Ecological Engineering, 2 (1993) 333–345
Elsevier Science Publishers B.V., Amsterdam

Forest reconstruction as ecological engineering

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(Received 5 October 1992; accepted 6 May 1993)

ABSTRACT

Land restoration involves reconstruction of the native biota in a sustainable form. If reconstruction involves deliberate manipulation of biological organisms and the physical–chemical environment to achieve specific human goals, it qualifies as ecological engineering. Restoration which uses natural processes to achieve endpoints which are unpredictable but can be accepted because they are "natural" is not ecological engineering. In Japan a system of forest reconstruction has been developed which is based on knowledge of the potential vegetation of a site, knowledge of the methods of germination and growth of the species which compose the mature vegetation and a method of site preparation and planting. This ecological engineering approach has been used on 285 sites, in a variety of habitats, to form dense stands of vegetation to hide industrial complexes, control visual, noise and chemical pollution, stabilize soil and beaches and provide urban green space. The technique has also been used to restore tropical rain forest.

INTRODUCTION

The land is frequently disturbed by human activities. While ecological engineering-informed land management can reduce disturbance to the environment of a site, in many situations such as road and industrial construction, it is difficult or impossible to avoid substantial impacts. In these circumstances it is necessary to reestablish and restore the ecological systems in order to reduce erosion, recreate greenness, reduce noise and air pollution and reestablish habitat for organisms.

Land restoration is a subfield of applied ecology (Cairns, 1988) and has developed a variety of methods for rebuilding ecosystems on disturbed sites. Frequently, these methods replicate the processes of natural recovery, called ecological succession, on disturbed land. Indeed, in situations where there is adequate time and the site can be protected from further disturbance, merely allowing the natural processes of recovery to operate undisturbed by human intervention is a viable strategy. But the cost is time.

In temperate forest regions recovery of the site and the reestablishment of mature ecological systems will probably require from 100 to 200 years to restore the life forms and incorporate a relatively large percentage of the potential species in physically small areas. In large areas the rate of recovery may be much slower (Golley, 1965). In tropical rain forests, the equivalent time may exceed 500 years.

In many situations it is not possible or desirable to wait for natural recovery. In these instances the process of reestablishment of ecological systems must be accomplished through direct human management.

In either natural or managed restoration four steps are required. First, the disseminules of the species used in restoration must be transported to the site. Second, these disseminules must germinate if they are plants or become established if they are animals. Germination and establishment was called ecesis by Clements in his classic study of the process of ecological succession (Clements, 1916). Third, the organisms must grow, compete for resources and resist herbivory and predation. In this stage they also begin to react on the physical–chemical environment and alter the rates of water movement and erosion of the surface soil. Finally, the biota must store sufficient nutrients to reproduce.

In the ordinary process of succession each species goes through these four steps. Many species can not maintain themselves in competition with other species in the new environment. The sequential replacement of species and the change in life form from low-growing herbs and grasses to shrubs to trees in humid temperate regions led ecologists to call this restoration process succession. Succession has been a central focus in American ecology (Golley, 1977); studies of succession have not been as important in those countries where disturbance has been less ubiquitous. Further, in extreme environments, such as deserts, succession does not occur as such. The species that initially invade and live on these sites form the mature natural vegetation.

Restoration ecology and ecological engineering differ from conventional vegetation management of civil engineering because they employ the native biota of the region in rebuilding ecosystems. In the approach we are promoting ecological knowledge of the biology, and ecology of the biota is used to select species with the appropriate properties for reconstruction of vegetation. Restoration ecologists also utilize the natural processes of succession and direct it or change its rate.

Because ecological knowledge of species performance may be inadequate, civil engineers often resort to using exotic or domesticated species which are well known biologically and economically in restoration projects. They also use fertilization and irrigation to assure that the site is covered quickly and erosion is stopped. On severe steep slopes the danger of failure may be so great that the civil engineer chooses to use steel and concrete to stabilize the soil rather than risk slumping.

These comments imply a definition of ecological engineering which requires further elaboration. Engineering involves manipulation of materials to construct objects and processes following a design or plan to serve specific human purposes. Design is not by chance, nor is it bricolage (Levi-Strauss, 1962). The materials used in engineering may be natural organisms, which have evolved and been selected for specific niches, or the materials may be human-made, such as iron and concrete. In contrast, ecological science, as in restoration ecology, is the study of the interactions of living organisms and their environment. Applied ecology and restoration ecology try to design with nature, using ecological processes to achieve ecological communities like those which evolve naturally under the processes of evolution, adaptation and development.

Within engineering the activities may be placed on a gradient from ecological engineering at one end and conventional civil engineering at the other. The gradient describes the tendency to use natural evolved materials in ecologically recognizable ecosystems, versus the tendency to use human-made materials in human designs to overcome what are conceived to be natural obstacles. The contrast between using native plant materials on roadcuts versus concrete and steel illustrates the extremes of this hypothetical gradient. Obviously, all kinds of compromises between the extremes are employed in real-life engineering activities.

Thus, restoration ecology forms a contrast with ecological engineering, but the contrast is less extreme than the contrast between ecological and civil engineering. In this case the restoration ecologist tries to direct and manage natural processes of recovery to obtain vegetation patterns that fit the expected regional patterns for the site. The objective is to restore the natural, bioregional ecological communities to something like a former condition. Ecological engineering, in contrast, is directly and intentionally manipulating natural materials for specific purposes within human-made designs. The ecological engineer is not letting "nature take its course" but is acting as an engineer informed by and knowledgable of ecological systems. The ecological engineer uses the information of basic ecological science in solving specific technical problems of human society.

In this paper we describe an ecological engineering technique that was developed by the senior author and has been used on over 285 sites on the Japanese archipelago. This method qualifies as an ecological engineering technique because it uses knowledge of the ecology and biology of native Japanese species and the potential vegetation of Japan to build engineering systems which hold soil, reduce pollution, provide visual screening, and reduce noise. It is anticipated that these engineered systems will eventually replicate the mature ecosystems of the site without going through the lengthy process of succession. In that case the engineered systems will be converted into permanent adapted ecosystems. These techniques are now being extended to tropical rain forest in Malaysia, Brazil, and *Nothofagus* forest in Chile.

THE RECONSTRUCTION METHOD

The method employed by the Miyawaki team (Miyawaki, 1988) is based on three kinds of information:
(1) knowledge of the potential natural vegetation on the site;
(2) an understanding of the germination and establishment biology of the dominant species of the potential natural vegetation; and
(3) methods of planting large numbers of seedlings in prepared seedbeds at the site.
Each of these points will be described.

The potential vegetation: Potential vegetation is a concept of vegetation science, developed in Europe by Tuxen (1956). It does not imply an ecological climax, in the sense of Clements (1916) or a climax as a steady-state, in current American ecological terminology. Potential vegetation is an abstract concept of a vegetation made up of the plant species present in remnants of the plant cover, without human influence. The vegetation scientist studies patches of natural vegetation and, through understanding the relations of species to each other and the physical conditions of the site, reconstructs the potential patterns. The potential patterns give the ecological engineer an endpoint or a design goal to guide reconstruction.

Knowledge of the potential vegetation of Japan is based on a long-term, intense study of the potential and actual vegetation by Miyawaki and associates (Miyawaki and Fujiwara, 1988). During the 1970s, Japan was mapped in a hierarchical system of plant communities (Fig. 1), identifying the association, alliance, order, class, as well as lower order units such as subassociations and variants. These descriptions were based on species observed on plant relevees using the conventional methods of vegetation science (Miyawaki et al., 1978, 1983). The number of maps that have been published from this research exceeds 900. The vegetation of Japan also is described in a series of volumes which presents the data obtained by thousands of relevees in tables, maps, verbal and photographic descriptions (for example, Miyawaki, 1980).

The technical work underlying these descriptive texts was based on field examination of the actual vegetation and the remnants of mature vegeta-

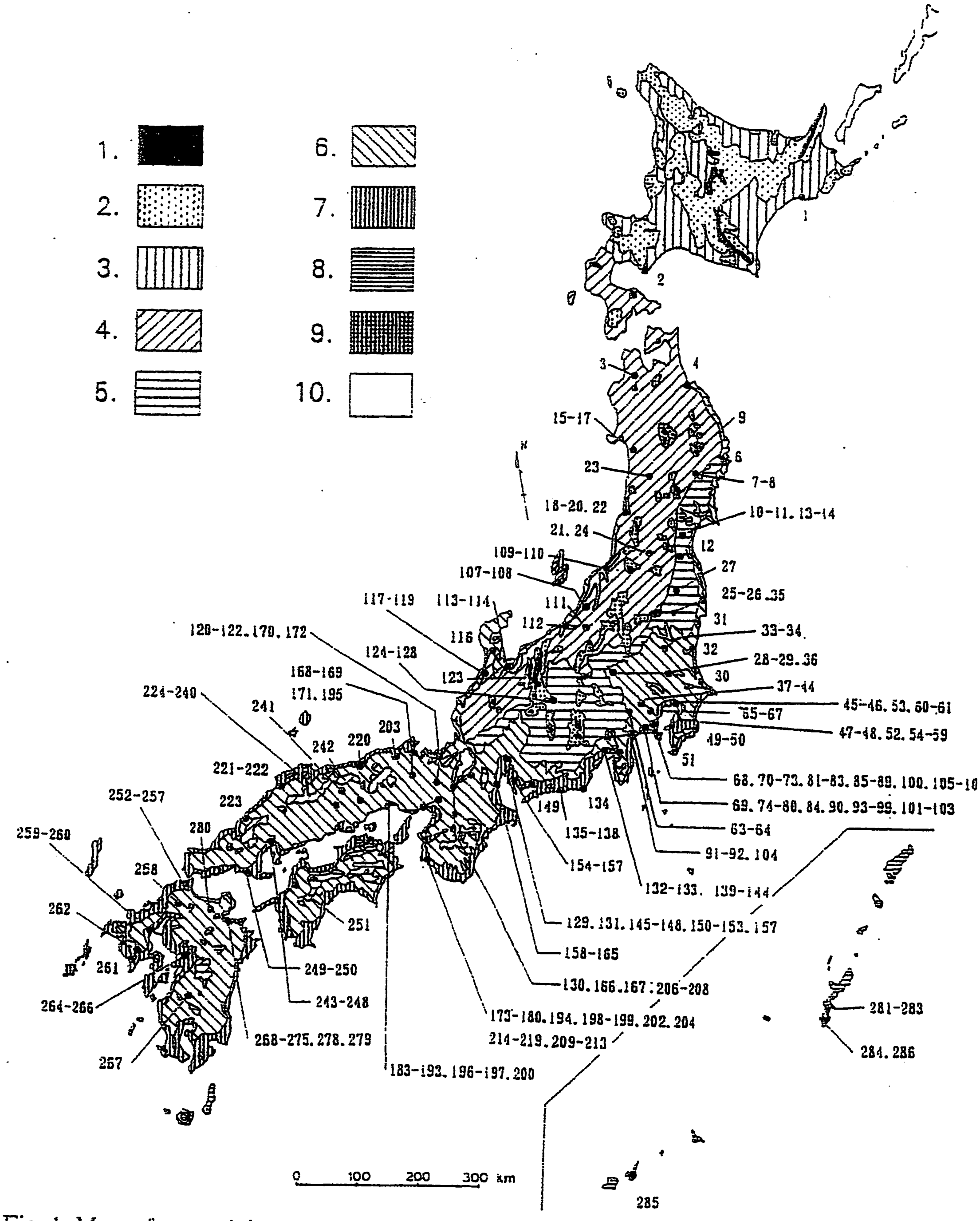


Fig. 1. Map of potential vegetation of Japan; indicated by the code numbers, the sites where restoration projects have been successfully carried out. The legend indicates the following vegetation types: 1. *Vaccinio–Pinion pumilae*, 2. *Vaccinio–Piceeta*, 3. *Tilia maximowwicziana–Quercus mongolia*, 4. *Saso kurilensis–Fagion crenatae*, 5. *Sasamorpho–Fagion crenatae*, 6. *Quercion acuto–myrsinaefolia*, 7. *Maeso–Castanopsion sieboldii*, 8. *Psychotrio–Castanopsion sieboldii*, 9. *Psychotrio manilensis–Acerion oblongii*, 10. *Alneta japonica–Saliceta sachalinensis*.

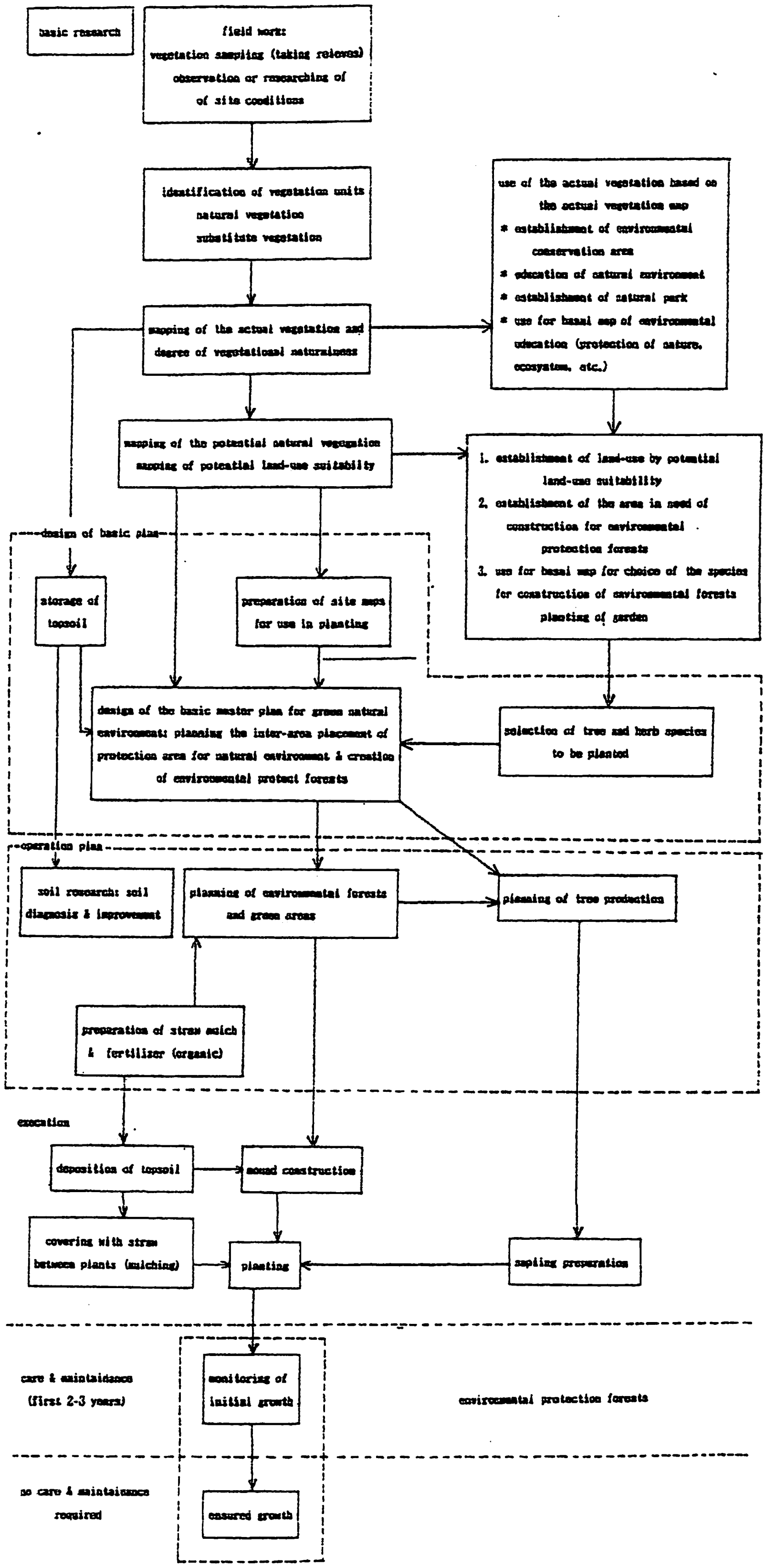
tion that still exist in Japan around Shinto shrines, Buddhist temples, and villages throughout the country. These pieces of natural vegetation vary in size and composition and they have been influenced by centuries of human activity. Nevertheless, they represent patterns of premodern Japanese vegetation. They exist even in the urban area of Tokyo. Before 1950 there were relatively few maps of the vegetation of Japan, but beginning in 1967, maps of potential vegetation began to be constructed for the country using these remaining stands of vegetation and ecophysiological knowledge of the relation of species to environmental factors which could be determined in the field (Miyawaki, 1985). In addition to maps of potential vegetation, the actual vegetation occurring in each region has also been studied and maps on a scale of 1:200000 have been prepared for the Cultural Agency of the Japanese Ministry of Education, Science and Culture (1969–1976) and the Japanese Environmental Agency (1975–1977). More-detailed maps at a scale of 1:50000 also have been prepared for the Japanese Environment Agency since 1985.

The consequence of this vegetation science analysis of Japanese potential and actual vegetation is that reconstruction activity can be directed to specific goals which fit the climate, soil and geological characteristics of the site (Fig. 2). The species of the potential vegetation can be selected for planting and the naturally occurring plant community can be reconstructed with considerable confidence. The background of knowledge of potential and actual vegetation reduces the role of chance in land reconstruction. It also avoids the need to use exotic vegetation in a project.

Forest reconstruction is based on the canopy trees and it is assumed that understory plants and animals will reinvade the site as the canopy develops, eventually recreating an ecological system. This assumption has not been adequately tested. The only other group of organisms that has been investigated has been the soil fauna (Miyawaki et al., 1977; Aoki and Harada, 1985). The soil fauna of restored communities begins to show species abundance and diversity characteristic of the potential community after the canopy has developed and become closed (Fig. 3). But this is an area of research requiring more attention.

Germination and establishment biology: Reconstruction of the vegetation requires that seeds be collected from specimen plants, germinated in nurseries and grown in containers for 1–2 years. The major objective is to grow seedlings with strong root systems because the root system is the key to successful survival of the plantings and the stabilization of the soil.

Fig. 2. A diagram of the sequence of steps in forest restoration.


basic research
field work:
vegetation sampling (taking relevés)
observation or researching of
of site conditions
identification of vegetation units
natural vegetation
substitute vegetation
use of the actual vegetation based on
the actual vegetation map
* establishment of environmental
conservation area
* education of natural environment
* establishment of natural park
* use for basal map of environmental
education (protection of nature,
ecosystem, etc.)
mapping of the actual vegetation and
degree of vegetational naturalness
mapping of the potential natural vegetation
mapping of potential land-use suitability
1. establishment of land-use by potential
land-use suitability
2. establishment of the area in need of
construction for environmental
protection forests
3. use for basal map for choice of the species
for construction of environmental forests
planting of garden
design of basic plan
storage of
topsoil
preparation of site maps
for use in planting
design of the basic master plan for green natural
environment: planning the inter-area placement of
protection area for natural environment & creation
of environmental protect forests
selection of tree and herb species
to be planted
operation plan
soil research: soil
diagnosis & improvement
planning of environmental forests
and green areas
planning of tree production
preparation of straw mulch
& fertilizer (organic)
execution
deposition of topsoil
mound construction
covering with straw
between plants (mulching)
planting
sapling preparation
care & maintaidance
(first 2-3 years)
monitoring of
initial growth
environmental protection forests
no care & maintainance
required
ensured growth

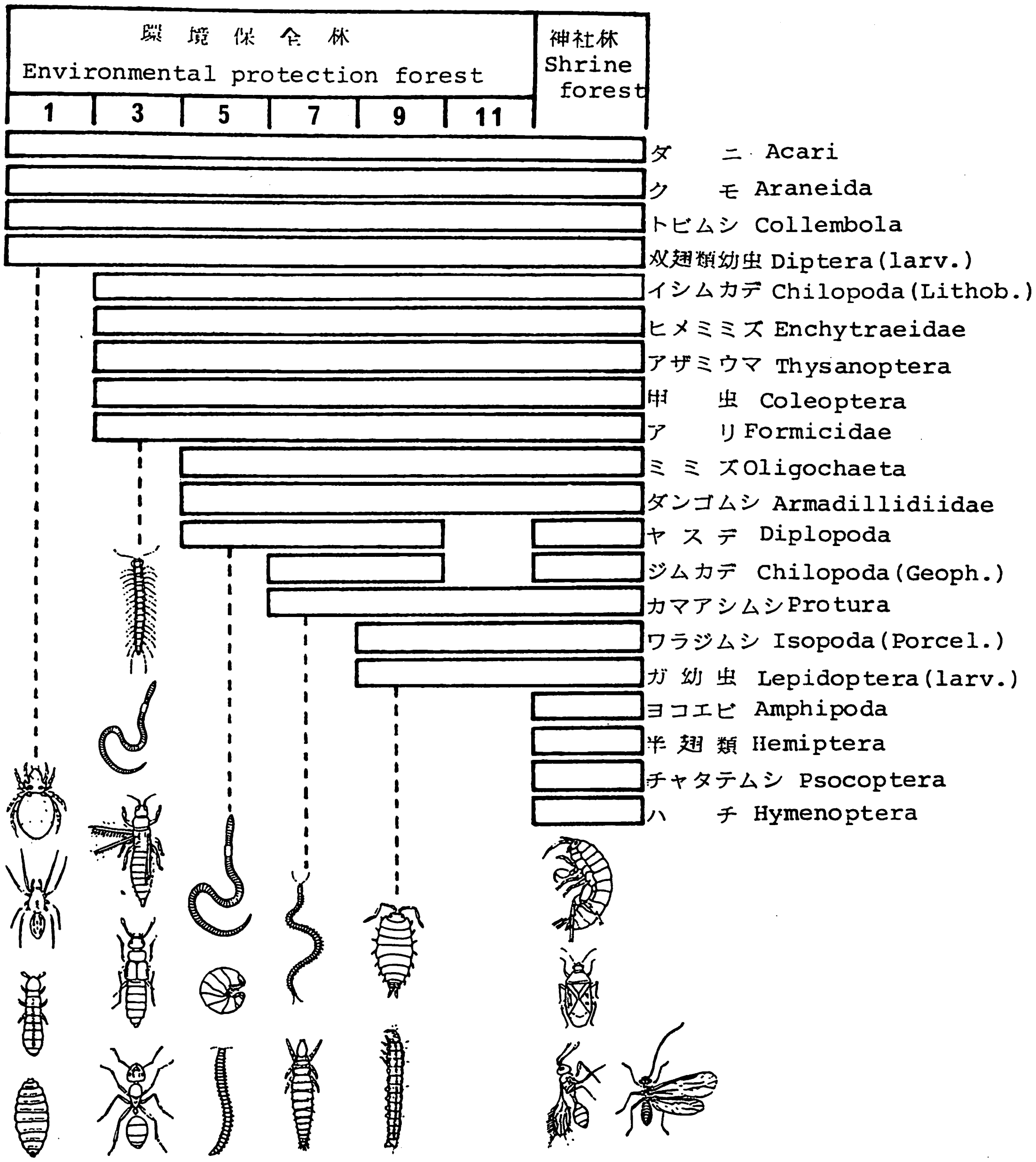


Fig. 3. Establishment of the soil fauna in restored forests of different ages. The shrine forest represents a stable forest type. Based on Aoki and Harada (1985).

Japan is a country where gardening and horticultural knowledge has a long and deep history. Methods of growing the dominant and even rare species are relatively well understood. Forests have been reconstructed on a large scale, as for example around the Meiji Shrine in Tokyo, and to the uninitiated eye these appear to be natural stands. This traditional knowledge coupled with modern botanical scientific studies of the physiology of species provides the background needed to establish nurseries for growing the tens of thousands of seedlings needed in a large project. Seedlings are grown in pots and planted when they are 2 years old.

The planting process: The planting process is a unique environmental education experience for the local community. The steps for reconstruction (Fig. 2) involve site preparation, planting, and a post-planting survey. Site preparation usually involves surface plowing of the site to create low mounds of loose soil which will provide the surface for planting and prevent flooding of seedlings during the frequent rains which are a feature of the Japanese environment. On construction sites where the top soil has been reserved, 20 to 30 cm of top soil are returned to the site. Straw and organic fertilizer may be applied to the mounds if soil analyses indicate that an amendment is required. If the planting is on a steep slope, temporary planting beds are constructed of bamboo (Fig. 4). The area on the planting mounds is divided by cord into approximately 1-m squares and three planting holes are located in each square.

Planting of seedlings occurs during a planting festival, including local authorities, families, school children and guests. These ceremonies include

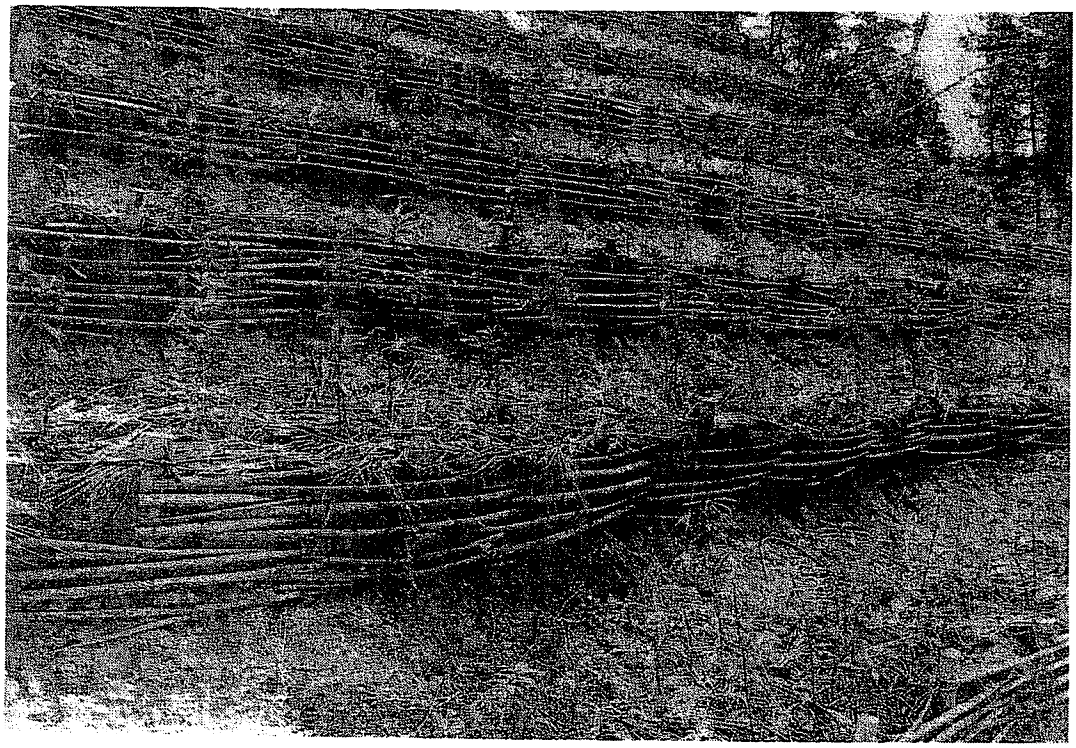


Fig. 4. Construction of earth berms, held in place by bamboo revetments, for tree planting on steep slopes. This Japanese example is designed to revegetate a steep cut-bank on a highway construction project.

Fig. 5. Mulched and recently planted forest designed to shield an industrial facility in Japan.

comments on environmental awareness, and the value of forests. The festival participants are instructed on how to plant trees and then they are invited to select seedlings from tanks of water and plant the seedlings in the prepared holes in the squares on the site. The species of trees are provided to the planters in the approximate proportions they occur in the potential vegetation. However, there is no attempt made to have the planters arrange these in a natural pattern in the planting beds. The large number of trees seedlings and individual planters automatically results in complex patterns of trees.

Presence of local or regional authorities, adults and children all planting trees together is recorded by the press and supports the feeling of local community action. Through these festivals the people of the area identify with the forests they have planted and expand their environmental awareness. Thus, the engineering process also yields social results that feed-back on the project and enhance its overall success.

Following the planting ceremony straw mulch is placed around the seedlings (Fig. 5). This is the final technical step in the operation and no further management or maintenance is required. A slogan describes the effect of cessation of further input – "no management is good management". Even so, survival of seedlings is frequently over 90% and is

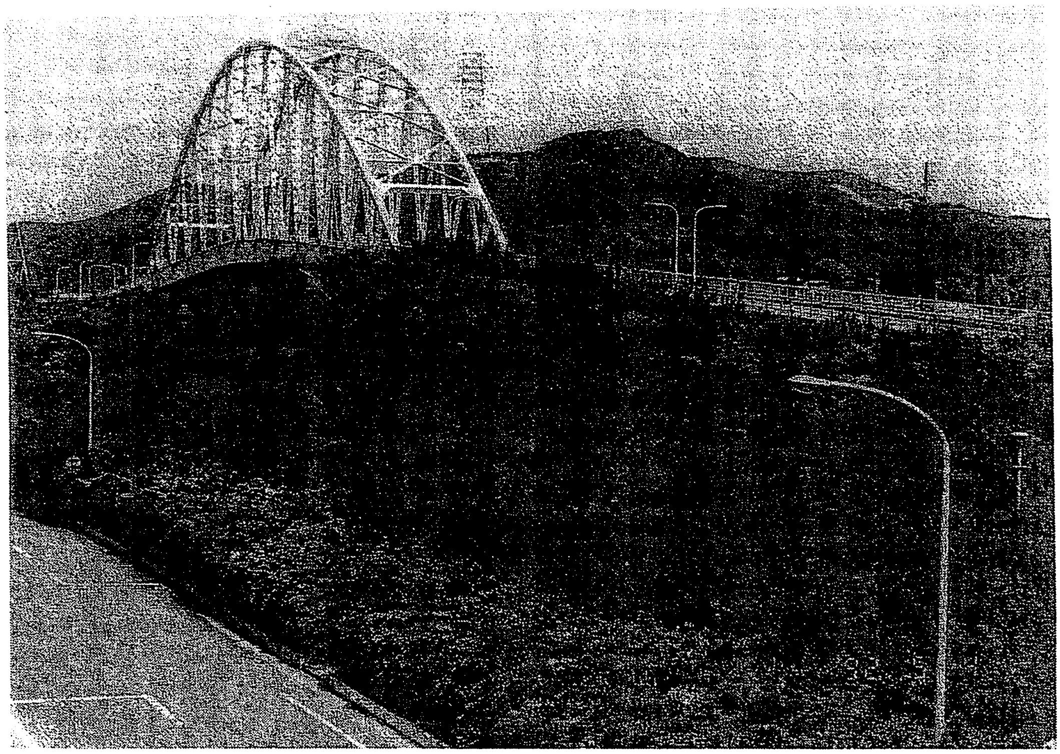


Fig. 6. Established forest in a construction area in Japan.

sometimes as high as 99% in the first year. Growth of stem height is usually double the planting height in the first year. This rate of growth continues for several years so that a closed canopy is achieved in about 5 years. As the stems grow, the canopy is raised in height (Fig. 6). Natural competition between species takes place and some individuals are eliminated from the populations as the canopy becomes closed.

This planting technique also has been used in unusual locations and in industrial applications. Unusual locations include cliff faces and beach front sites. As was shown in Fig. 4, on a cliff face it is necessary to contruct bamboo basket-like planting beds along the cliff face to hold the soil for planting. As the trees become established their roots enter cracks in the rock, leaving a rock-face community on extremely steep slopes. This system also is effective in controlling soil movement on steep road cuts. On a beach front site exposed to periodic overflow of sea water the naturally adapted species are planted more closely (five per square meter) and are irrigated the first year to assure their establishment in the sandy and rocky substrate. Thereafter, a dense stand develops into a characteristic beach front dune complex and holds the site even under considerable disturbance. Industrial applications usually are designed to shield buildings or machinery from roads and housing developments and reduce noise and air pollution. In this instance employees do the planting but the system used for restoration is identical to that used in the tree planting festivals.

DISCUSSION

The Miyawaki reconstruction technique originally was designed for reconstruction of broad-leaved forests on small sites in Japan. In these locations rainfall is adequate year around. The object is to provide rapid revegetation to reduce visual, noise, or chemical pollution, erosion control, or urban green areas on relatively small and often highly valuable sites. Examples include industrial plants of Nippon Steel Company, Kansai Electric Power Company, and revegetation of man-made islands in Tokyo Bay. If the soil has been scraped, as in a large construction project, then fertilization of the soil in the prepared beds is required. Otherwise the main inputs are the the seedlings, site preparation, and mulching. In difficult locations, for example on cliff faces within the broad-leaved forest region, site preparation and fertilization may increase the costs of reconstruction.

This technique requires a relatively large initial capital investment, but maintenance costs after the project is planted are essentially nil. It is difficult to calculate the economic costs because values differ greatly from country to country. In Japan seedlings are produced at a cost of about 400 to 500 yen (or roughly US$2.00) per plant. At this expense it would require about US$60 000 per hectare for restoration in the United States. Clearly this expense can be borne only by industry or government, for very critical areas. In comparison, in the southern United States pine seedlings are grown in nurseries for 0.5–1 cents per plant and the costs of the seedlings in replanting pine land is about 5 to 7% of the total costs (Donald Marx, USFS, pers. commun.). Hardwood seedlings may cost up to 4 cents per plant. Clearly, there is a considerable cost of the reconstruction operation, although conversion of costs from Japanese to USA currency is difficult to determine.

This technique has also been applied outside the broad-leaved forest region of Japan. Applications include northern forests on Hokkaido and beach front sites near Yokohama. Recently, it has been successfully extended to *Diptocarp* rain forest sites in Sarawak where over 300 000 seedlings were planted in 1992, to Amazonian rain forest in Brazil and to *Nothofagus* forest in Chile.

It is important to note that this ecological engineering technique is not designed to recreate natural ecosystems. While natural ecosystems may ultimately evolve on an engineered site, the goal of the process is to create dense stands of forest vegetation quickly. These stands serve specific purposes, such as shielding industrial complexes from housing districts. The use of species characteristic of the native vegetation means that no further management is required after the trees are planted. The species are adapted to the environmental conditions of the site and to the competitive relations among the elements of the vegetation. While this process requires a substantial initial investment, there is little or no maintenance cost, a high likelihood of success and rapid achievement of the objectives. In those circumstances where a dense vegetation stand is required, this well-tested technique qualifies as a viable alternative for land managers and civil engineers. Its use is not restricted to Japan, but a knowledge base of plant biology and ecology is required before it can be applied in other countries successfully.

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REPRINTED FROM:

ECOLOGICAL ENGINEERING

The Journal of Ecotechnology

Ecological Engineering, 2 (1993) 333–345
Elsevier Science Publishers B.V., Amsterdam

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(Received 5 October 1992; accepted 6 May 1993)

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