both are judged as an unsuitable growing base because most plants cannot be deep-rooted

dipyridyl because of the soil's reduced condition. There were moderate and weak platy structures in the topsoil at sites MG and IT2, respectively, but there were no structures or massive structures in any other horizons at these sites or at site IT1 (Table S1). However, rock fragments of various sizes were contained in the soil profiles at sites IT1 and IT2. Few live roots appeared in the soil profile at any sites (Table S1) because the soil surveys were conducted almost immediately after the completion of embankment construction. However, penetrated roots of the planted pine (*Pinus densiflora* and *P. thunbergii*) seedlings at sites IT1 (3 years old) and IT2 (1 year old) reached depths of 168 and 117 cm according to observations of a dug-out root system after a soil survey conducted 3 years and 1 year after seedling planting, respectively (Fig. 3A, B). Conversely, the depth of root penetration of seven pine seedlings at site MG (4 years old) ranged from 18 to 25 cm (data not shown).

The soil physical properties and vertical distributions of *S*-values in the embankments at sites MG, IT1, and IT2 are shown in Table 3 and Fig. 4, respectively. The soil at site MG, which was constructed during the early coastal forest restoration work (FY 2013), was generally hard throughout the soil profile (Fig. 4A) but particularly at depths of around 20–40 cm (i.e., just below the topsoil) and ≥ 80 cm, which we termed “consolidated.” Both “consolidated” layers in soil at site MG would be the vestiges of the compacted soil surfaces

that were formed separately during two episodes of embankment construction. These soil layers showed high bulk densities and low water permeabilities, with hydraulic conductivities below 30 mm h^{-1} in the Cdr and C1 horizons (Table 3). By contrast, the soils at sites IT1 and IT2, which were constructed in the middle stage of the recovery works (FY 2016 and FY 2017) using deep tillage or low compaction for preparation of the embankment, were relatively soft, at least from the topsoil to a depth of 150 cm (Fig. 4B, C). Thus, soils within this depth range were highly porous compared with MG soils, although their bulk densities remained relatively high (Table 3). Regarding water permeability, the hydraulic conductivity was generally higher in IT1 soils than MG soils (Table 3) but was not determined for IT2 soils.

The soil at site MG was classified as Spolic Reductic Technosol according to the World Reference Base for Soil Resources (WRB) 2014 classification (IUSS Working Group WRB 2015), mainly due to the high content of artefacts throughout the soil profile, and the presence of a layer with reducing conditions, as indicated by the strong positive reaction of the dipyridyl test in the Cgr and Cdr horizons (Table S1). By contrast, the soils at sites IT1 and IT2 were classified as Spolic Technosol according to the WRB 2014 classification because of the high content of artefacts and absence of a low-permeability horizon in the profile (Table S1).

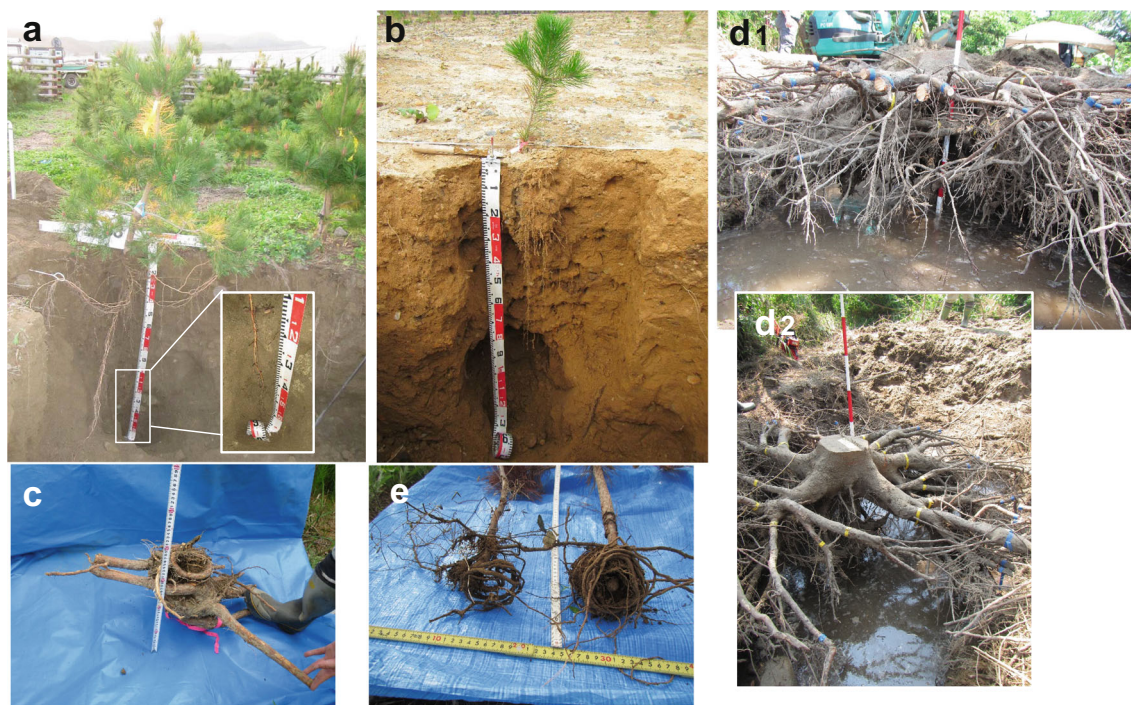


Fig. 3 Photographs of root system development in pine (*Pinus densiflora* and *P. thunbergii*) trees planted on anthropogenic soils. A: 3-year-old seedling at site IT1 (maximum root depth, 168 cm). B: 1-year-old seedling at site IT2 (maximum root depth, 117 cm). C: 7-year-old tree at site

CB1. D1, D2: 30-year-old tree at site CB2 (maximum root depth, 80 cm). E: 3-year-old trees at site TK2. The roots shown in C and E were coiled with no vertical spread

3.2 Soils created by landfilling of the damp lowlands of coastal sand dunes in Chiba Prefecture

Since the 1990s, the Chiba Prefectural Office has used landfilling to construct growing bases for reforestation of the coastal disaster prevention forests in the damp lowlands behind coastal sand dunes (Nohara and Takahashi 2007). Thus, the soils at sites CB1 and CB2 were constructed by landfilling swamp areas without any deep tillage treatment during embankment construction.

The soil at site CB1 comprised silty loam (SiL) or SiCL (Table S2). No structures were present in the soil profile, but there were some small-sized gravels, which originated from the dredged soils obtained from Sakuta River estuary. In addition, the soil at this site was generally quite hard, wholly consolidated, and tightly packed (Fig. 5A, Table S2), resulting in the root systems of the planted trees developing only to the depth of the planting hole (ca. 30 cm deep) and the main roots of these trees being coil-shaped, allowing them to remain in the hole without any vertical spread (Fig. 3C). The bulk densities of the soil horizons were generally high ($> 1.25 \text{ Mg m}^{-2}$), with the exception of the AC horizon (Table 3). The volumetric percentage of the solid phase in each horizon was also relatively high, although the total porosity (i.e., the sum of the liquid and gaseous phases) was not particularly low. Coarse pores were quite scarce in the Cdg1 and Cdr2 horizons, at ca. 1 vol%. The coefficient of permeability ranged from 1 to 35 mm h^{-1} in all horizons except Cdr3, which had a much higher value (109 mm h^{-1}). Water sometimes pooled on the surface of the soil at site CB1 after rain (data not shown).

By contrast, the embankment at site CB2 was generally soft and loose throughout the soil profile (Fig. 5B, Table S2) except for a “consolidated” layer from a depth of 50 to 110 cm at a width of 0–1 m along the survey line (Fig. 5B). According to our soil morphological observations, this “consolidated” layer is likely to have been artificially formed by the dropping and hardening of riprap to support construction vehicles such as dump trucks carrying landfilling materials during the afforestation work. The soil at site CB2 comprised sandy materials (S, SL, LS, and sandy clay) without structure (Table S2). Some coarse subrounded gravels were present in the C3 horizon, which may be a vestige of the thrown riprap layer that was placed on the original swamp. The root systems of the planted trees extended to the depth of the original ground surface before landfilling (i.e., to a depth of ca. 80 cm in the buried horizons 2ACb and 2Cb; Fig. 3d₁, d₂) due to the presence of ground water below the 2ACb horizon (Table S2). The bulk densities of the soils ranged from 0.6 to 1.6 Mg m^{-3} and were generally high except in the A horizon (Table 3). The volumetric percentage of the solid phase was quite low in the A horizon, which was highly porous, while the solid phase distributions in the other horizons ranged from 36 to 60 vol%, which was similar to the range observed in the

CB1 soils. However, the liquid phase had a smaller distribution in CB2 soils than in CB1 soils.

The soil at site CB1 was classified as Spolic Technosol according to the WRB 2014 classification because of the high artefact content. By contrast, the soil at site CB2 was classified as Spolic Subaquatic Technosol according to the WRB 2014 classification due to the high artefact content in the profiles and the permanent submergence of the buried horizons by ground water (Table S2).

3.3 Soils in green areas of seaside parks on artificial islands in Tokyo Bay

The artificial islands in Tokyo Bay are comprised of a deep land basement made from incinerated garbage and demolition debris (Matsudaira 2019). This basement was covered with soil materials generated at another construction area mixed with solid waste to allow nature to thrive. The surface soil is 30 cm thick and maintained for plant growth by mixing it with bark, branches, and leaf composts from urban parks in Tokyo (Matsudaira 2019). Sites TK1 and TK2 are anthropogenic soils with similar histories to the artificially constructed islands but with different construction years (Table 1).

In the soil at site TK1, the feces of larvae of some beetle species had accumulated on the surface of the A horizon (Table S3). Moreover, obvious pedogenic processes were recognized in the soil profile throughout. There was a very weak very fine granular structure in the A horizon and a weak (fine-) medium subangular blocky structure in the C1–C3 horizons. Live tree roots of various sizes (i.e., from very fine to coarse roots) were also observed in deeper soils in the C3 horizon (ca. 80 cm deep). Although TK1 soils were, if anything, partially hard and consolidated (Fig. 6A), they had high porosity and a high water permeability in the A–C3 horizons (Table 3) with only soil in the 2C horizon being extremely firm (i.e., consolidated) and quite high density (Tables 3 and S3). The soil comprised SiL, SiCL, and silt (Si) (Table 3).

In the soil at site TK2, soil structures were observed to a limited extent in the topsoil, such as in the A (weak fine granular) and C (moderate medium subangular blocky) horizons (7 cm thick; Table S3). The soil at this site was consolidated—very firm in the under layer soils below the C2 horizon (Table S3), which generally correlated with the vertical distribution of soil hardness (Fig. 6B). Live roots were also observed to a limited extent in the A horizon (Table S3), with the main roots of planted trees forming coiled shapes in the planting holes before spreading vertically (Fig. 3E). The bulk densities of TK2 soils ranged from 0.6 to 0.8 Mg m^{-3} , which were the lowest among all sites (Table 3), because most of the materials originated from the Kanto loam layer (Table 1), which was derived from volcanic ash parent material. However, the water permeabilities of these soils were also quite low, with the exception of the topsoil (A–C) horizons, despite the soil porosity being relatively high and the

Table 3 Physical characteristics of the soils in the growing bases at the study sites

Site	Horizon ^{+B61}	Permeability ^{†1}				Bulk density (Mg/m ³)	Soil pore composition ^{†2}			Three-phase distribution			Maximum water holding capacity (vol%)	Minimum air capacity ^{†3} (vol%)
		After 5 min (ml/min)	After 15 min (ml/min)	Ave (ml/min)	Hydraulic conductivity (mm/h)		Total (vol%)	Fine (vol%)	Coarse (vol%)	Solid phase (vol%)	Liquid phase (vol%)	Gaseous phase (vol%)		
MG	Cgr	13.2	9.0	11.1	53.2	1.75	33.5	4.4	29.1	66.5	3.9	29.5	38.0	-4.5
	Cdr	6.5	5.2	5.8	28.1	1.61	39.3	12.2	27.1	60.7	6.1	33.1	39.0	0.3
	C1	4.8	4.1	4.4	21.3	1.49	43.5	19.7	23.8	56.5	7.7	35.9	39.5	4.0
	C2	26.1	20.0	23.0	110.5	1.49	43.7	17.9	25.8	56.3	6.0	37.7	37.3	6.4
	C3	8.9	8.9	8.9	42.8	1.23	53.6	14.2	39.4	46.4	9.3	44.4	57.8	-4.2
IT1	C4	19.3	16.4	17.8	85.7	1.38	45.9	13.2	32.7	54.1	7.3	38.6	40.6	5.3
	C1	20.2	18.0	19.1	91.6	1.36	49.6	n.d. ^{†5}	n.d. ^{†5}	50.4	15.3	34.2	45.2	4.3
	C2	27.1	19.7	23.4	112.4	1.36	49.4	14.3	35.1	50.6	17.5	31.9	47.5	1.9
	C3	21.2	15.1	18.1	87.1	1.36	49.6	n.d. ^{†5}	n.d. ^{†5}	50.4	19.1	30.6	47.1	2.6
	C4	13.8	12.7	13.3	63.8	1.66	38.2	18.2	20.0	61.8	22.3	15.9	43.3	-5.1
	C5	35.0	33.1	34.0	163.3	1.60	40.3	19.9	20.3	59.7	22.5	17.8	45.1	-4.8
	C6	13.4	11.6	12.5	59.9	1.56	42.1	n.d. ^{†5}	n.d. ^{†5}	57.9	21.8	20.2	44.8	-2.7
IT2	C7	19.1	16.9	18.0	86.4	1.56	42.0	18.2	23.8	58.0	22.1	19.9	44.6	-2.6
	C8 ^{†4}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	1.44	49.7	20.1	29.6	50.3	29.4	20.3	13.3	36.4
	C1	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}
	C2 ^{†4}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	1.18	56.2	19.3	37.0	43.8	19.4	36.8	47.2	9.0
	C3 ^{†4}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	1.18	56.2	23.0	33.2	43.8	22.9	33.3	50.8	5.4
	C4 ^{†4}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	1.24	54.2	28.6	25.6	45.8	28.3	26.0	48.6	5.7
	C5 ^{†4}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	1.48	45.2	25.3	19.9	54.8	29.2	16.0	43.4	1.8
CB1	C6	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}
	AC	7.6	6.8	7.2	34.5	1.05	59.6	30.0	29.6	40.4	35.0	24.5	56.3	3.3
	Cdg1	0.2	0.1	0.2	0.9	1.46	45.4	44.0	1.4	54.6	44.1	1.3	48.8	-3.5
	Cdg2 ^{†4}	4.6	4.8	4.7	22.6	1.35	49.2	n.d. ^{†5}	n.d. ^{†5}	50.8	42.7	6.5	49.0	0.2
	Cdr1	1.6	1.3	1.4	6.9	1.25	53.1	39.3	13.8	46.9	44.4	8.7	51.0	2.1
	Cdr2	3.7	3.2	3.5	16.7	1.41	47.3	46.5	0.8	52.7	44.4	2.9	49.9	-2.6
	Cdr3	25.6	19.9	22.8	109.3	1.25	53.4	44.2	9.2	46.6	46.1	7.3	54.8	-1.4
CB2	Cd	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}
	A	132.5	126.7	129.6	622.1	0.58	78.3	27.9	50.4	21.7	25.7	52.6	73.4	4.9
	AC	86.4	78.2	82.3	395.0	0.97	64.1	23.8	40.3	35.9	19.0	45.1	62.3	1.8
	C1	19.4	17.6	18.5	88.8	1.38	49.2	26.1	23.1	50.8	43.6	5.6	53.0	-3.8
	C2	33.6	30.2	31.9	153.1	1.29	52.4	25.4	27.0	47.6	19.6	32.8	47.5	4.9
	C3 ^{†4}	83.4	n.d. ^{†5}	83.4	400.3	1.30	51.9	n.d. ^{†5}	n.d. ^{†5}	48.1	16.5	35.4	55.4	-3.5
	2ACb	78.1	72.2	75.2	360.7	1.42	47.7	22.2	25.5	52.3	28.9	18.7	47.7	0.0
TK1	2Cb1	44.5	40.9	42.7	205.0	1.46	46.1	15.7	30.3	53.9	37.1	9.0	46.2	-0.1
	2Cb2	106.1	102.8	104.5	501.4	1.63	39.9	32.0	7.9	60.1	42.7	-2.8	45.5	-5.7
	A	208.8	217.5	213.1	1022.9	1.13	84.5	37.8	46.7	15.5	37.0	47.4	66.1	18.4
	C1	52.7	57.3	55.0	263.8	1.20	78.4	36.4	41.9	21.6	36.1	42.3	74.1	4.3
	C2	151.1	149.5	150.3	721.3	1.34	77.6	40.7	36.8	22.4	40.0	37.5	56.7	20.9
	C3	165.7	170.0	167.8	805.6	1.23	78.2	38.9	39.3	21.8	39.5	38.7	74.1	4.1
	2C	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	2.83	45.8	28.2	17.6	54.2	29.1	16.7	44.3	1.5
TK2	A-C	215.0	216.0	215.5	1034.4	0.62	77.6	46.4	31.2	22.4	45.6	32.0	75.7	1.9
	Cd1	14.7	14.0	14.4	69.0	0.78	72.0	57.5	14.5	28.0	62.9	9.1	71.0	1.0
	Cd2	7.5	6.4	6.9	33.2	0.80	71.4	56.2	15.2	28.6	59.7	11.7	72.6	-1.2
	2Cd1	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}
	2Cd2	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}	n.d. ^{†5}

[†] Lowercase letters indicate the subordinate characteristics within master horizons according to the Guidelines for soil description (FAO 2006)

^{†1} Data of permeability shows the respective measured values after 5 and 15 min from the beginning of the experiment and the average values of them

^{†2} Data of porosity shows the measured values according to the porous plate method (Kawada and Kojima 1976)

^{†3} Minus value of minimum air capacity is caused by swelling of soil volume with water saturation treatment

^{†4} Data obtained from soil samples using 100-ml cylinders

^{†5} Not determined

solid phase distribution relatively low compared with the other anthropogenic soils (Table 3). The soil consisted of SiL, SiCL, clay loam, clay, and SL (Table S3).

The soil at site TK1 was classified as Urbic Technosol according to the WRB 2014 classification because of the high content of artefacts such as demolished concrete rubble. By

contrast, the soil at site TK2 was classified as Spolic Technosol according to the WRB 2014 classification due to the high content of artefacts in the profile.

4 Discussion

4.1 Soil classifications and physical and morphological features of anthropogenic growing bases

All of the anthropogenic soils surveyed in the present study except for the TK1 soils were varieties of Spolic Technosols (IUSS Working Group 2015) because the soil profiles had thick layer(s) with artefacts that contained large amounts of the soils cut from neighboring hills or generated by road or housing construction (Table 1). The soils at sites MG, CB2, and TK1 had Reductic, Subaquatic, and Urbic as principal qualifiers (Table 1) due to the presence of reducing conditions (Table S1), permanent submergence (Table S2), and other artefacts with a high rubble, refuse, and industrial waste content (Matsudaira 2019, Table S3), respectively. Moreover, the five soils that were used as growing bases for afforesting (or reforesting) the coastal forests at sites MG, IT1, IT2, CB1, and CB2 were Transportic, while the soils at sites MG, CB1, TK1, and TK2 had Densic or Endodensic as supplementary qualifiers (Tables S1, S2, and S3). Only the soil at site CB1 appeared to have gleyic properties based on the colors of the Cdr1–Cdr3 horizons, although it was not possible to

determine whether this soil was Reductic, because the dipyrindyl test was not conducted at this site (Table S2). The soil textures varied among the sites, ranging from Siltic to Loamic and Arenic (Table 1).

The soils at sites IT1, IT2, CB2, and TK1 had relatively soft layers in their profiles, which were described as loose, soft, or firm according to their compactness (Tables S1, S2, and S3). Namely, no planar continuous hard pan layers were present in their profiles regardless of their construction age (Figs. 4B, C, 5B, and 6A). All of the soils except those at site TK1 generally had a thick (ca. 100 cm and above) soft layer throughout their profiles with S -values of $> 1.0 \text{ cm drop}^{-1}$ as determined using a dynamic cone penetrometer, which corresponds to a cone resistance of 16.8 kgf cm^2 (1.65 MPa), according to Nishimura et al. (1987). The soil at site TK1 was also not consolidated throughout the profile and had some soft and compact layers at certain points in the subsoils (P2 and P3; Fig. 6A). In general, these soils satisfied the soil hardness requirement based on the criteria of the Research Committee of the Japanese Institute of Landscape Architecture (2000). Moreover, we observed live roots of the trees planted at those sites (IT1, IT2, CB2, and TK1) in deeper soils, at least 80 cm in depth. Therefore, we concluded that these soils would be appropriate growing bases.

The soils at sites IT1, CB2, and TK1 had high water permeabilities that ranged from 60 to 1000 mm h^{-1} (Table 3). While water permeability was not tested at site IT2, the soil porosity and solid phase distribution were the same as at other

Fig. 4 Contour diagrams of soil hardness in the growing bases of restored coastal forests with embankment construction

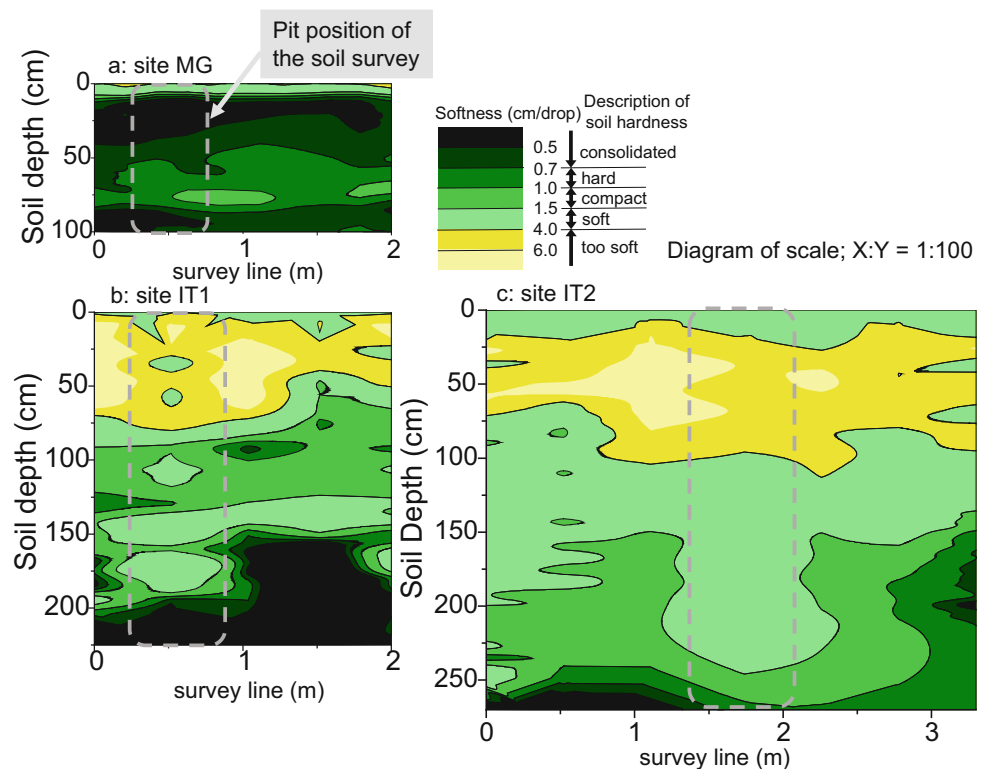
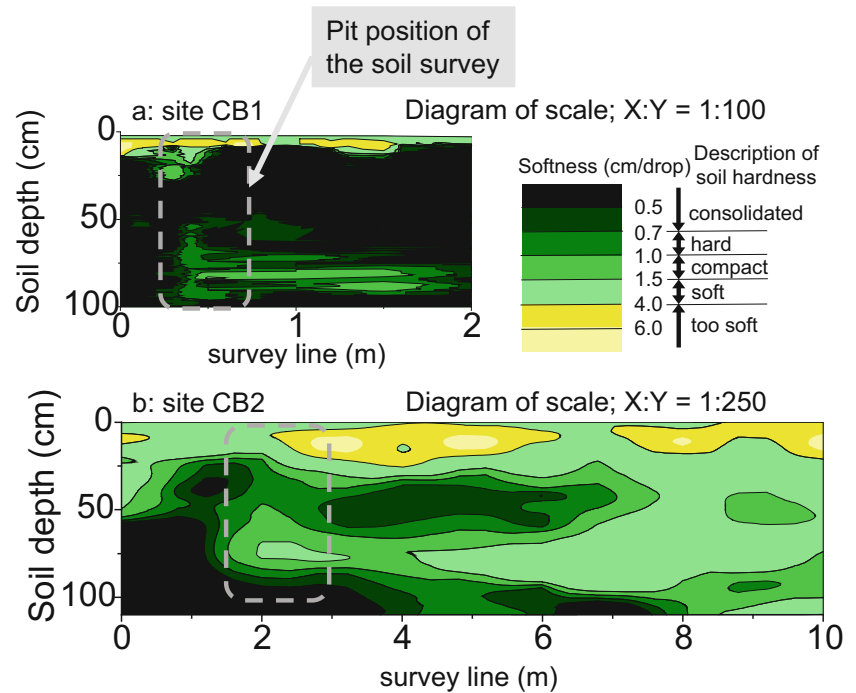


Fig. 5 Contour diagrams of soil hardness in the embankments of coastal forests with landfilling in the damp lowlands of coastal sand dunes in Chiba Prefecture



sites (Table 3) and the embankment had a 2% slope (Table 1) allowing run-off from the soil surface, so water permeability was never an issue here. The high water permeability in the TK1 profile may have been caused by the developing structure formation and the concomitant high porosity and low solid distribution of the soils throughout the profile (Tables 3 and S3), which implied that pedogenesis has steadily progressed in the horizons at this site, which was constructed 40 years previously, although the soil of the bottom layer (i.e., 2C horizon) was not pedogenetic (Table 3). However, the bottom soil layer at site TK1, which would not have been affected by physicochemical pedogenic or biological processes, showed consolidation and no penetrated roots in the 2C horizon (Table S3), indicating that this layer has not exhibited any pedogenic processes for at least 40 years. Compaction of the soil horizons by wheeling heavy machinery sometimes creates a large mechanical resistance to the root growth and/or restricts the rate of aeration to the roots (Bengough and Mullins 1990). Lipiec and Hatano (2003) reported that cone resistance values of 1–1.7 MPa were critical for the inhibition of root growth, the upper range of which roughly corresponds to an S -values of 1.0 cm drop⁻¹ in the present study. The soil physical conditions observed in the anthropogenic growing bases at sites IT1, IT2, CB2, and TK1 in the present study satisfied the criteria of both the Research Committee of the Japanese Institute of Landscape Architecture (2000) and FAJ (2018), as well as the critical values related to root growth reported by Lipiec and Hatano (2003). In addition, our results indicate that the soil physical properties in anthropogenic

growing bases remain stable for at least several decades, since site TK1 was completed in FY 1979 (Table 3).

By contrast, the physical properties of the soils at sites MG, CB1, and TK2 had several common problems for use as growing bases. First, these soils contained quite hard layers that were very firm and consolidated at relatively shallow depths (Tables 3, S1, S2, and S3). In addition, all of these soils had a thick and continuous planar hard pan layer with S -values below 1.0 cm drop⁻¹ (Figs. 4, 5, and 6), which is the critical value for sound root growth (Lipiec and Hatano 2003), indicating that these hardened soils would be quite difficult for the roots of planted trees to penetrate according to the soil hardness criteria of the Research Committee of the Japanese Institute of Landscape Architecture (2000). Moreover, the soil profiles contained almost impermeable continuous layers at sites MG and CB1 and very slowly permeable layers at site TK2 within 100 cm of the ground surface, although these conditions do not satisfy the requirement of the Stagnic as supplementary qualifiers according to WRB 2014 classification. Some of the soil layers at sites MG and CB1 had hydraulic conductivities of < 30 mm h⁻¹, which are below the FAJ (2018) requirements for “standard specification for forest maintenance/conservation” and will have inhibited root growth of the planted seedlings (Table 3).

In the Cdr horizon at site MG, there was a vestige of strong gleyzation, which was caused by the reduction of Fe³⁺ and the mineralization of dissolved organic matter originating from wood chips under anaerobic conditions due to water stagnation (Table S1). In addition, the soil in the Cgr horizon at site

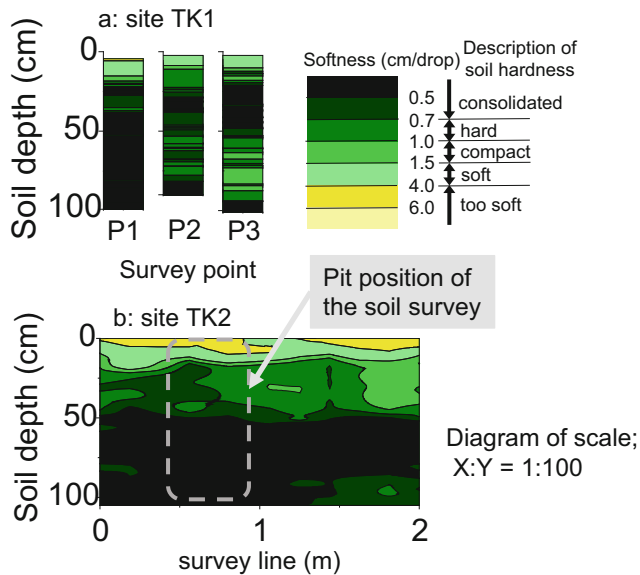


Fig. 6 Contour diagrams of soil hardness in anthropogenic soils in green areas of seaside parks on artificial islands in Tokyo Bay

MG had filamentous mottles of irons that had been cemented between moderate platy structures under anaerobic conditions (Table S1). These soil morphological features were likely to have resulted from strong compaction of the soil by the repeated wheeling of heavy machinery during construction of the growing bases, confirming the findings of Ono et al. (2016), Shinomiya et al. (2017), and Ono and Imaya (2019).

The unsuitable soil conditions that were caused by traveling heavy machinery during previous embankment preparation may also induce root rot in the planted seedlings, as suggested by Hasegawa (1985), Hasegawa and Inomata (2015), and Horn (2015). The observed poor soil physical properties in the growing bases remained the same in our follow-up survey in 2019 (data not shown) and are likely to be maintained in the soil profiles for some years, as observed for the suitable growing base soils mentioned above, which is consistent with the reports of Nohara and Takahashi (2007) and Ono et al. (2019).

4.2 Precautions to be taken when constructing the growing bases for coastal disaster prevention forests with high resilience for tsunami

The function of coastal forests as disaster prevention facilities has been recently recognized in many reports based on the recurrent experiences of devastating tsunami disasters, such as the 2004 Indian Ocean tsunami and the tsunami that hit northeastern Japan in 2011 (Danielsen et al. 2005; Forbes and Broadhead 2007; Sakamoto 2015). Consequently, it is extremely important that information on the recovery of coastal forests from tsunami impacts is accumulated to allow ecosystem-based disaster risk reduction, because natural disasters such as tsunamis will recur. In Japan, embankment, which involves the preparation of healthy growing bases in restored coastal forests, is an effective procedure that enhances

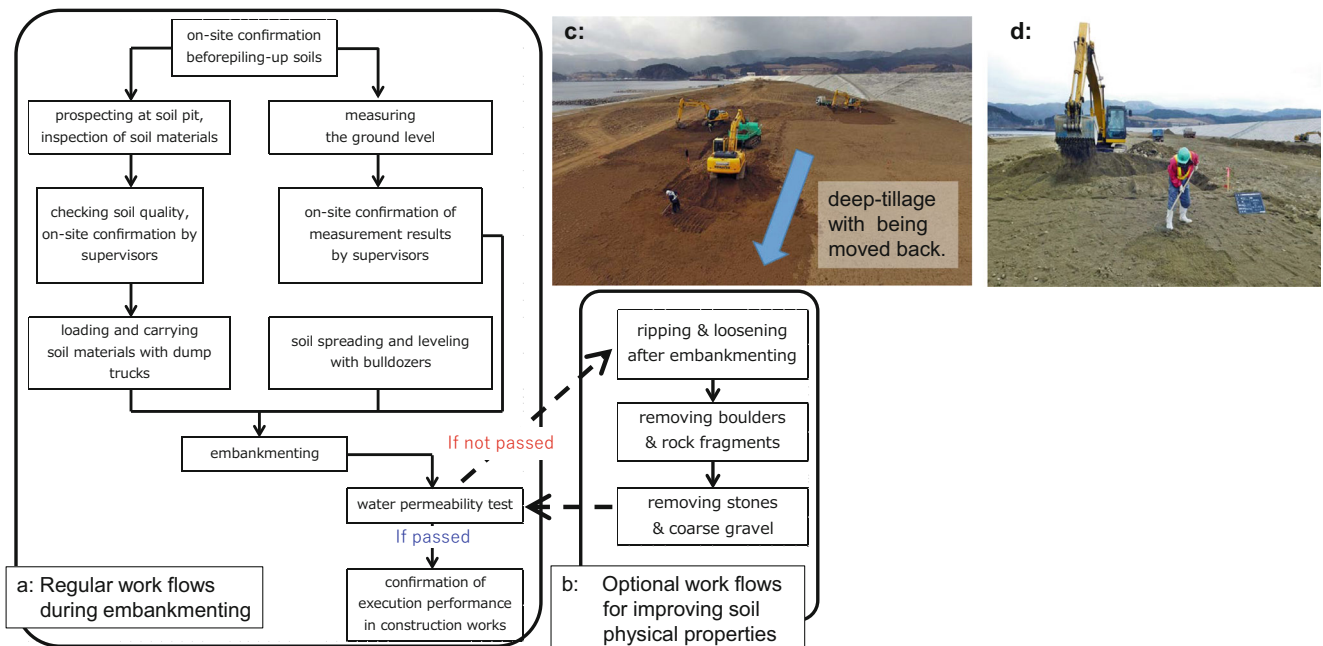


Fig. 7 Work flow for the preparation of anthropogenic growing bases in the restored coastal forest at site IT1. A: regular work during embankment of the growing bases. B: optional work for improving the soil physical

properties of the artificial growing bases. C, D: photographs of deep tillage work using a backhoe with a skeleton bucket and the subsequent manual ground leveling

the tsunami damage–reducing functions of these disaster prevention facilities.

The present study showed that poor soil physical properties, such as hardness, and low water permeability, as a result of soil compaction from the heavy machinery that was used to prepare the growing bases were maintained for up to four decades (Tables 3, S1, S2, and S3; Figs. 4, 5, and 6; Nohara and Takahashi 2007). Thus, the formation of hard and impermeable layers during growing base construction could greatly impede the reforestation of coastal forests affected by tsunamis because it would be difficult to improve the physical properties of anthropogenic soils in forested lands using techniques that are commonly used in agricultural farmlands, paddy fields, or orchards, such as deep tillage treatment or the installation of drainage facilities, if afforestation has already occurred. Thus, it is important to consider the physical conditions of the soils that are formed during growing base preparation. To address this, FAJ and prefectural governments introduced several countermeasures. For example, the Sendai District Forest Office, FAJ, and some prefectural offices conducted several types of additional tillage for heavily compacted soils, as well as regular embanking work just after embankment construction and before planting trees, as seen at site IT1 (Fig. 7). During these trials, various types of machinery were used, including a backhoe with a skeleton bucket, a ripper dozer, and a plow/subsoiler (Ono et al. 2016; Shinomiya et al. 2017; Ono and Imaya 2019). In addition, Iwate Prefectural Government used backhoes to place and spread the soil materials at site IT2 during embanking to avoid the need for heavy machinery to travel on the ground surface (rooftop) of the prepared growing bases (Table 1, Fig. 8). The construction of these growing bases by artificial embanking markedly reduced the soil hardness and improved the water

permeability (Figs. 7 and 8), allowing steady root development of 1- and 3-year-old planted pine trees (Fig. 3A, B).

There is a Japanese aphorism regarding domestic forestry in Japan that says “Tekichi Tekiboku” (“the right tree for the right land”), which means that the forester must select suitable lands for planting seedlings during afforestation (Morisada 1993). This remains a great principle for forestry in Japan, and most foresters in Japan have dealt with natural soil according to this aphorism. Consequently, it is unusual for afforestation to be performed using anthropogenic soil (Technosol) as a growing base, so we still have only a limited understanding of the physical properties of Technosols and their relationship with root development in artificial land developments not only in Japan but also in other countries, despite this being of interest in the fields of agriculture, forestry, civil engineering, and landscape engineering (Horn 2015; Morel et al. 2015; Hout and Vidal-Beaudet 2017). Construction work on the embanked growing bases, particularly in the early restoration works in the coastal forest, has often involved compacting the embanked materials in each spreading lift (30-cm thickness) (Nohara and Takahashi 2007), following regular earthwork procedures for constructing the foundations of farm roads (Chiba Pref 2014). Embankments constructed in such regular earthworks were usually compacted firmly, with little or no consideration of whether the physical condition of the soil was good for tree growth. There have been many reports of park development and erosion control afforestation going wrong when anthropogenic growing bases are used (Morimoto 1985; Yabashi and Konko 1985, 1987; Nohara and Takahashi 2007; Murakami 2015; Shinomiya et al. 2016). Therefore, the additional procedures and new endeavors for avoiding soil compaction through the use of heavy machinery during embankment construction at sites IT1 and IT2, i.e., optional tillage after soil preparation (Fig. 7B, C, D) and without wheeling or bulldozing by heavy machinery on the ground surface (rooftop) of the prepared growing base (Fig. 8), respectively, seemed to be quite inventive compared with the existing construction work. The findings of the present study anew highlight the importance of avoiding compaction of the soil through the use of heavy machinery when constructing growing bases for afforesting coastal forests.

Unfortunately, the present study lacks a quantitative consideration of the requirements for stabilizing the soil of the embanked foundations, i.e., the criteria of sufficient soil strength and soil compaction. The requirements for soils compacted for creating a stable foundation and for soils that are loosened to ensure conditions suitable for good tree growth are quite directly opposed. Thus, this area seems to have potential for further investigation. In addition, the current study might become the thresholds of future studies for providing further consideration to alleviate some of the problems that might be encountered when creating anthropogenic soils

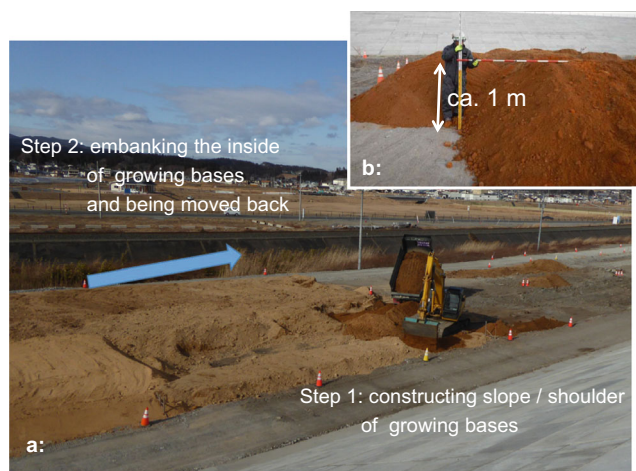


Fig. 8 A: photograph of embanking work during the construction of an artificial growing base without wheeling or bulldozing by heavy machinery on the ground surface (rooftop) at site IT2. B: height of the soil materials discharged from a dump truck (1-m depth)

to restore the resilience to disaster of coastal forests that are at risk from tsunamis.

5 Conclusions

The steady afforestation and/or reforestation of the coastal forests with high resilience for tsunami before they are damaged is relatively important in the many countries that are at risk from tsunamis in the future, as unexpected tsunami disasters have occurred frequently in recent years. After the tsunami disaster in eastern Japan in 2011, FAJ and various prefectural governments in Japan have eagerly attempted to undertake embanking and amendment of growing bases to allow the restoration of coastal forests with a higher resilience against tsunamis. In the present study, we clarified the relationships between the soil physical properties and root development of pine trees planted on growing bases that were artificially constructed by embanking in restored coastal forests, compared these physical properties with previously reported critical values for the root penetration resistance, and evaluated the effectiveness of anthropogenic soils (Technosols) for healthy root development in restored coastal forests with higher resilience for tsunami. We found that the anthropogenic growing bases constructed by embanking at sites such as IT1 and IT2 had a markedly reduced soil hardness and improved water permeability (Figs. 7 and 8), ensuring healthy deeper root development of the planted pine trees to a greater depth (Fig. 3A, B). Coastal forests are currently being reforested throughout Japan not only as part of the recovery work from previous tsunami damage and spreading pine wilt disease but also in preparation for a Nankai Trough earthquake. The findings of this study will help to alleviate some of the problems that have previously been encountered on afforestation/reforestation sites in many countries that are at risk from tsunamis, such as soil compaction, water stagnation, and hindrance of root growth in the planted trees.

Acknowledgments We are grateful to the staff of the Tohoku Regional National Forest Office in Forest Agency of Japan; Department of Agriculture, Forestry and Fishery in Chiba Prefectural Government; and the Iwate Prefectural Forestry Technology Center for their kind support and for arranging our field research. We sincerely thank Drs. Kunio Kawaku, Shuzo Hasegawa of Geo-Green Tech. Inc., and Dr. Keigo Inomata of Daitou Techmo Green Inc. for their help and encouragement. We also appreciate the kind support of the technical assistant Ms. Keiko Sawai from Tohoku Research Center, the Forestry and Forest Products Research Institute, for assisting with our field surveys, sample preparations, and analyses.

Funding This study is partly funded by the research program I (grant No. #201701) by the FFPRI “Establishment of guidelines for afforestation of coastal forests on embankments that have the merits of high resistance to tsunami (from 2017 to 2019)” and by the research program II (grant No. #201411) by the FFPRI “Elucidation of cause of ponding on a banking

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