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Assessment of Broad-Leaved Forest Stand Management: Stock Densities, Thinning Costs and Profits over a 60-Year Rotation Period

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Abstract

There are many broad-leaved forests in Japan that were formerly managed for charcoal production, which have been abandoned for decades. Appropriate thinning can revitalize these forests if the cost balance of the management is positive. Two critical elements are the construction of spur roads to facilitate mechanized harvesting operations and management planning that considers stand properties such as the growing stock, species, and tree size distribution. We surveyed three abandoned former broad-leaved coppice stands; one coastal, one cool temperate and one warm temperate. The stock in all three stands exceeded 300 m^3 ha^{-1}, two- to three-fold the official forest registry data estimates. The dominant species in terms of tree numbers are Castanopsis sieboldii, Pieris japonica, *and* Quercus glauca. *Medium-sized trees involve those well suited for firewood, i.e.,* Quercus acuta, Quercus glauca, Quercus serrata, *etc. Each plot contained a few large trees that potentially have a high market value, e.g.,* Cinnamomum camphora, Zelkova serrata, Abies firma, *etc. The average income from harvested trees was estimated to be 10200 JPY (Japanese Yen) m^{-3}, whereas the thinning costs would be 3200 to 5400 JPY m^{-3}, with the additional spur road construction costs. The management cost balance of a broad-leaved stand in a 60 year rotation was evaluated with both Net Present Value (NPV) (for interest rates of 1, 2, 3, and 4%) and Internal Rate of Return (IRR). This balance was compared with that of a typical plantation stand of Japanese cedar (*Cryptomeria japonica*) and of a fast-growing plantation stand of Chinese fir (*Cunninghamia lanceolata*). The estimated NPVs were largest for the fast-growing plantation stand, second largest for the typical plantation stand, and lowest for the broad-leaved stand with a NPV interest rate of 1%. However, the IRR of the broad-leaved stand was the highest, followed by that of the fast-growing plantation stand, while the IRR of the typical plantation stand was the lowest. This order was the same for NPVs assuming higher interest rates.*

1 JPY=0.0086 € on April 29, 2019.

Keywords: broad-leaved forest, abandoned forest, forest management, cost assessment, thinning, Internal Rate of Return

1. Introduction

Natural woodlands comprise 42% of Japan's forest area and most consist predominately of broad-leaved species (Forestry Agency 2018). These were historically managed for the provision of woody fuels such as firewood and materials for charcoal production. After the 1950s, when the main commodity fuel source changed to fossil fuel, many broad-leaved forests were abandoned, and have remained unmanaged in the decades since. In recent decades, problems such as oak disease and invasion of bamboo have occurred in these abandoned stands because management practices such as thinning were not applied. It is established that thinning can revitalize such abandoned woodlands and enhance CO_2 sequestration (Kominami 2019).

Management practice, including thinning operations, is essential to balance operational costs. Key elements are the construction of spur roads to enable mechanized harvesting operations and development of a management plan that considers stand properties such as the amount of growing stock, tree species and size distribution. However, most recent developments of forest harvesting operations in Japan have been focused on conifer plantations.

Spinelli et al. (2017) reviewed trends and perspectives in coppice harvesting in European countries. Spinelli et al. (2010) also reported a small-scale cable yarding method that is often applied to coppice harvesting. Tolosana et al. (2018) analyzed mechanized whole-tree harvesting operations in Spanish coppice stands. Läspä and Nurmi (2018) and Dembure et al. (2019) studied thinning operations for bio-energy wood and fast-growing pine for timber, respectively. Although these studies were focused on lower value timber, more recently Abbas et al. (2019) have summarized forest operation costs and supply of higher value hardwoods in the United States.

In Japan, there have been many studies of mechanized thinning operations for conifer plantation stands (e.g. Iwaoka et al. 1999, Suzuki 2000, Oka et al. 2006, Nakagawa et al. 2007, Suzuki et al. 2010, 2016b, Setiawan et al. 2013, Mizuniwa et al. 2016, Yamasaki et al. 2018). However, studies of the thinning of broad-leaved, natural stands are rare: Kanzaki et al. (1985, 1986) provides two precious examples in studies using a specially developed cable logging system called a Triangular Running Skyline system (TRS, Suzuki et al. 1996, 1997, Suzuki and Kanzaki 1998). Suzuki et al. (2016) and Fukuda et al. (2019) assessed the economic cost balance of harvesting broad-leaved stands with a cable logging system under feed in tariff (FIT) legislation for woody biomass power generation (Toyama et al. 2017, Suzuki et al. 2017), but the studies dealt with clear cut felling as opposed to thinning.

Natural regeneration of conifer species is in most cases difficult in Japan, because of abundant rainfall and temperate climate, which support competing vegetation such as weeds and coppice species. In contrast, natural regeneration of broad-leaved species is easy.

This study assesses management costs of a broad-leaved stand including spur road construction and thinning operations as well as income from harvested timber. First, the stock of abandoned broad-leaved

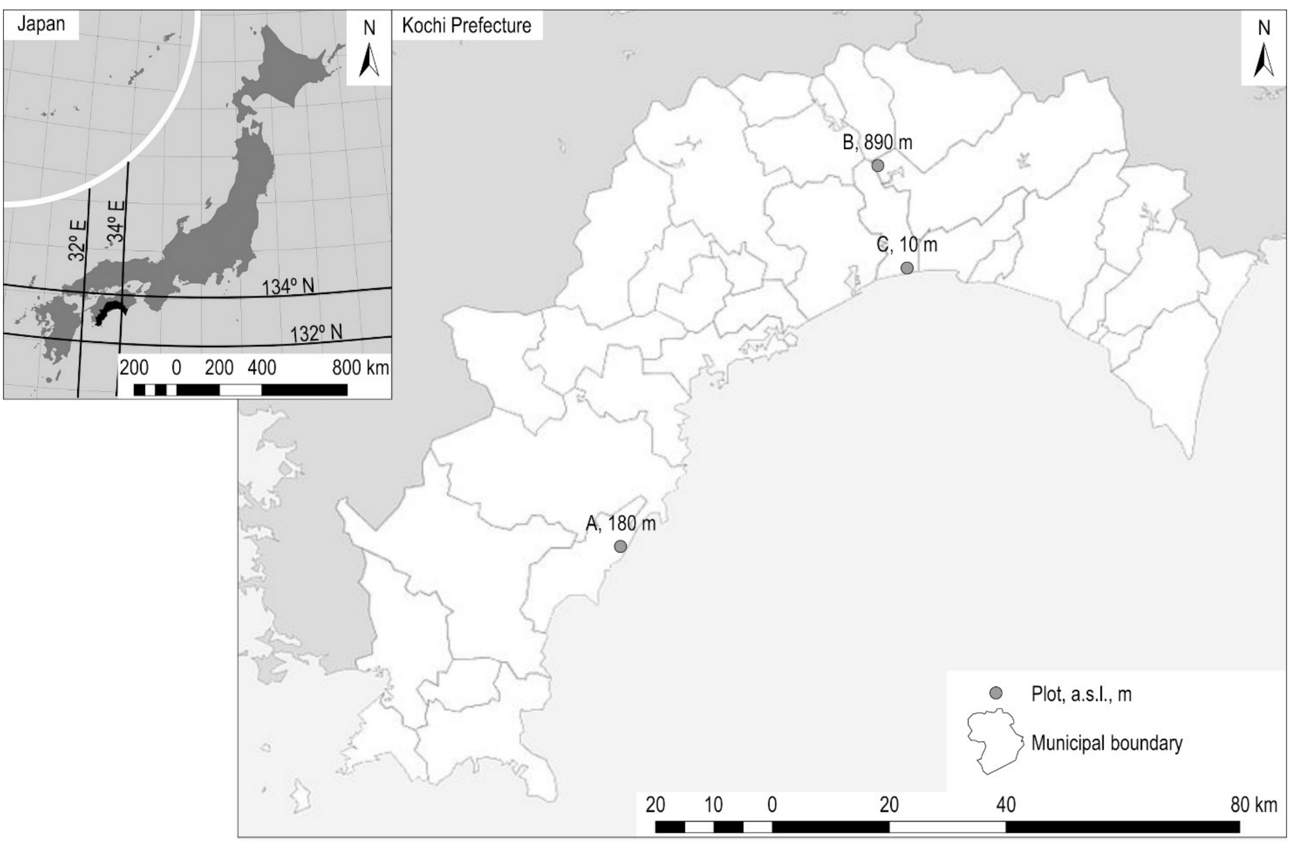

Fig. 1 Location of study plots

stands were calculated from a plot survey. Although stocks of coniferous plantation stands are precisely accounted through official forest registry data, similar data for broad-leaved natural stands do not exist and can only be estimated. The official forest registry data for broad-leaved natural stands are expressed in rough figures such as 100 or 150 m^3 ha^{-1} (Suzuki et al. 2016a, Fukuda et al. 2019), probably because the municipality did not perform a stock survey. The potential income is then estimated for each tree species and diameter class by reference to the thinning and timber selling records of Tsubuku (2008, 2017). Harvesting methods and costs are assumed from our previous study (Suzuki and Yoshimura 2019). Finally, the cost balance of broad-leaved stand management over a rotation period is evaluated using both Net Present Value (NPV) and Internal Rate of Return (IRR) approaches. The resulting balance is compared with that of a typical plantation stand of Japanese cedar (*Cryptomeria japonica*) and of a fast-growing plantation stand of Chinese fir (*Cunninghamia lanceolata*). Japanese cedar is one of the most popular coniferous plantation species in Japan. Chinese fir is considered as a fast-growing species that can potentially substitute more traditional plantation species in Japan, for which the collection of silvicultural knowledge has been the focus of recent research (Forest Tree Breeding Center 2018).

2. Materials and Methods

2.1 Study Sites

Three plots of broad-leaved natural stands were established in the Kochi Prefecture, one of four prefectures on Shikoku Island, in south western Japan (Fig. 1). All three plots were located in abandoned former coppice stands. The first plot, A, was located in Sugaru, Kuroshio Town, in an area that was clear felled between summer and winter 2014 (Suzuki et al. 2016a). Five sub-plots, 20x20 m each, were located in each of five sub compartments that covered 6.27 ha in total. Prior to harvest, species, height and diameter at breast height (DBH) were measured for all trees having DBH

Table 1 Description of study plots

ID	A	B	C
Name	Sugaru, Kuroshio town	6th Compartment, Kochi University Forest	Nursery area, Field Science Center, Faculty of Agriculture and Marine Science, Kochi University
Property	Abandoned coppice stand, coastal	Former charcoal wood production stand, cool temperate	Patch stand, warm temperate
Location	N 33°6′ 28″ E 133°8′ 29″	N 33°42′ 26″ E 133°36′ 56″	N 33°33′ 2″ E 133°36′ 30″
A.S.L., m	180	890	10
Plot size	20x20 m x 5	10x10 m x 3	18x13 m x 1
Dominant species			
in number	*Castanopsis sieboldii*	*Pieris japonica*	*Quercus glauca*
	Cinnamomum camphora	*Sapium japonicum*	*Castanopsis sieboldii*
	Toxicodendron succedaneum	*Acer sieboldianum*	*Zelkova serrata*
	Quercus acuta	*Clethra barbinervis*	–
	–	*Abies firma**	–
in timber volume	*Castanopsis sieboldii*	*Abies firma**	*Castanopsis sieboldii*
	Quercus acuta	*Quercus acuta*	*Cinnamomum camphora*
	Cinnamomum camphora	*Kalopanax septemlobus*	*Zelkova serrata*
	Toxicodendron succedaneum	*Quercus serrata*	*Quercus glauca*
	Prunus jamasakura	*Carpinus laxiflora*	*Quercus acutissima*
	Quercus acutissima	*Betula grossa*	–
	Eurya japonica	*Acer sieboldianum*	–

* *Abies firma* is a conifer. The *Abies firma* trees in Plot B are naturally regenerated ones

of 2cm or greater. The stands were located close to sea and displayed typical characteristics of coastal, warm temperate stands. The plot was located at an altitude of 180 m (Table 1).

The second plot, B, was established in the 6th Compartment of the Kochi University Forest, located in a mountainous part of the Kami City region. Three sub-plots, 10x10 m each, were located in the 5.10 ha Sub-compartment I, at distances more than 50 m apart from each other. Species identification and DBH were recorded for all trees larger than 4 cm DBH in September 2018. Tree heights were measured by sampling approximately 10% of all trees in the plot. The heights of the remaining trees was estimated using a regression formula obtained from the measured DBH. The plot was located 890 m above sea level (a.s.l.), and was characteristic of cool temperate stands and contained some naturally seeded *Abies firma* trees.

The third plot, C, was established in a 1.09 ha nursery area at the Field Science Center, Faculty of Agriculture and Marine Science, Kochi University, which contained several stand patches. One of these patches was selected as the plot, covering an area of 13x18 m. Measurements were the same as for Plot B, but for all trees with a DBH greater than 2 cm. The University campus is located near the sea within the Nankoku City region, at an altitude of 10 m. The stand was characteristic of warm temperate conditions.

Plots A and B have slope of 20–30 degrees, while Plot C is almost flat. Spur road construction cost will be up to 3000 JPY m^{-1} even on slopes of Plots A and B (Yamasaki et al. 2018).

2.2 Calculation of Stock and Estimation of Potential Income and Harvesting Costs

2.2.1 Calculation of Stock

Stem volume was obtained using a table provided for broad-leaved trees in the Shikoku area (Forestry Agency Planning Division 1970) derived using tree DBH and height. The lower threshold of the measured DBHs was different among the three plots, i.e. ranging between 2–4 cm. Therefore, trees were classified for DBH larger than 5 cm at 5 cm intervals.

2.2.2 Estimation of Potential Income

Tsubuku (2008, 2017) found that broad-leaved trees could be economically used as timber for beams, pillars, and boards when their DBH was greater than 20 cm and with a market price of 6000 to 20 000 JPY (Japanese yen, €=124 JPY on April 29, 2019) m^{-3}, depending on species and timber quality. Tsubuku (2008, 2017) also showed that the trees with a DBH of 40 cm or larger could be sold as special use timber, attracting market values of up to 90 000 JPY m^{-3}. In our study, market values of trees with DBH of 20–39 cm and 40 cm or larger were assumed to be 9000 and 30 000 JPY m^{-3}, respectively. Trees with DBH of 15–19 cm were assumed to be sold as firewood with a value of 6500 JPY m^{-3}, taking into consideration water content and using a conversion factor from weight to volume (Tsubuku 2008, 2017, Suzuki et al. 2012, 2013). Smaller trees with DBH of 14 cm or less were assumed to be sold for wood chip with a value of 3000 JPY m^{-3} (Tsubuku 2008, 2017, Suzuki et al. 2016a, Yamasaki et al. 2018, Suzuki and Nagai 2018). Alternatively, there is an option to sell woody biomass to power generation plants. When a stand is certified as properly managed stand under the FIT legislation, all biomass could be shipped as »unused timber«, attracting a price of around 10 000 JPY m^{-3} (the precise price is 9984 JPY m^{-3}, which was converted from 7680 JPY t^{-1} with an official conversion factor for broad-leaved species of 1.3 t m^{-3}, Fukuda et al. 2019).

2.2.3 Estimation of Harvesting Costs

In our recent study (Suzuki and Yoshimura 2019), the costs of harvesting methods for thinning broad-leaved stands were examined, comparing small-scale machines with the construction of narrower spur roads and mid-scale machines with the need for wider spur roads, finding that the smaller scale system is economically favourable. In that system, the spur road width is 2.5 m with trees felled motor-manually (Nakahata et al. 2014). For extraction distances of less than 25 m, a processor with a 0.25 m^3 bucket capacity directly extracts, processes and bucks the cut trees (Suzuki et al. 2010, Setiawan et al. 2013, Suzuki et al. 2015). For extraction distances of 25–50 m, a winch-mounted mini forwarder and a grapple machine of 0.20 m^3 bucket capacity size perform winching and bucking, respectively, with a 2 person-crew; extracted trees are then processed motor manually (Taniyama 2004, Suzuki et al. 2015). Hourly costs for workers and machines (Miyata 1980, National Forestry Extension Association in Japan 2001) and the configuration of the systems are listed in Tables 2 and 3, respectively. The harvesting costs of grappling and winching, including felling, are calculated as 2768 and 4740 JPY m^{-3}, respectively. However, these costs were based on thinning operations in conifer plantations with slope inclinations of 20–30 degrees. Labelle et al. (2016, 2017) reported that the harvesting productivity of broad-leaved trees or non-straight conifer trees is approximately 15% lower than for conifer trees with straight stems. Therefore, the costs of broad-leaved tree harvesting would be 1.15 times that of the originally estimated cost listed

Table 2 List of hourly costs

Item	Hourly cost JPYxhour-1	Source
Operator	2725	Setiawan et al. (2013)
Chainsaw	346	Setiawan et al. (2013)
Mini-forwarder	2060	Suzuki et al. (2015)
Grapple, 0.20 m^3	1898	Setiawan et al. (2013)
Processor, 0.25 m^3	4875	Setiawan et al. (2013)

Note: The standard bucket capacities, i.e., 0.20 and 0.25 m^3, indicate corresponding sizes of excavator-based machines

Table 3 Logging system configurations

Method	Grappling	Winching
Logging distance, m	0–24	25–50
Number of crew, N	1	2
Chainsaw	–	1
Mini-forwarder	–	1
Grapple, 0.20 m^3	–	1
Processor, 0.25 m^3	1	–
Productivity, m^3 crew-hour^{-1}	3.13	2.22
Hourly cost, JPY crew-hour^{-1}	7600	9754
Resulting cost, JPY m^{-3}	2428	4400
Source and notes	Setiawan et al. (2013) Site F	Taniyama (2004) Suzuki et al. (2015)

Note: Felling operation is conducted by 1 person-crew with a productivity of 9.04 m^3 crew-hour^{-1} (Nakataha et al. 2014). Its hourly cost is 3071 JPY crew-hour^{-1} and its resulting cost is 340 JPY m^{-3}

in Table 3. That is, around 3200 and 5400 JPY m^{-3} for grappling and winching, respectively.

For extraction distance greater than 50 m, a mini-forwarder mounted winch could perform a simple cable system operation (Birundu et al. 2016, 2017). However, the costs would increase considerably, approaching 20 000 JPY m^{-3} (Suzuki and Yoshimura 2019). This method has, therefore, been excluded from consideration in this study. To engineer extraction distances of less than 50 m, the road density should extend to 100 m ha^{-1} with a road arrangement

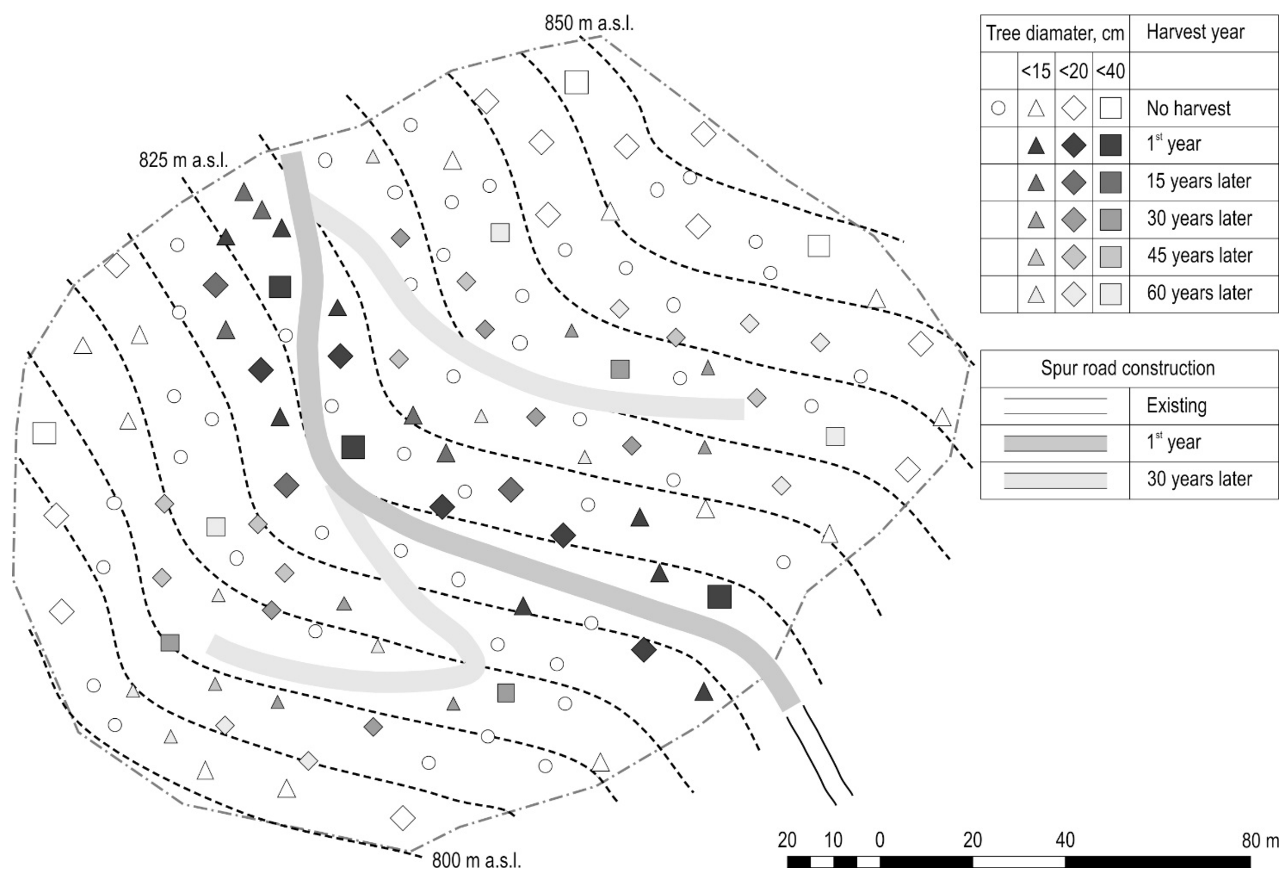

Fig. 2 Conceptual map of a broad-leaved stand with spur road construction plan

factor assumed to be 1 (Sundberg and Silversides 1988, Kanzaki et al. 1990). Similarly, road density should be increased to 200 m ha^{-1} to decrease the extraction distance to no more than 25 m.

2.3 Assumptions and Evaluation of the Management Plan

Assume that there is a broad-leaved stand containing sufficient stock to warrant to be thinned. Although the stand has no spur road network within the area, an existing spur road terminates close to the stand boundary (Fig. 2). In the first year of management, spur roads are constructed so that the road density reaches, for example, 100 m ha^{-1}. The construction cost of spur roads is the primary investment for this first year. A given portion of standing trees can be thinned and extracted using the newly prepared operation systems. At the second opportunity for road construction, 30 years later as shown in the example in Fig. 2, trees standing in previously inaccessible areas will become available for harvesting.

Income is calculated as the selling price of harvested trees minus their harvesting costs. A management plan is made so that appropriate thinning is applied to maximize the quality of the remaining growing stock within the stand. The cost balance of broad-leaved stand management within a given rotation period is then evaluated with both Net Present Value (NPV) and with Internal Rate of Return (IRR). NPV is calculated using the following formula (Okamoto 1994):

$$\mathrm{NPV} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \left\{ \left(P_{\mathrm{i}} - I_{\mathrm{i}} \right) \times \left(1 + r \right)^{-i} \right\} \qquad (1)$$

Where:

i year

n rotation period, year

P_{i} profit at i$^{\mathrm{th}}$ year

I_{i} investment at i$^{\mathrm{th}}$ year

r interest rate.

Interest rates were set to 1, 2, 3, and 4% (i.e. 0.01, 0.02, 0.03, and 0.04). The IRR is defined as such an interest rate that NPV=0; IRR can be determined through iterative numerical calculation. The rotation period n is set to 60 years, to reflect a typical rotation of Japanese cedar (Aruga et al. 2014, Toyama et al. 2017).

The final balance is compared with that of a typical plantation stand of Japanese cedar (*Cryptomeria japonica*) and of a fast-growing plantation stand of Chinese fir (*Cunninghamia lanceolata*). The hypothetical management plan for the Japanese cedar stand was determined from Toyama et al. (2017) and a standard yield class table for Japanese cedar within the Kochi Prefecture (Kochi Prefecture 2012). Chinese fir is a fast-growing species that is thought to be suited to the warm climate in western Japan (Forest Tree Breeding Center 2018). Its growing stock reaches the same volume of 60-year-old Japanese cedar within 30 years (Forest Tree Breeding Center 2018), meaning that two rotations can be accomplished during 60 years.

3. Results and Discussion

3.1 Stock and Estimation of Possible Income

Fig. 3 summarizes the results of the plot survey. The dominant species are listed in Table 1, both in terms of numbers and timber volume. Although the stock level was lowest in Plot A, even there it reached nearly 300 m^3 ha^{-1}, which is two- to three- times the estimated levels given in the official forest registry data (Suzuki et al. 2016a, Fukuda et al. 2019). The Plot B stand was abandoned at least 70 years ago, when it became part of the Kochi University Forest. This explains why Plot B has a larger stock level than Plot A and also contains some larger trees with stem volumes greater than 2 m^3. Plot C has the largest stock levels of all because it is a squared patch stand whose four edges are all open. The numerically dominant species in Plots A, B, and C are *Castanopsis sieboldii*, *Pieris ja-*

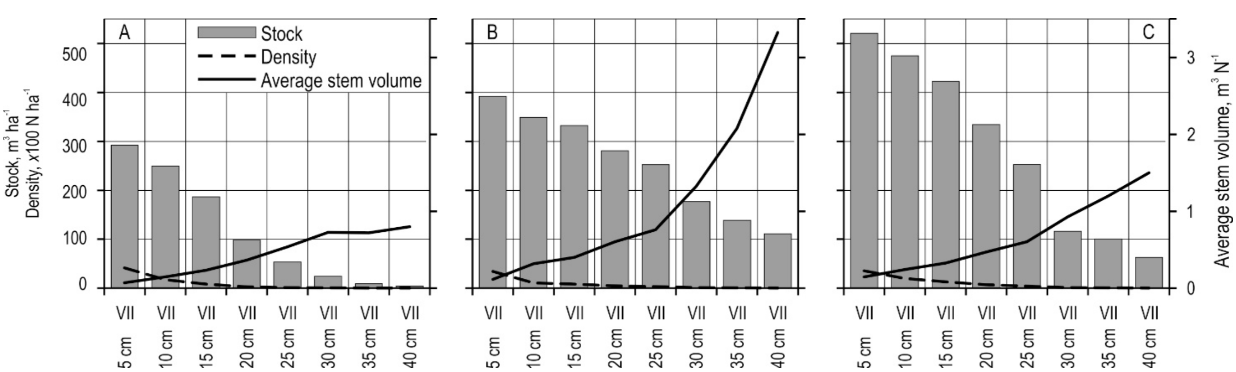

Fig. 3 Stock, density, and average timber volumes of Plots A, B, and C

Table 4 Estimated yield and income

Diameter cm	Usage	Price JPY m^{-3}	Density N ha^{-1}	Stem volume m^3 ha^{-1}	Net stem volume* m^3 ha^{-1}	Income* 1000 JPY ha^{-1}	Unit price* 1000 JPY m^{-3}
–14	Chip	3000	6317	92	55	166	
15–19	Firewood	6500	452	70	42	273	
20–39	Timber	9000	368	190	114	1024	
40–	Special timber	30 000	19	58	35	1036	
Sum/Average				410	246	2499	10.2
15–	Fuelwood (FIT)	9984	839	317	190	1900	
10–		9984	1414	357	214	2136	

Data are averaged for Plots A and B. Usage rate is 0.6. *: Net stem volume, income, and unit price are considered with the usage rate

ponica, and *Quercus glauca*, respectively. Medium sized trees with a DBH range of 15 to 19 cm include those suited for firewood, i.e., *Quercus acuta*, *Quercus glauca*, *Quercus serrata*, etc. Each plot contains a few large trees that potentially have high market values, including for example *Cinnamomum camphora*, *Zelkova serrata* and *Abies firma*.

Table 4 summarizes the potential income of broad-leaved stands as an average of Plots A and B. Plot C was excluded from this calculation because its stock levels could not be directly estimated from comparison to normal stands. The utilization rate was set to 0.6. The modelled income would only be achieved if all trees were cut. Income from both timber (DBH 20–39 cm) and special timber (DBH 40+ cm) accounts for 41% of the total income. The average income from harvested trees was estimated to be 10 200 JPY m^{-3}, which is almost equal to the unit price of fuelwood for large scale power generation, i.e. 9984 JPY m^{-3}.

3.2 Evaluation of Assumed Management Plan

Table 5 is the management plan for a typical plantation of Japanese cedar with a rotation period of 60

Table 5 Management perspective of a typical plantation stand of Japanese cedar (*Cryptomeria japonica*)

Age years	Profit 1000 JPY ha^{-1}	Investment 1000 JPY ha^{-1}	Practice
1	–	520	Site preparation, planting
5	–	330	Weeding
15	–	210	Clearing
25	–	126	Thinning
35	85	–	Commercial thinning
50	233	–	Commercial thinning
60	1812	–	Final cut
Sum	2130	1186	–

Management cost and income are determined from Toyama et al. (2017) and Kochi Prefecture (2012). Income includes harvesting cost

Table 6 Management perspective of a fast-growing plantation stand of Chinese fir (*Cunninghamia lanceolata*)

Age years	Profit 1000 JPY ha^{-1}	Investment 1000 JPY ha^{-1}	Practice
1	–	520	Site preparation, planting
5	–	198	Weeding
10	–	210	Clearing
15	–	126	Thinning
20	85	–	Commercial thinning
25	233	–	Commercial thinning
30	1812	520	Final cut, Site preparation, planting
35	–	198	Weeding
40	–	210	Clearing
45	–	126	Thinning
50	85	–	Commercial thinning
55	233	–	Commercial thinning
60	1812	–	Final cut
Sum	4259	2108	–

Management cost and income are determined from Toyama et al. (2017) Kochi Prefecture (2012), and Forest Tree Breeding Center (2018) Income includes harvesting cost years. Profit from commercial thinning and final cut includes harvesting costs.

The management plan of a fast-growing plantation of Chinese fir is shown in Table 6. Planting and weeding costs are reduced because Chinese fir can regrow from cut stems as in coppicing (Forest Tree Breeding Center 2018). Nonetheless, such costs are included in Table 6 to provide a conservative estimate. Based on the simple assumption that Chinese fir grows twice as fast as Japanese cedar, the total profit and investment, without considering interest rates, is simply twice that of Japanese cedar.

As for the management plan for a broad-leaved stand (Table 7), it is assumed that every 30 years 40% of trees larger than 40 cm DBH are harvested, except for the first year when 100% are harvested (i.e. when the stand is first brought back into active management). For commercial thinning, trees larger than 15cm DBH are thinned at a 40% thinning rate (by volume). Smaller diameter trees are assumed to grow on to larger diameter classes during the cutting interval. Incomes for firewood, timber, and special timber are modelled as 1500, 1000, and 6000 JPY m^{-3} net, including harvesting costs. Spur road construction cost is modelled as 3000 JPY m^{-1} (Yamasaki et al. 2018). The utilization rate is 0.6.

Table 7 Management perspective of a broad-leaved forest including spur road construction

Age years	Profit 1000 JPY ha^{-1}	Investment 1000 JPY ha^{-1}	Practice
1	278	300	Road construction (100 m ha^{-1}) Harvesting extra-large trees commercial thinning
15	71	–	Commercial thinning
30	154	300	Road construction (100 m ha^{-1}) Harvesting extra-large trees commercial thinning
45	71	–	Commercial thinning
60	154	–	Harvesting extra-large trees, commercial thinning
Sum	727	600	–

It is assumed that every 30 years 40% of trees larger than 40 cm in DBH are harvested, except for the 1st year when 100% is harvested. For commercial thinning, trees larger than 15 cm in DBH are thinned with 40% thinning rate in volume. Smaller diameter trees are supposed to grow on to larger diameter class during cutting interval. Incomes for firewood, timber, and special timber are assumed as 1500, 1000, and 6000 JPY m^{-3} including harvesting cost. Spur road construction cost is 3000 JPY m^{-1} (Yamasaki et al. 2018). Utilization rate is 0.6.

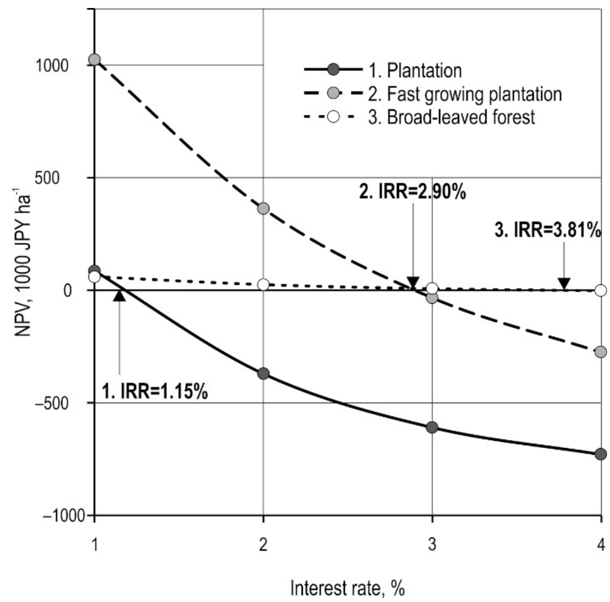

Fig. 4 NPV and IRR of three management scenarios

The estimated NPVs were greatest for the fast-growing plantation stand, then for the typical plantation stand, and lowest for the broad-leaved stand with an interest rate of 1% (1.025, 0.086, and 0.060 million JPY ha^{-1}, respectively, Fig. 4). However, the IRR of the broad-leaved stand was the highest, followed by that of the fast-growing plantation stand, with the typical plantation stand being the lowest (3.81, 2.90, and 1.15%, respectively). This order was the same for NPVs calculated with higher interest rates. This is because the cash flow of the Chinese fir stand management is twice as great as that of Japanese cedar management. However, in these management scenarios, profits are mainly obtained at a late stage of the rotation. The cost balance, therefore, changes to become negative when the interest rates are higher. Although the broad-leaved tree management scenario has the smallest cash flow, profits are obtained at an earlier stage of the rotation, thus yielding the highest IRR.

4. Conclusions

Our plot survey of broad-leaved stands revealed that stock levels are far higher than the estimates by the official forest registry. Although abandoned coppice stands mainly consist of small sized trees, they also typically contain a considerable number of mid-sized trees suited for timber use, as well as several large-sized trees that are occasionally traded as high-quality timber.

Thinning operation can be profitable when spur roads are constructed with sufficient density. Extraction through winching or direct grappling requires a spur road density of 100 to 200 m ha^{-1}. Given the observed diameter distribution and species composition, the average price of harvested trees approaches 10 000 JPY m^{-3}, sufficient to compensate thinning and spur road construction costs.

A projected management cost balance over a 60 year rotation period indicated that a managed broad-leaved stand would have a higher IRR than both a typical coniferous plantation and a fast-growing plantation, although the NPV is positive but lower than that of plantations when interest rates are low.

This study demonstrates a positive perspective for the renewed management of broad-leaved stands. However, the modelled thinning operation costs were estimated from previous research on coniferous plantations. For example, Kuboyama (2018) reported that harvesting costs of broad-leaved species resulted in two- to three-fold of that of conifer species for woody fuel production. Actual operational data needs to be obtained and analysed to provide greater certainty to the results presented here.

Acknowledgments

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