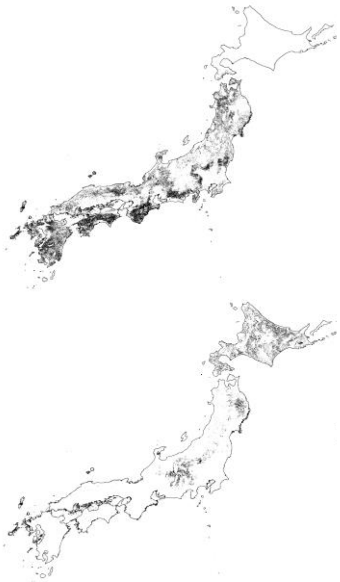

Reforestation following harvesting of conifer plantations in Japan: Current issues from silvicultural and ecological perspectives

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Abstract

Following the Second World War, the number of Cupressaceae plantations in Japan increased, in accordance with government policy for the restoration of timber resources and conservation of soil and water. Currently, these even-aged plantations occupy approximately 44% of the forested area and 24% of the national land area of Japan. Although many of these plantations have become available as timber resources, there are several silviculture-related problems associated with reforestation following clear-cutting of these plantations. The abundant annual precipitation in Japan allows for dominance by competitive vegetation, which makes natural regeneration difficult and increases the cost of silvicultural operations during and after the planting of seedlings. Because the number of seedling producers has decreased, there has been little incentive to keep seedling production techniques up to date. Additionally, damage to planted seedlings by the overabundant sika deer (*Cervus nippon*) population has increased dramatically in the last dozen years or so. To determine how to overcome these difficulties, various studies are underway in Japan. For example, seedling studies have examined the relationship between seedling size and competitive ability with other species in reforested areas, and have led to the development of lower-cost systems to produce customized Cupressaceae seedlings, as well as measures to minimize transplanting damage to seedlings. Previous studies have shown that no-weeding operations might lower the risk of sika deer browsing seedlings, although this silvicultural countermeasure may potentially reduce seedling growth. Studies have also examined the types of physical protection against sika deer browsing that are most efficient. We must combine these findings into a unified silvicultural system for successful restoration via lower-cost plantations.

Keywords

Cervus nippon; *Chamaecyparis obtusa*; Clear-cutting; *Cryptomeria japonica*; Customized seedlings; Plantations

Contents

1 Plantations for forestry in Japan: past and present

1.1 A brief history of plantation forests in Japan

Japan is composed of four main islands: Kyushu, Shikoku, Honshu, and Hokkaido, from south to north. Approximately 67% of the area of these islands is forested. Natural forests on Hokkaido have been dominated mainly by mixed forests comprising *Abies*, *Picea*, and deciduous broadleaf tree species such as *Quercus*, *Betula*, *Tilia*, and *Ulmus*. In contrast, natural forests on the other three islands have experienced dramatic changes over the past 5,000 years. Soil pollen analysis has shown that Cupressaceae trees, mainly Japanese cedar (*Cryptomeria japonica* D. Don) and hinoki cypress (*Chamaecyparis obtusa* Endl.), have been abundant on these three islands during geological history, except during the latest glacial period (Ooi 2016) (Fig. 1). A statement in the oldest chronicles of Japan, "Nihon-shoki", completed in 720 A.D. indicated the "use of *sugi* (Japanese cedar) and *kusu* (*Cinnamomum camphora* J. Presl) timber to make ships, *hinoki* (hinoki cypress) timber to build palaces, and *maki* (*Sciadopitys verticillata* Siebold et Zucc.) timber for caskets". This implies that Cupressaceae forests, mixed with angiosperm species, were abundant in Japan and used as timber resources during that era. Japanese people logged these forests until the Japanese Middle Ages (13th–15th centuries). Presently, the distribution of natural forests comprising Japanese cedar and hinoki cypress mixed with broadleaf trees is scattered and restricted to isolated stands (Tsumura et al. 2007).

After the Middle Ages, Japan experienced two large civil wars, one from 1467 to 1590 and the other from 1868 to 1869. More recently, Japan entered World War II (1941–1945). These conflicts had a destabilizing effect on Japanese society and led to uncontrolled logging of forests on a greater spatial scale, resulting in vast deforestation and a dramatic decrease in forest timber resources. During and after the first civil war, intensive plantations were implemented to restore forest timber resources for the first time in Japanese history, mainly along the Pacific coast (Yamauchi 1947) (Fig. 2). The species planted were Japanese cedar and hinoki cypress, probably because their seeds were widely available, can adapt to a wider range of environments (Nishizono et al. 2014), and are easier to cultivate than other native tree species. Following the civil war in the 19th century, the Japanese government implemented a policy (1899–1920) to increase plantation forests, mainly on harsh grasslands to restore timber and water resources and to improve ground stability in mountainous regions. This policy recommended planting diverse woody species, including angiosperms; however, Japanese cedar and hinoki cypress were the most frequently planted species. Consequently, approximately 3,400 km^2 of Cupressaceae plantations were created by this policy (Yamauchi 1947). A similar policy was undertaken after World War II; grasslands were reforested, and natural broadleaf tree forests (including secondary forest) were converted into Cupressaceae plantations, with some Pinaceae plantations of Japanese larch (*Larix kaempferi* Carrière) at higher-altitude regions and on Hokkaido and Sakhalin fir (*Abies sachalinensis* Mast.) on Hokkaido (1951–1986). Thus, the area of conifer plantations increased from 49,300 km^2 in 1951 to 103,500 km^2 in 2007 and these even-aged plantations currently occupy approximately 44% of the forest area and 24% of the national land area of Japan (Forestry Agency 2010) (Fig. 3). At present, plantations of Japanese cedar, hinoki cypress, and Japanese larch cover approximately 45,000 km^2, 26,000 km^2, and 10,000 km^2, respectively, or about 80% of the total plantation forest area in Japan (Forestry Agency 2012) (Fig. 4).

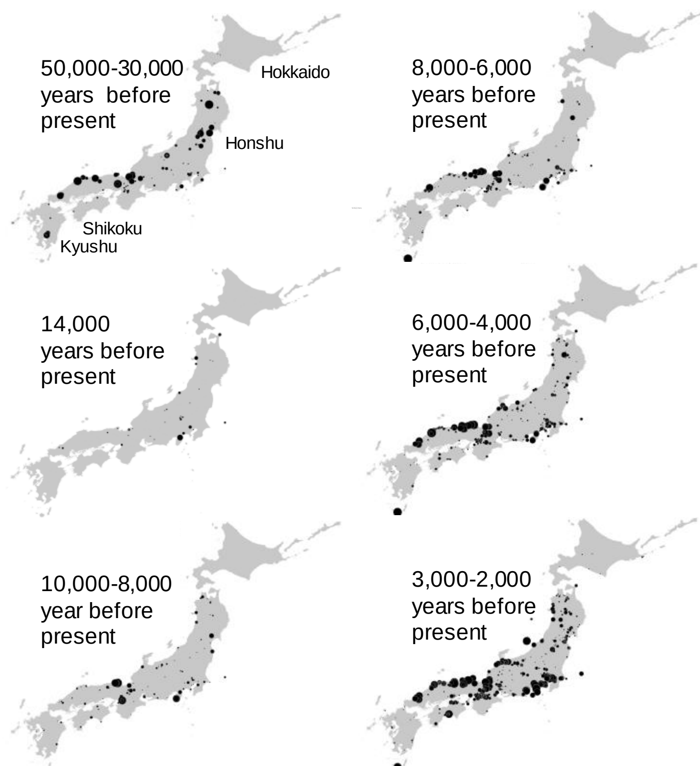

Figure 1. Pollen occurrence probability of *Cryptomeria* and *Chamaecyparis*. Temporal changes in *Cryptomeria* and *Chamaecyparis* pollen occurrence probability in soil profiles before the human population in Japan began to increase. The size of solid circles is proportional to probability values from 0.01 to 0.6. Because *Cryptomeria* and *Chamaecyparis* pollen grains are indistinguishable, these maps show the chronological distributions of the two species. Data were obtained from electronic appendices in Ooi (2016).

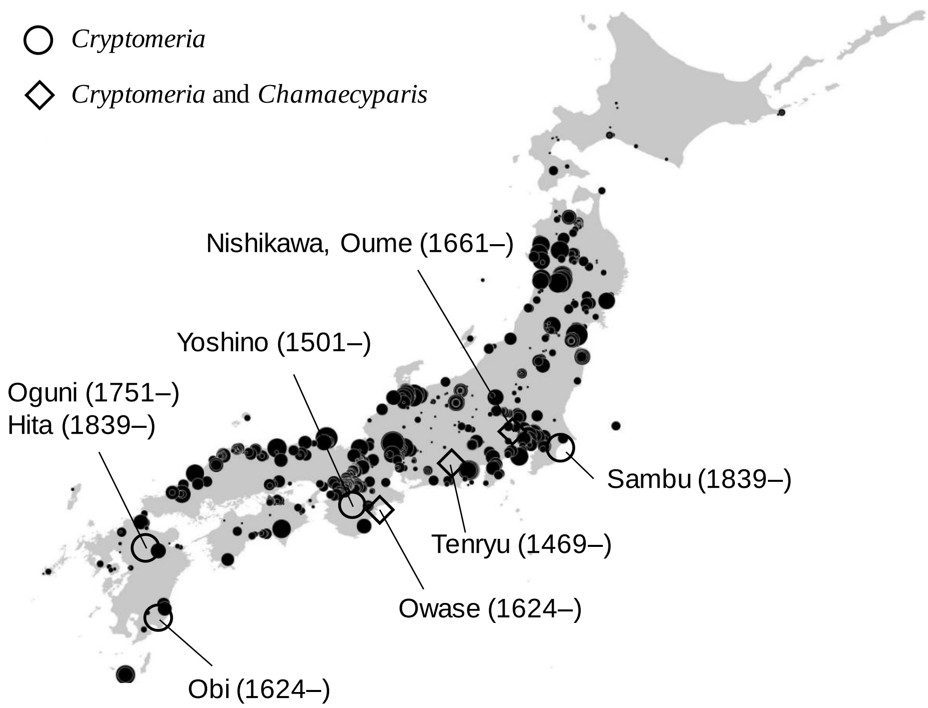

Figure 2. Plantations implemented to restore forest timber resources for the first time in Japanese history. Occurrence probability of *Cryptomeria* and *Chamaecyparis* pollen in soil profiles from 400–1,200 years before present (Ooi 2016), and the locations in Japan where these species were planted 170–500 years ago (Yamauchi 1947).

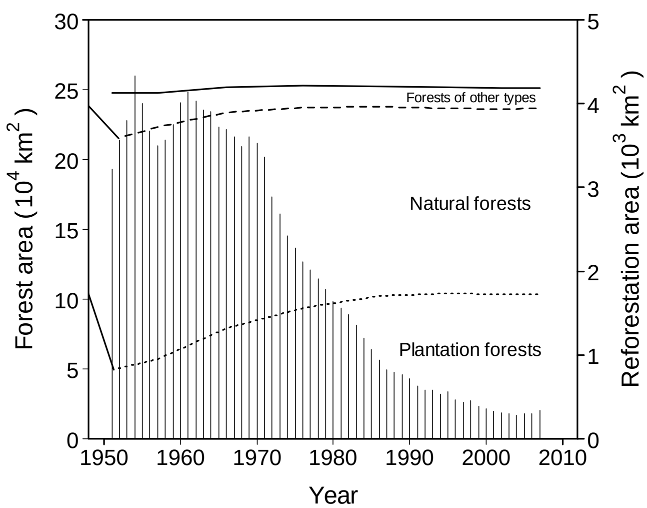

Figure 3. Recent changes in the forest areas. Changes in the areas of plantation forests, natural forests, and other types of forest between 1951 and 2007 in Japan (left axis). Dotted, dashed, and solid lines represent plantation, natural, and other forests, respectively. Data were obtained from the Forestry Agency (2010). The vertical distance between lines represents area. Vertical bars represent reforested areas per year during the same period (right axis). Data were obtained from the Forestry Agency (2012).

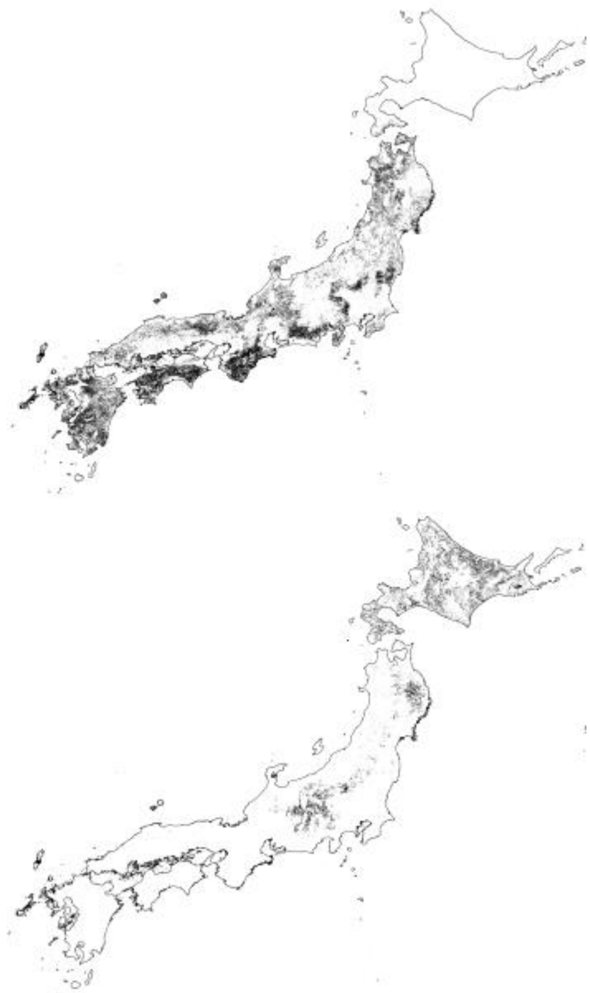

Figure 4. Distribution of conifer plantations. Distribution of Cupressaceae (upper) and *Larix* and *Abies* (lower) plantations ca. 1996 in Japan. This map was created by reclassifying a vegetation map produced by the 5th National Survey on the Natural Environment by the Ministry of the Environment of Japan (1994–1998).

1.2 Current issues in reforestation after harvesting of conifer plantations

As a result of the recent policy described above, the age structure of even-aged plantations has changed from a positively skewed to a unimodal distribution (Forestry Agency 2017a) (Fig. 5). The age of these even-aged plantations is around 40–55 years. Because these plantation trees generally reach maturity as timber resources and are ready for harvest, some of them are being clear-cut in the current decade. From an economic perspective, natural regeneration after clear-cut logging is not realistic, due to the inability of Japanese cedar and hinoki cypress to create advanced seedling banks under the canopy (Ota et al. 2012, 2015). Thus, plantation forestry is a very important approach to restoring forest cover in Japan, in a forestry context (Kajimoto et al. 2016).

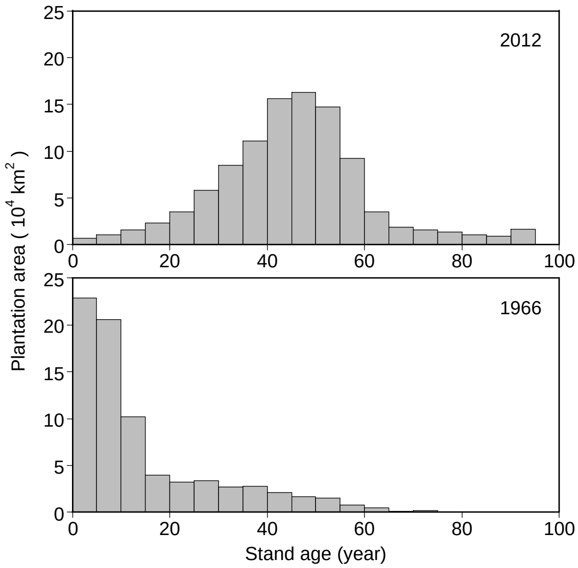

Figure 5. Age structure of conifer plantations. Age structure of Japanese conifer plantations in 1966 and 2012. Data were obtained from the Forestry Agency (2017a). Bars indicating an age of 90–95 years include stands aged >95 years.

There are, however, several silviculture-related problems with reforestation after clear-cutting of these even-aged plantations; as a result, harvesting and reforestation have not progressed significantly. A typical feature of Japanese forests is the presence of extremely competitive, rapidly growing vegetation. Annual precipitation in Japan ranges from 1,500–3,000 mm (or more), and the precipitation is the most abundant in temperate regions of the world (Kunstler et al. 2016). These climate conditions allow for dominance by tall grasses (e.g., *Reynoutria sachalinensis* Nakai, *Miscanthus sinensis* Andersson, *Macleaya cordata* R. Br.), clonally spreading shrubs (e.g., *Rubus* spp.), and dense dwarf bamboo (*Sasa* and *Sasamorpha* spp.), all of which attain a height of over 2 m within a few years in open sites (Masaki et al. 2012). In logged areas, weeding must be continued for 5–7 years after planting, and the cost of weeding during the first 10 years following planting accounts for 50% of total reforestation costs. This problem was insignificant 50 years ago, when labor costs were much lower than at present; however, clear-cutting and reforestation costs in Japan are now nearly four to five times higher than those in Sweden. Steep topography is another feature of the Japanese islands. Flat land, which occupies only a small percentage of the topography of Japan (e.g., land <5° is ca. 30%), is used mainly as residential or agricultural land, with forests being located on steeper slopes (Fig. 6). More than 30% of plantation forests for timber production are found on slopes exceeding 20°, and more than 10% on slopes exceeding 30° (Fig. 6). Thus, working conditions are severe, raising the cost of silvicultural operations throughout the reforestation process, from timber harvest, seedling planting, and weeding to thinning. During recent decades, thinning has been the dominant silvicultural activity, and planting activities have been stacked (Forestry Agency 2012) (Fig. 3); thus, the number of seedling producers has decreased dramatically. Therefore, up-to-date techniques, such as the containerized seedlings developed in European countries, were little studied in Japan until recently. Finally, seedling damage by sika deer (*Cervus nippon* Temminck) foraging in new plantation sites is currently a serious issue in Japanese forestry. By browsing leaves and shoots, the deer damage planted Japanese cedar, hinoki cypress, Japanese larch, Sakhalin fir, and other seedlings (Koizumi 2002; Akashi 2006; Akashi 2009; Yamanaka et al. 2014). In addition to new plantations, young and mature conifer plantations are also harmed by deer scrubbing their antlers on stems and feeding on the inner bark (Oi and Suzuki 2001; Akashi and Terazawa 2005; Honda et al. 2008; Sano 2009). The area damaged by sika deer increased 3.5-fold between the 5-year periods of 2004–2008 and 2009–2013, and sika deer were responsible for 77% of the forest area damaged by wild animals in 2015, followed by rodents at 9% (Forestry Agency 2017b). In the following sections, we review the effects of problems due to silvicultural techniques and deer browsing on plantations in greater detail, in relation to the issues presented by competing vegetation, and introduce the results of recent silvicultural and ecological studies in Japan to address these problems.

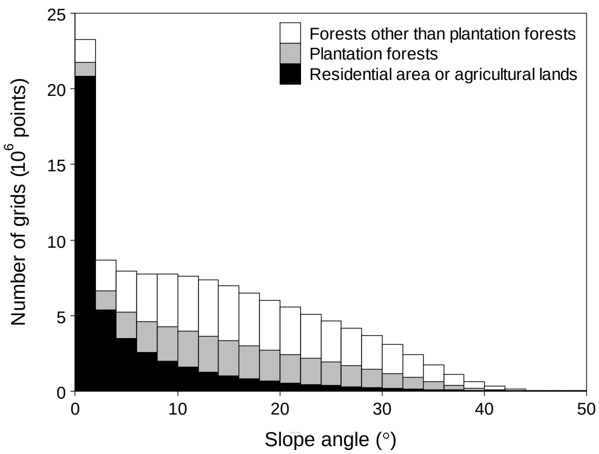

Figure 6. Land use patterns with relation to slope angle. Land-use frequency distributions by slope angle in forests excluding coniferous plantations (white), coniferous plantations (gray), and other land-use types mainly comprising residential area or agricultural land (black) in Japan. Frequency distributions were obtained by counting pixels in a slope angle raster, derived from a digital elevation model (DEM) based on fundamental geological data provided by the Geospatial Information Authority of Japan, as follows. A 10-m resolution DEM was resampled to a resolution of 50 m and slope angles were calculated using ArcGIS 10.4 (ESRI, Redlands, CA, USA). A vegetation map (5th National Survey on the Natural Environment, Ministry of the Environment of Japan) was then reclassified into the three categories described above. Finally, slope angle frequency distributions were calculated for each land-use category.

2 Silvicultural studies of seedlings for reforestation in Japan

2.1 Container-grown and bare-root seedlings in reforestation

Seedling quality, in terms of morphology and physiology, is a critical component of successful plantation establishment. Currently, container-grown cuttings or seedlings are favored over bare-root seedlings for reforestation in Japan due to their higher survival rates. This advantage has led to the use of this stocktype in reforestation programs, and to a longer planting season (Yamagawa et al. 2013; Yagihashi et al. 2015; Harayama et al. 2016; Narimatsu et al. 2016; Suwa et al. 2016). Other desirable traits of this stocktype include greater seasonality in the production of container seedlings, and the protection of seedlings within a plug during handling and transportation. A review of a large database of seedling survival in many species in North America (e.g., Douglas-fir and loblolly pine) showed that container seedlings are generally more tolerant to transplant shock and have higher survival rates in harsh environments than bare-root seedlings (Grossnickle and El-Kassaby 2016). This finding is supported by several recent studies done in Japan, in which container-grown Japanese cedar seedlings were found to have higher water potential than bare-root seedlings after summer outplanting (Simbo et al. 2016; Sugihara and Tange 2016), and to recover earlier from water stress through more rapid root development (Hirata et al. 2014). Container-grown hinoki cypress seedlings also exhibited higher survival rates after outplanting than bare-root seedlings (Suwa et al. 2016). Water contained in the media surrounding container seedling roots can improve their water environment by increasing water availability in the root zone immediately after planting.

Alleviation of planting stress is a critical step in the reforestation process that ensures seedling survival and plantation establishment. The ability of container-grown seedlings to avoid planting stress by rapidly growing new roots and becoming fully integrated into the site hydrologic cycle is a major asset of this stocktype. However, after surviving initial transplantation shock, the fate of seedlings (i.e., whether container-grown or bare-root seedlings perform better during the reforestation process) will be determined mainly by competition for site resources, such as light, water, and nutrients. Previous studies in Japan have reported that the advantage of container-grown seedling lies in a greater ability to overcome transplant shock, which in turn leads to a higher survival rate, rather than a higher subsequent growth rate. A study comparing post-transplant performance in container-grown seedlings versus bare-root seedlings, based on a dataset from multiple sites, found similar growth and survival rates in both stocktypes (Kabeya et al. 2016). One possible reason for this outcome may be the large difference in quality among seedlings produced by different nurseries. The protocol for producing container-grown seedlings has not been sufficiently established, such that unexperienced growers tend to produce lower-quality seedlings. Therefore, a proper seedling production protocol, with specified growing conditions and quality control, must be established to develop a successful reforestation program in Japan.

Both stocktype traits and the conditions of the potential transplant site should be considered to maximize survival against transplant shock. Several studies have examined seedling performance based on species characteristics in relation to container cell volume, plant density, and nursery conditions in European and North American species (e.g., Douglas-fir, black spruce, western hemlock, longleaf pine, and cherrybark oak) (Landis et al. 2010). These data were derived from long-term research on seedling stocktypes that started in the 1960s. In Japan, however, similar studies began as little as 10 years ago, such that there are insufficient data to evaluate the relationships between nursery conditions and field performance after outplanting. Different growing methods among nurseries may also contribute to variation in seedling quality and field performance after outplanting. There are now two main types of multi-cavity container trays used in Japan: 40 (5 × 8) cavities per tray (150 cc per cavity) and 24 (4 × 6) cavities per tray (300 cc per cavity). However, there has been little discussion of the most suitable cavity size for the major tree species in Japanese forests. Further research is needed to clarify the effects of cavity size on the physiological and morphological traits of seedlings of different species.

2.2 Techniques for reducing transplant shock

A transplanted seedling contributes to improving reforestation efficiency and reduced total cost only if it recovers quickly from transplant shock and survives the initial stage under harsh field conditions. Hardening techniques, such as periodically reducing the amount of irrigation (Pallardy and Rhoads 1993), adjusting the amount of fertilizer (Jalkanen et al. 1998), and applying a short-day treatment (Luoranen et al. 2007), have been tested for species such as oak species (Pallardy and Rhoads 1993), Sitka spruce (Jalkanen et al. 1998), and Norway spruce (Luoranen et al. 2007) during the growing period in the nursery, or as a plantation treatment. Such techniques for improving seedling stress resistance should also be developed for Japanese plantation seedlings. One possible technique for conferring stress resistance, reported for hinoki cypress, is partial defoliation of the seedlings, which effectively reduces transplant shock and results in high survivorship and growth performance in bare-root seedlings. The lack of response to defoliation in container-grown seedlings suggests that defoliation is unnecessary for improving their transplant success (Yamashita et al. 2016). Following leaf removal, bare-root seedlings enhance their survivorship without reducing initial stem growth. Therefore, using defoliated bare-root seedlings may be a possible alternative for future reforestation activities, replacing more costly container-grown seedlings.

2.3 Advantages and disadvantages of container-grown seedlings

A beneficial feature of container-grown seedlings is that their root systems exhibit minimal damage during transplanting. Rough handling of seedlings and root loss during transplanting reduces initial survival and growth of bare-root seedlings in the field (Struve 2009; Grossnickle 2016; McKay et al. 1993). In contrast, rough handling has little effect on subsequent root and shoot growth in container-grown seedlings (Struve 2009). Due to the loose structure of a bare-root seedling root system, greater care is required to properly place the root system into the hole dug for planting. Consequently, seedling survival may depend on the experience of the transplanting worker. In contrast, ease of planting is a recognized benefit of container-grown seedlings, because roots are retained within the plug. It has also been reported that container-grown seedlings are easier for nursery workers to use compared to bare-root seedlings (e.g., Fujii 2016). In the bare-root system, nursery transplanting is hard work for seedling growers, who are mostly members of the older generation in Japan. In contrast, the container system is more "worker-friendly" because it is safe and efficient. Because container-grown seedlings can be planted during most seasons, an on-demand supply of seedlings can shorten the time that they spend in the nursery and save maintenance costs.

Conversely, the price of container-grown seedlings is twice that of the bare-root seedlings that have been used traditionally. Higher production cost is a barrier to the popularity of container-grown seedlings (Forestry Agency 2012). Seeds of Japanese cedar, hinoki cypress and Japanese larch have low germination rates (50% or less), and we must therefore transplant each seedling germinated in nursery beds into each container; this makes nursery work laborious and raises costs. Non-destructive techniques to improve seed germination rates are currently being developed by selecting viable seeds using an automated system with near-infrared rays. Another concern is that container-grown seedlings tend to exhibit a high degree of taper and slenderness (height of seedling / diameter at ground level) due to the limited growing space between seedlings in containers. Experimental research on the influence of such taper problems on seedling mortality and growth in reforestation areas is ongoing.

3 Ecological studies of the impact of sika deer on conifer plantations in Japan

3.1 Increase in sika deer populations

Overabundant ungulate populations and related problems have been reported in various areas globally, including Europe (Putman and Moore 1998; Senn and Suter 2003; Kuijper 2011), North America (McNulty et al. 1997; Côté et al. 2004; Simard et al. 2013), New Zealand (Tanentzap et al. 2009), and Japan. The spatial distribution of sika deer increased dramatically (> 2.5-fold) between 1978 and 2014 in Japan, based on presence/absence observations at 5-km grid bases in almost all parts of the Japanese major islands (Ministry of the Environment 2015). The rapid increase in the sika deer population has caused economic and ecological losses in forestry, especially since the 1990s, and has impacted agriculture and ecosystem conservation (Takatsuki 2009). Several factors appear to have triggered and accelerated the increase of sika deer populations since the late 1980s: decreased mortality induced by warm winters and less snowfall, increased carrying capacity generated by logged sites and pastures, reduced human activities and hunting pressure in the countryside, abandonment of farmlands due to the decreasing and aging human population, and elimination of gray wolves (*Canis lupis* Linnaeus) (Miura and Tokida 2009; Uno et al. 2009; Ohashi et al. 2016). The increase in favorable habitats for sika deer (e.g., the recovery of forest areas following clear-cutting in the 1960s–1970s in mountainous areas, and the abandonment of farmlands and secondary forests around villages) appears to explain the expansion of sika deer populations throughout Japan during the past few decades (Agetsuma 2013).

3.2 History of the sika deer problem in Japan

The conflict between the forestry industry and sika deer in Japan is not a new issue. There are descriptions of conifer seedling damage by sika deer and suggested countermeasures in silviculture textbooks that were published >100 years ago (Nakamuta 1894; Mori 1898; Doi 1919). Surprisingly, people at that time employed measures that were essentially the same as those used currently to protect planted conifer seedlings: fencing plantation areas, covering seedlings with shrub branches, painting coal tar on leaves, and shooting sika deer. Following the implementation of these measures, sika deer populations decreased greatly in the latter half of the 19th century in Japan (e.g., Hokkaido; Kaji et al. 2000) due to exploitation for deerskin for military use and exportation. Thus, the Hunting Rule was established in 1892 by the Japanese government to regulate the hunting season and protect current-year fawns (Akasaka 2013). The Game Act subsequently designated all deer species as hunting targets in 1918. Following overhunting during World War II, the hunting of female sika deer was banned in 1948 and the hunting of male sika deer was limited to one individual per day in 1978. Between the 1960s and the 1970s, field mice (*Apodemus* spp.), voles (*Myodes* spp.), and hares (*Lepus brachyurus* Temminck) were the mammals most harmful to conifer plantations, not sika deer (Shidei 1987).

Sika deer populations became overabundant again during the late 1980s and 1990s. Female deer were again designated as game animals in 1994, and the Specific Wildlife Conservation and Management Plan (SWCMP) was started in 1999 in response to forestry and agricultural damage by sika deer and wild boars (*Sus scrofa* Linnaeus), and local extinction of the Japanese black bear (*Ursus thibetanus* G. Cuvier) and Japanese serow (*Capricornis crispus* Temminck). Despite efforts to control sika deer populations, economic losses in agriculture and forestry due to wild animals could not be reduced in the 2000s. The Ministry of the Environment, and of Agriculture, Forestry, and Fisheries, announced a nationwide campaign ("drastic strengthening scheme for wildlife culling") in 2013, aiming to halve the sika deer and wild boar populations by 2023 (Ministry of the Environment 2017). In some regions in Japan, decreasing trends in agricultural and forestry economic losses or the sika deer population index have been reported in recent years (e.g., Hokkaido Government 2017).

3.3 Countermeasures against sika deer in Japanese reforestation sites

Population control or culling of sika deer is now conducted energetically in various parts of Japan under the SWCMP; however, the effectiveness of population control efforts on the mitigation of conifer seedling damage remains unclear. The removal of 11 sika deer from a 1 km^2 zone with abundant deer (36.2 deer km^{-2}) decreased damage to planted Japanese cedar seedlings during the culling year, but seedlings received similar amounts of damage during the year following culling as they had in the year prior to culling (Enoki et al. 2016). Comparing pre- and post-culling, the removal of 14 sika deer in a single 4-ha reforestation site in a deer-abundant area (15–30 deer km^{-2}) did not affect the amount of damage done to Japanese cedar and hinoki cypress seedlings (Otani et al. unpub.). Deer culling in relatively small areas was effective for no less than 2 years in highly populated areas. The Forestry Research Institute in Shizuoka prefecture is developing a new killing method, using sodium nitrate ($NaNO_3$) mixed with alfalfa hay pellets (Ohba 2015), reporting that methemoglobinemia develops exclusively in ruminant animals, and that the ingestion of 0.8 g sodium nitrate per body weight caused death to all of four captive sika deer. However, due consideration is required from an ethics and animal welfare perspective before applying this method in the field. Because sika deer can shift their activity pattern to nocturnal to avoid hunting (Kamei and Ohshima 2010; van Doormaal et al. 2015), elimination of sika deer from a particular site appears to be very difficult. Furthermore, because deer populations can recover quickly after a severe disturbance, such as a population crash or intense hunting pressure (Kaji et al. 2004; Miller et al. 2010), culling alone may not be an effective countermeasure against damage to reforestation caused by sika deer.

Deer-proof fences and tree shelters have been employed in many reforestation sites across Japan; however, fencing failures have frequently occurred, especially during the initial stage of fence installation in the 20th century (Takayanagi and Yoshimura 1988; Nakamura and Amikura 1998; Ikeda 2006). Snow accumulation is the most destructive factor for fences in northern Japan. Also, steep slopes (Fig. 6) often cause fencing malfunctions (Arai 2008). Proper establishment of deer-proof fences can protect reforestation sites for at least 4 years (Kaji et al. 2010). Fence malfunction can occur due to inadequate installation and maintenance; thus, most publicly-run forestry institutes have published manuals on the installation and maintenance of deer-proof fences. However, the routine checks and maintenance of fences that are essential to maintaining functionality are labor-consuming and difficult to practice; human populations are decreasing in areas where forestry is conducted, and 30% of forestry laborers are over 65 years of age (Forestry Agency 2015; Ministry of Agriculture, Forestry and Fisheries 2015).

Although the relationship between deer density and fencing failure frequency has not been examined statistically, a combination of fencing and deer culling may be effective in reforestation sites. Plantation sites and forest edges created by clear-cutting provide good food resources for sika deer (Takatsuki 1989; Furubayashi and Sasaki 1995), such that deer-proof fences must be kept functional around reforestation sites. Such measures would also limit increases in sika deer populations. Deer-repellent chemicals are an alternative countermeasure; however, their effectiveness is doubtful in deer-abundant areas (Unno et al. 2015).

Some silvicultural techniques have been suggested to protect planted conifer seedlings. Reducing weeding frequency in reforestation sites was reviewed in terms of lowering costs during the initial stage of reforestation, and Japanese cedar seedlings received 40% less damage by sika deer in no-weeding versus weeding sites (Nomiya et al. 2013). A combination of tree shelter and no-weeding operations resulted in better survival in hinoki cypress seedlings than in those with fencing and without weeding, in an area with moderate deer density (ca. 10 deer km^{-2}, Shimada 2010). When moderate deer density can be maintained using appropriate culling measures, abundant understory vegetation appears to be effective in reducing damage to conifer seedlings in reforestation sites (Ward et al. 2008). Depending on deer density, non-weeding operations may be a possible method to reduce conifer seedling damage by sika deer at sites with lower weed productivity, where planted seedlings are not likely to be overtopped by the surrounding vegetation (Yamagawa et al. 2016).

4 Direction for future studies

Japanese cedar and hinoki cypress physiologically require more light than other coexisting tree species. Natural forests comprising Japanese cedar and hinoki cypress display an almost even-aged structure, suggesting that past regeneration of these species has occurred following large scale disturbances (Ota et al. 2008). Considering this physiological traits and the ecology of these species, clear-cutting and planting at specific spatial scales is likely to represent an appropriate way to maintain these species in sustainable forestry. Therefore, we must solve the problems described previously based on our increasing ecological and silvicultural knowledge.

Once seedlings have been established in the field, bare-root and container-grown seedlings can exhibit comparable shoot growth rates (Hirata et al. 2014). Therefore, when seedlings are planted in sites with little competing vegetation, or in locations with a mild environment, either seedling type can be used, even at smaller sizes and greater slenderness (height / diameter ratio or top / root ratio). However, such sites are rather exceptional in Japanese forestry. In more common sites with harsh environments or more competing vegetation, planting larger seedlings (stocktypes) in combination with a hardening technique, such as defoliation, prior to outplanting may be a preferable option to improve seedling survival and growth. It is necessary to determine which stocktype or hardening treatment is optimal for maximizing *in situ* seedling performance, depending on environmental conditions, planting season, and the skill level of the workers, and to simultaneously establish an on-demand seedling supply system. Thus, further research is required on seedling stress resistance, hardening techniques, and the physiological and morphological characteristics of seedlings both in the nursery and in the field.

From an economics perspective, it is currently hard to identify a minimal density of local sika deer populations that will enable coexistence with agriculture and forestry; the deer cause damage even at low densities of <2 deer km^{-2} (Miura and Tokida 2009). Even intermediate damage to conifer seedlings is unacceptable, because Japanese cedar seedlings with 20–50% foliage loss show delayed growth, by 1–3 years, with respect to reaching heights comparable to those of intact seedlings (Kon et al. 1984). Such growth delays require additional weeding operations. These findings suggest that sika deer exclusion from young plantations is essential for establishment in reforestation sites with minimal economic loss. Studies are needed to examine acceptable sika deer densities and environmental conditions in areas surrounding reforestation sites, so that protective materials, such as deer-proof fences, will function properly. Additionally, large Japanese cedar seedlings (1.4–1.8 m in height) receive less damage than normal-sized seedlings (Ootsuka et al. 2008; Sasaki et al. 2013). As explained above, large seedlings are preferred to mitigate competition with other types of vegetation. However, nursing and planting costs should be reduced before this approach is applied in reforestation (Nomiya et al. 2016).

All of these components, which have been developed independently, need to be combined within a unified reforestation system. In this context, a "continuous operating system" has been tested during the current decade in Japan, in which land preparation is conducted using an excavator immediately following harvesting, seedlings are brought in using forwarders, and are then planted immediately after logs are removed by the forwarders. In this system, because soil preparation and planting are carried out promptly after harvesting, the process of weeding during the first year can be omitted. Additionally, because opportunities for weed invasion are reduced, we can expect labor savings during the first 10 years after planting. Containerized seedlings are generally used in this system due to their higher survival rates, and to the fact that they are easy for workers to plant, even in unprepared sites. It remains to be determined whether larger seedlings can be incorporated into this otherwise advantageous system.

Research on seedling silviculture and efficient deer population management approaches is rapidly progressing in Japan. These reforestation techniques must be developed in harmony with cost performance and environmental conservation. Problems are gradually being solved through such studies, and training programs to foster technical expertise in forestry and wildlife management have begun throughout Japan. Appropriate strategies and substantial schemes for reforestation sites are expected to be established in the near future. However, sociological considerations are also important due to the impact of Japan’s decreasing and rapidly aging human population.

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