Open Journal of Forestry
2013. Vol.3, No.4, 122-128
Published Online October 2013 in SciRes (http://www.scirp.org/journal/ojf)

Scientific Research
http://dx.doi.org/10.4236/ojf.2013.34020

An Evaluation Model for Improving Biodiversity in Artificial Coniferous Forests Invaded by Broadleaf Trees

Yozo Yamada, Sayumi Kosaka
Graduate School of Bio-Agricultural Sciences, Nagoya University, Nagoya, Japan
Email: yozo@agr.nagoya-u.ac.jp

Received July 16th, 2013; revised August 17th, 2013; accepted August 29th, 2013

Increasing attention is being paid to the various functions of forests, especially the conservation of biodiversity. In Japan, 67% of national land is covered by forest, 41% of which is artificial forest (i.e., plantations). Therefore, efforts to conserve forest biodiversity should also target artificial forests. In this study, we investigated the increase in biodiversity resulting from broadleaf tree invasion of artificial coniferous forests. We examined diversity indices and combinations of indices to identify which ones can aid forest managers in evaluating forest diversity. We also studied classification according to the richness of diversity, which corresponded to the growth stages of *Chamaecyparisobtusa* and *Cryptomeria japonica* plantation forests. Moreover, we developed a model that will contribute to sustainable forest management and biodiversity over an entire area. The model, based on a specific rotation scenario in a geographic information system, is easy to use and presents spatial and temporal changes at sites visually.

Keywords: Artificial Forest; Invading Broadleaf Trees; Broadleaf Tree Diversity; Sustainable Forestry Management; Basin Scale

Introduction

The importance of forest biodiversity has been discussed since the United Nations Conference on Environment and Development (UNCED) in 1992. The UNCED adopted the Declaration on Forest Principles in Agenda 21, which is a series of principles for sustainable forest use (Lund et al., 2004). In 1994, the Montréal Process Working Group agreed on seven criteria of sustainable forest management and 54 indicators of the criteria. Criterion 1 stipulates the conservation of biological diversity and states that conserving the diversity of organisms and their habitats supports forest ecosystems and their ability to function, reproduce, and remain productive (Montreal Process, 2009). Many studies have confirmed the importance of forest diversity, although most have focused on natural forests (Burslem, 2004; Ehrlich, 1996; Kondoh, 2002; Noss, 1990).

Artificial forests account for approximately 6.5% of the global forested area. The percentage of artificial forest varies by country. In Japan, 68.5% of the land area is covered by forest, 41.3% of which is artificial forest (FAO, 2012). By age, artificial forests in Japan form a nearly perfect normal distribution, with a top age of 50 years. Thus, vast areas of forest require immediate thinning (Forestry Agency, 2012). However, many of the artificial forests that require thinning have been deteriorating, mainly because of reductions in forestry surplus. In countries such as Japan that have vast areas of artificial forest, biodiversity loss has become a problem, even in the artificial forests since last few decades. Many artificial forests are designed as monoculture plantations with the aim of growing high-quality timber. Thus, these forests are generally dark with sparse understory vegetation. Brockerhoff et al. (2008) noted that artificial forests usually have less habitat diversity and complexity. Yamaura (2007) also suggested that artificial forests have been treated as a homogeneous non-habitat (matrix) and ignored in biodiversity conservation.

However, the environment in an artificial forest can be altered to become more favorable to biodiversity. Hartley (2002) indicated that earlier thinning schedules or longer rotations can strongly affect biodiversity, as can reserve trees that are left after plantation harvest and remain through a second rotation. Busing and Garman (2002) argued that proportional thinning retains understory stems, thereby expediting the recruitment of shade-tolerant trees. El-Keblawy (2005) suggested the importance of reducing forest crowns to promote species growth. Yamaura (2007) proposed that the negative effects of artificial forest could be mitigated by increasing the complexity of the structure and composition of a plantation through extended rotation, strong thinning, wider tree spacing, and the retention of broadleaf trees and coarse woody debris in clear-cuts. Brockerhoff et al. (2008) also stressed that to sustain native biodiversity within an artificial forest, managers should consider using a greater diversity of planted species, extending rotation lengths in some stands, and adopting a variety of harvesting approaches.

The overall aim of the present study was to promote the diversity of invading broadleaf trees in artificial coniferous forests. We examined effective diversity indices and combinations of these indices that can be used by forest managers to evaluate forest diversity. In addition, we studied classification according to the richness of diversity, which was found to correspond to growth stages in *Chamaecyparisobtusa* and *Cryptomeria japonica* artificial forests. Moreover, to help forest managers maintain sustainable forests with rich biodiversity over the entire area, we developed an easy-to-use model that shows spatial and temporal changes at forest sites visually. The model, implemented in a geographic information system (GIS), is based on a specific rotation scenario.

Methods

Survey Location

Our survey was conducted at Danto National Forest (35˚6'N, 137˚28'E), located in Shitara-cho, Aichi Prefecture, Japan. The forest covers 5303 ha, 93% of which is artificial forest dominated by hinoki (*C. obtusa*). It ranges from 400 to 1150 m above sea level, with an average annual temperature of 11.7˚C and annual precipitation of 2036 mm.

The Chubu Regional Forest Office of Forestry Agency has performed systematic thinning and promoted understory vegetation in their forests, with the farsighted (100-year) goal of creating diversified, vital, and sound forests for the coexistence of log production and various public benefit functions (Chubu Regional Forest Office, 2011).

Danto National Forest is divided into about 1300 sub-compartments, and the Forest Office has created specific management plans and concrete management schedules for each sub-compartment. As part of this management, the sub-compartments are arranged to achieve a proper balance of vegetation types and different stages of succession to aid in the conservation of biodiversity in the entire forest.

Vegetation Survey

We chose six hinoki (*C. obtusa*) sub-compartments (aged 13, 36, 44, 56, 76, and 118 years) and eight sugi (*C. japonica*) sub-compartments (aged 26, 45, 55, 60, 72, 79, 98, and 116 years). We also selected four additional plots: two hinoki (aged 34 and 55 years) and two sugi (aged 34 and 55 years) sub-compartments in the Inabu Experimental Forest of Nagoya University, located near the Danto National Forest. These plots served as controls, representing forests in which management has been insufficient.

As in our previous study (Kosaka & Yamada, 2013), we established 10 m × 10 m plots within areas representative of each sub-compartment. We examined all broadleaf and planted trees that were taller than 1 m. For the broadleaf trees, we determined the number of species and population size. We also measured the tree height and diameter at a height of 50 cm from the ground surface. For planted trees, we measured the height and diameter and counted the number of planted trees in 20 m × 20 m areas to calculate the stand density.

Analysis at the Sub-Compartment Scale

For the analysis of broadleaf tree diversity within sub-compartments, we used the number of species, population size, proportion of basal area, and two species diversity indices: the Shannon-Wiener index and inverse Simpson index. We clarified the characteristics and diversity of invading broadleaf trees during each growth stage in artificial forests to discuss practical ways of retaining broadleaf trees to encourage biodiversity

Analysis at the Basin Scale

Using a GIS and the forest age data from the forest register, we determined the distribution of broadleaf tree diversity across the entire Danto forest by sub-compartment. Broadleaf tree diversity was classified into three levels based on forest age, which was estimated from our analysis at the sub-compartment scale.

We set up a rotation scenario in which all forests more than 80 years old are entirely cut and the plots are then replanted with the same tree species. That is, clear cutting and reforestation are repeated every 80 years in each sub-compartment. We simulated the change in broadleaf tree diversity in Danto forest from the present to 40 years later and discussed the spatiotemporal evaluation of broadleaf tree diversity shown by the model.

Results and Discussion

Analysis at the Sub-Compartment Scale

The invading broadleaf trees were divided into the following three categories by height:

Lower layer (Shrub): tree height is more than 1 m and less than 4 m.

Middle layer (Sub-tree): tree height is more than 4 m and less than 8 m.

Upper layer (Tree): tree height is more than 8 m.

We analyzed every diversity index and its layer composition by forest age. All diversity indices indicated a similar trend of change in forest age. For hinoki forests, **Figure 1** shows the relation between forest age and number of species, while **Figure 2** shows the relation between forest age and proportion of basal area. Both indices increased significantly after an age of 76 years. After that, in the mature stage, the number of species decreased slightly at 118 years old, but the proportion of basal area continued to increase. The young stage represented by the 13-year-old forest also had abundant species and was jungle-like in its appearance, but its proportion of basal area was not very large. The middle stage, from 36 to 56 years old, was the stage of height growth, when the crowns closed entirely. Thus, the lack of sunlight in this stage led to a decrease in invading broadleaf trees.

For the sugi forests, **Figure 3** shows the relation between forest age and number of species, while **Figure 4** shows the relation between forest age and proportion of basal area. The sugi forests exhibited a slightly different tendency from hinoki forests. As shown in the figures, both indices increased remark-

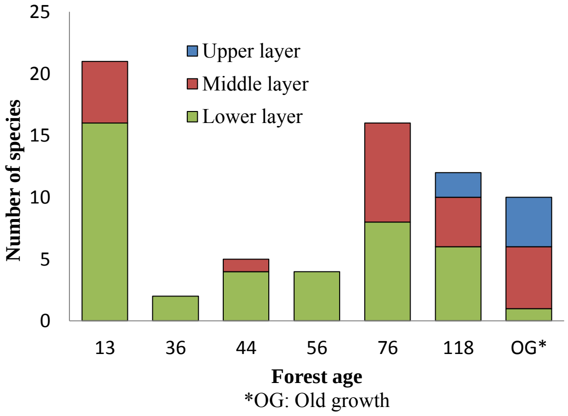
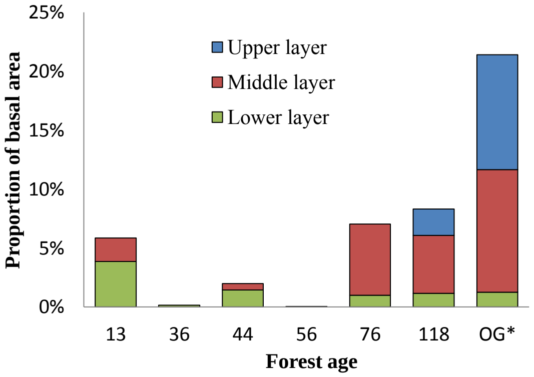


Figure 1.
Forest age and number of species in hinoki (*C. obtusa*) forests.



*OG: Old growth

Figure 2.
Forest age and proportion of basal area in hinoki (*C. obtusa*) forests.

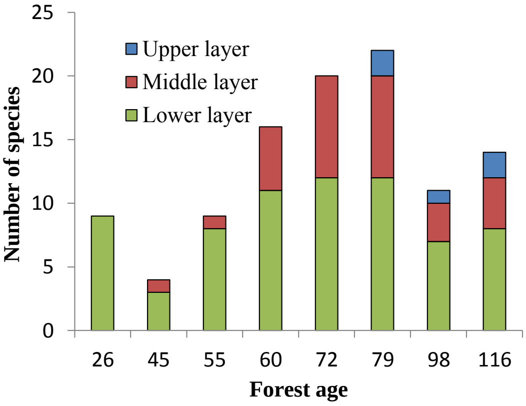


Figure 3.
Forest age and number of species in sugi (*C. japonica*) forests.

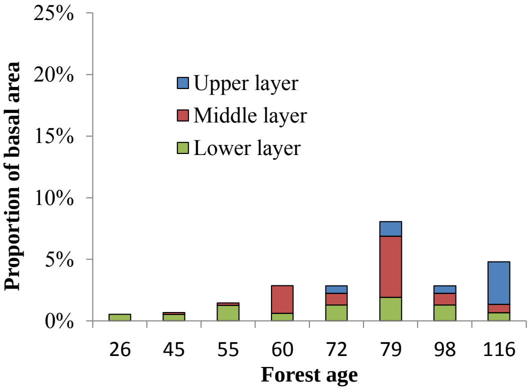


Figure 4.
Forest age and proportion of basal area in sugi (*C. japonica*) forests.

ably from 60 years of age and kept increasing until 79 years. The proportion of basal area also reached its maximum at 79 years. The young stage, represented by the 26-year-old forest, had fewer species compared to the young-stage hinoki forest, whereas the middle stage (from 45 to 55 years) retained a relatively large number of invading broadleaf species.

The layer composition developed toward the upper layer as both hinoki and sugi forests reached the mature stage. In the Danto forest, invading broadleaf trees remained, because they were not cut as long as they impeded thinning or threatened safety.

From these results, we can define three stages on the basis of the diversity of invading broadleaf trees: young, middle, and mature. The young stage includes forests less than 25 years old that have relatively rich diversity of invading broadleaf trees, unless those trees were cut by intense weeding and cleaning operations.

The middle stage includes forests more than 26 and less than 60 years old. These forests have poor diversity of invading broadleaf trees because of a lack of sunlight. Although this stage does not have good conditions for understory vegetation, it is indispensable for the production of high-quality logs. These low-light conditions will not be improved until commercial thinning begins. Commercial thinning usually starts at age 40, but its effect on improving the light conditions does not appear until a few decades later.

The mature stage includes forests more than 61 years old and has rich diversity and a developed layer of invading broadleaf trees. Commercial thinning is performed repeatedly at 15- to 20-year intervals; thus, favorable light conditions for invading broadleaf trees are kept and improved unless broadleaf trees are cut during thinning.

In comparison, the four control plots in the Inabu Experimental Forest of Nagoya University were typical examples of poorly tended forests. The understory was very dark, with insufficient light for the invasion of understory vegetation. Consequently, we found no invading broadleaf trees in these plots.

To promote understory vegetation, management measures such as thinning must be implemented at appropriate times based on a specific density control plan. **Figure 5** shows the relation between forest age and stand density in Danto forest, Inabu Experimental Forest, and Hayami forest, which we examined in our previous study (Kosaka & Yamada, 2013). In forests less than 40 years old, before launching commercial thinning, we found no remarkable differences in stand density among the plots, including the two plots at Inabu. However, the stand densities differed after 50 years. As shown in **Figure 5**, Hayami forest has maintained the lowest density and is considered to have ideal density control. Danto forest has also maintained a low density, showing good performance and careful tending. In Inabu, 55-year-old plots have higher densities than

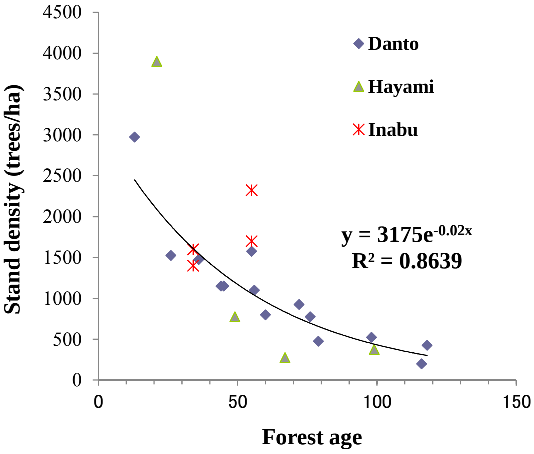


Figure 5.
Forest age and stand density.

plots of that age in the other two forests and are clearly too late for thinning.

We should also consider the traditional practice of removing all understory vegetation to provide safe and convenient working conditions for thinning. In this case, invading broadleaf trees will be cut as often as thinning takes place and will not be able to grow to create a layered forest structure. Both Hayami forest and Danto forest have their own guidelines, which say that invading broadleaf trees should remain as long as they do not impede thinning or threaten safety.

Selection of Diversity Indices for Broadleaf Trees

The five indices recorded in this research showed a similar trend of change in forest age, but we found that each index had certain advantages and disadvantages. For example, although the number of species is easy to survey, this measure cannot be used to estimate the degree of uniformity. Moreover, the number of species may increase in proportion to plot size. Population size can be used to estimate the degree of uniformity, but if one species dominates a plot, uniformity may be overestimated. Otherwise, this measure may tend to show a trend similar to that of the number of species. The proportion of basal area can indicate the species dominance in each layer, but the difference between dominance and diversity requires careful consideration. The Shannon-Wiener index is popular and easy to understand because it includes both the number of species and the population size.

The inverse Simpson index has the same characteristics and can indicate species uniformity. However both indices are influenced largely by the observed parameter.

Each index has own characteristics, making it difficult to choose a single index as the best for estimating the diversity of invading broadleaf trees. By using a few indices in combination, we can evaluate the different perspectives each provides and they can compensate for deficits in each other.

To determine the most effective combination of indices, we created a precedence matrix for each index and calculated the rank difference of each sub-compartment between pairs of indices. **Table 1** shows the average value. Smaller values indicate that both indices of a combination estimate diversity similarly, so we could use either one of the two. Meanwhile, a larger value means that the indices estimate diversity from different perspectives, so it is effective to use both indices. The inverse Shannon index is different from the other indices, with the exception of the Shannon-Wiener index.

Moreover, we cannot determine the best indices based on statistical results alone; other features should also be considered. **Table 2** shows the advantages, disadvantages, and applications of each index. On the basis of our results, to evaluate broadleaf tree diversity at the sub-compartment level, we recommend using the proportion of basal area to evaluate the species dominance in each layer and the inverse Simpson index to evaluate diversity from a different perspective than the proportion of basal area.

However, the total number of species did not largely differ among forest ages. On the other hand, when considering layer structure, the number of trees located lower in the canopy decreased with age, whereas the number of trees at intermediate levels increased with age. After age 67, an upper layer began to form, indicating that layer composition becomes more complex as the forest matures. In particular, layer composition within forests at age 99 approaches that of natural forests.

The number of species is an effective index for forest management, as species richness is a good indicator of current forest conditions. However, the evenness of species must also be considered. Furthermore, the number of species tends to in-

Table 1.
Average rank difference between pairs of indices.

	Number of species	Population size	Proportion of basal area	Shannon-Wiener index	Inverse Simpson index
Number of species	-	1.068	2.006	1.961	4.187
Population size	-	-	2.442	2.637	4.679
Proportion of basal area	-	-	-	2.004	3.510
Shannon-Wiener index	-	-	-	-	2.270
Inverse Simpson index	-	-	-	-	-

Table 2.
Merits, defects, and uses of each index.

Indexes	Merits	Defects	Applications
Number of species	High versatility	Ambiguous uniformity, Increasing in association with expansion of sample size	Provides a tentative evaluation of diversity
Population size	Degree of uniformity	Apt to show a similar trend to number of species	Can be substituted by number of species
Proportion of basal area	Dominancy, insusceptible to population size	Dominancy ≠ diverseness	For evaluating dominance
Shannon-Wiener index	Popular and easy to follow index	Large influence from parameter	For evaluating both the number of species and population size
Inverse Simpson index	Evaluation including uniformity of species	Large influence from parameter	For equivalent evaluations of several invading species

crease as plot size increases.

Analysis at the Basin Scale

To evaluate diversity of invading broadleaf trees at the basin level, it is important to consider fragmentation and networks of sub-compartments having rich diversity within the whole subject area or forest. Fragmentation is important for avoiding overly large expanses of even-aged plantations, as large monoculture areas may not have good effects in terms of biodiversity and ecosystem functioning. Meanwhile, the network should be maintained for all living organisms to move around and live in.

Every management plan must start with an understanding of the present condition of the entire subject forest. We propose the following steps to estimate invading broadleaf diversity in a whole forest. Here, "site" refers to the minimum scale of management, which in the Danto forest equals the sub-compartment scale.

Step 1 (GIS mapping): Specify the location of each site using a GIS. Next, add site-specific data obtained from the forest register, including the main planted species, its percentage of dominance, and forest age.

Step 2 (Categorization by growth stage): Classify all sites into three stages (determined previously): young stage (less than 25 years), middle stage (more than 26 and less than 60 years), and mature stage (more than 61 years).

Step 3 (Visual display): In the GIS, color-code each site according to its classification: young stage as green, middle stage as light green, and mature stage as dark green. That is, a darker color means richer broadleaf tree diversity.

Figure 6 shows the present condition of broadleaf tree diversity in Danto forest. Most of the area is light in color, indicating large homogeneous groups, with dark areas scattered throughout the forest. This situation is considered insufficient to maintain the diversity of invading broadleaf trees. To evaluate the potential for improving the diversity within Danto forest, we simulated changes in conditions up to 40 years in the future.

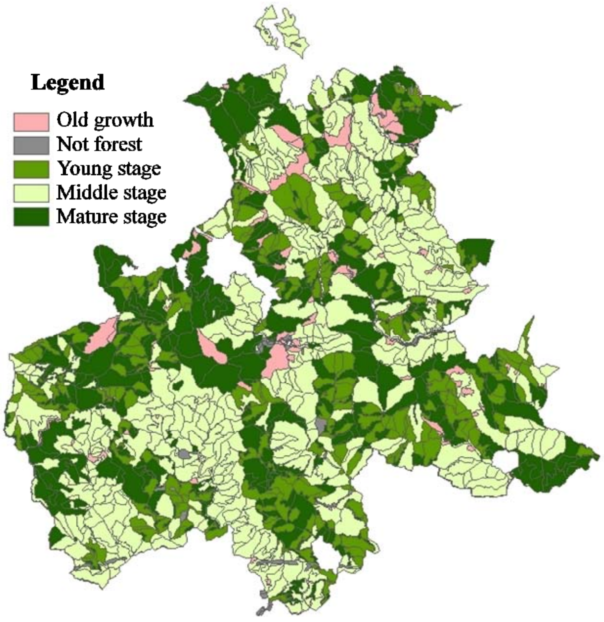


Figure 6.
Diversity of invading broadleaf trees in Danto forest (present).

Step 4 (Rotation scenario): All sites more than 80 years old are entirely cut and then replanted with the same tree species the following year.

Step 5 (Simulation): The change in broadleaf tree diversity from the present to 40 years later is simulated and the spatio-temporal changes shown by the diversity model are discussed.

Figures 7 and **8** show the simulation results after 20 and 40 years, respectively. After 20 years, the overall size of the dark area increased and the different dark areas began to coalesce, while the light areas became more fragmented. After 40 years, the dark areas increased in size further and were observed

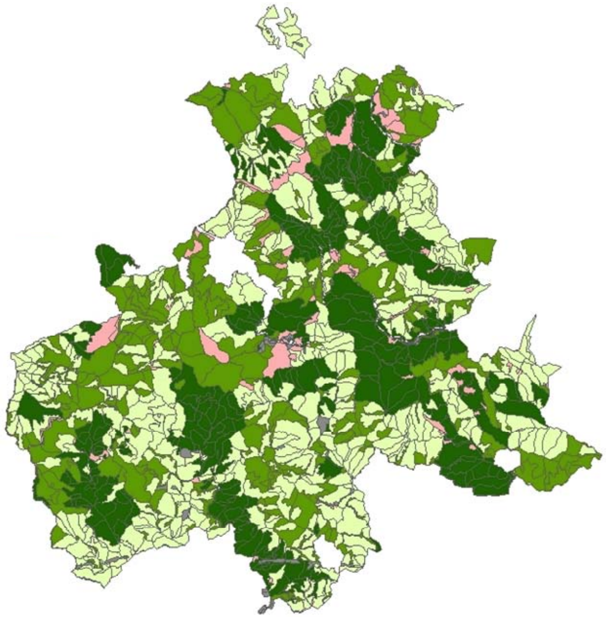


Figure 7.
Diversity of invading broadleaf trees in Danto forest (after 20 years).

Figure 8.
Diversity of invading broadleaf trees in Danto forest (after 40 years).

throughout the entire forest, while the fragmentation of the light areas continued. The network of dark areas at 40 years appeared to be strengthened and expanded compared to the present and after 20 years.

Figure 9 shows the change in proportion of the sub-compartments by stage. The proportion of mature stage sub-compartments decreased to 22% after 10 years under the 80-year rotation scenario and then recovered gradually to 42% after 40 years. Meanwhile, the proportion of young stage sub-compartments increased gradually to 35% after 30 years and then decreased. Middle stage sub-compartments occupied 44% of the area at present, increased to 48% after 10 years, and thereafter showed a downward trend. The overall percentages of high-diversity stages (i.e., the sum of the young and mature stages) were 56% at present, 51% after 10 years, 57% after 20 years, 72% after 30 years, and 65% after 40 years.

In this study, we created a simple scenario in which all sites more than 80 years old were cut completely; thus, the first decade was on the overcutting side, and, after 80 years, the sites returned to the starting point. Therefore, this scenario is strongly affected by the present site age and location, and we cannot change the arrangement of sites to improve the spatiotemporal diversity of invading broadleaf trees. Clearly, if we set a different rotation scenario in Step 4, the results may change.

Conclusion

Our sub-compartment-scale analysis suggested that we can classify each site into one of three stages according to the richness of diversity of the invading broadleaf trees: young stage, less than 25 years with rich diversity but small height; middle age, more than 26 years and less than 60 years with poor diversity; and mature stage, more than 61 years with rich diversity and a developed layer. For a Scots pine (Pinussylvestris) stand in northern Scotland, Mason (2004) recognized four phases of stand development: 1) stand initiation, from 0 to 20 years; 2) stem exclusion, from 20 to 80 years; 3) understory re-initiation, from 80 to 150 years; and (4) old growth, from 150 to 350 years. Busing and Garman (2002) concluded that most wood quantity, wood quality, and ecological objectives can be met with long rotations of approximately 260 years. The ranges of our proposed classification are shorter than those in previous studies. Invading broadleaf trees may still be in the process of growing even in our mature stage. In Japan, there are artificial forests older than 200 years, but the conventional long-rotation system in Japan is more than 70 and less than 100 years, considering economic efficiency and management conditions. Busing and Garman (2002) noted that certain objectives could be met with shorter rotations of 80 - 150 years, when treatments of thinning and canopy tree retention were applied. Hartley (2002) argued that during establishment, forest managers should consider innovations in snag and reserve tree management, in which mature native trees and/or understory vegetation were left unharvested or allowed to regenerate. The same idea applies to our study area: invading broadleaf trees should be retained as long as they do not impede thinning or risk safety.

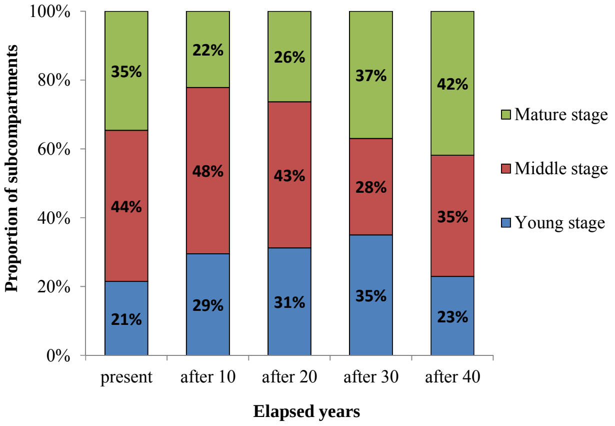


Figure 9.
Change in the proportion of sub-compartments by stage.

In this study, we examined five diversity indices for broadleaf trees and studied the features of each index. We then examined combinations of the diversity indices. The proportion of basal area and inverse Simpson index were identified as the index pair for evaluating the diversity of invading broadleaf trees at a single site. In future, we plan to test additional diversity indices to identify and confirm the most suitable indices for evaluating broadleaf tree diversity in artificial forests.

From the results of our basin-scale analysis, we proposed a model for evaluating the diversity richness of invading broadleaf trees in whole forests. The simulation showed a spatiotemporal change in richness. Regarding the importance of a basin-scale perspective, Kupfer et al. (2006) noted that the study of forest fragmentation effects was shifting away from a patch-based perspective focused on factors to a landscape-mosaic perspective that recognizes the importance of gradients in habitat conditions. Fischer et al. (2006) suggested that a landscape should include structurally characteristic patches of native vegetation, corridors, and stepping stones between them, a structurally complex matrix, and buffers around sensitive areas. Although our GIS-based model can show a basin-scale perspective, we could not quantitatively evaluate the fragmentation of sites as a structurally complex matrix and network of rich diversity sites as corridors in this study. In future, we plan to improve the rotation scenario of our proposed model by incorporating a road-construction plan and felling plan that specifies when and which sites to fell and plant.

REFERENCES

Brockerhoff, E., Jactel, H., Parrotta, J., Quine, C., & Sayer J. (2008). Plantation forests and biodiversity: Oxymoron or opportunity? *Biodiversity Conservation, 17,* 925-951. http://dx.doi.org/10.1007/s10531-008-9380-x

Burslem, D. F. R. P. (2004). Plant diversity in forests. *Encyclopedia of Forest Sciences, 1,* 40-44. http://dx.doi.org/10.1016/B0-12-145160-7/00021-1

Busing, R. T., & Garman, S. L. (2002). Promoting old-growth characteristics and long-term wood production in Douglas-fir forests. *Forest Ecology and Management, 160,* 161-175. http://dx.doi.org/10.1016/S0378-1127(01)00443-1

Chubu Regional Forest Office (2011). Forest for people; National Forest. http://www.rinya.maff.go.jp/chubu/introduction/gaiyou_kyoku/pamphlet/pdf/20110223kyoku-panhu.pdf

Ehrlich, P. R. (1996). Conservation in temperate forests: What do we need to know and do? *Forest Ecology and Management, 85,* 9-19. http://dx.doi.org/10.1016/S0378-1127(96)03746-2

El-Keblawy, A. (2005). Artificial forests as conservation sites for the native flora of the UAE. *Forest Ecology and Management, 213,* 288-296. http://dx.doi.org/10.1016/j.foreco.2005.03.058

FAO (2012). Global forest resources assessment 2010. http://www.fao.org/forestry/fra/fra2010/en/

Fischer, J., Lindenmayer, D. B., & Manning, A. D. (2006). Biodiversity, ecosystem function, and resilience: Ten guiding principles for commodity production landscape. *Frontiers in Ecology and the Environment, 4,* 80-86. http://dx.doi.org/10.1890/1540-9295(2006)004[0080:BEFART]2.0.CO;2

Forestry Agency (2012). Annual report on forest and forestry in Japan, fiscal year 2011.

Hartley, M. J. (2002). Rationale and methods for conserving biodiversity in plantation forests. *Forest Ecology and Management, 155,* 81-95. http://dx.doi.org/10.1016/S0378-1127(01)00549-7

Kondoh, M. (2002). What determines the biodiversity pattern? Unifying "intermediate disturbance hypothesis" and "procuctively hypothesis". *Biological Science, 53,* 195-203.

Kosaka, S., & Yamada, Y. (2013). Evaluation of broadleaf tree diversity at the basin scale: In case of artificial Chamaecyparisobtusa forests. *Open Journal of Forestry, 3,* 62-65. http://dx.doi.org/10.4236/ojf.2013.32010

Kupfer, J. A., Malanson, G. P., & Franklin, S. B. (2006). Not seeing the ocean for the islands: The mediating influence of matrix-based processes on forest fragmentation effects. *Global Ecology and Biogeography, 15,* 8-20. http://dx.doi.org/10.1111/j.1466-822X.2006.00204.x

Lund, H., Dallmeier, F., & Alonso, A. (2004). Biodiversity in forests. *Encyclopedia of Forest Sciences, 1,* 33-40.

Mason, W. (2004). Multiple-use silviculture in temperate plantation forestry. *Encyclopedia of Forest Sciences, 2,* 859-865. http://dx.doi.org/10.1016/B0-12-145160-7/00225-8

Montreal Process (2009). Criteria and indicators for the conservation and sustainable management of temperate and boreal forests. 4th Edition, 29 p.

Noss, R. F. (1990). Indicators for monitoring biodiversity: A hierarchical approach. *Conservation Biology, 4,* 355-364. http://dx.doi.org/10.1111/j.1523-1739.1990.tb00309.x

Yamaura, Y. (2007). Mitigating effects of broadleaved forest fragmentation on birds: Proposal of plantation matrix management. *Journal of Japanese Forest Society, 89,* 416-430. http://dx.doi.org/10.4005/jjfs.89.416