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論　説

Proposing a cost estimate of forest biomass usage as a distribution: An example of harvesting costs

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Abstract

Forest biomass can serve an alternative energy source, and its use could lead to the conservation of forest ecosystems and increase the carbon sequestration potential of forests. These are termed positive externalities in economics, and have prompted considerable interest in the supply potential of forest biomass and the socio-environmental impacts of forest biomass usage. However, almost all the existing studies on the costs of forest biomass usage have analyzed the fixed costs of forest biomass in various locations with substantially divergent results, often rendering the image that the cost of forest biomass is too case-dependent on analysis and analysis could be meaningless. This, in turn, has discouraged accurate calculation of the biomass usage potential of forests.

To fill this knowledge gap, the present study puts forth a novel proposition regarding the meta-analysis of forest biomass usage cost as a distribution, rather than a fixed cost, using a Bayesian meta-analysis. This is illustrated by estimating the cost of harvesting forest wood biomass in Japan. Estimating the cost of forest biomass usage as a distribution can more accurately update the current cost information of forest biomass. It would also be informative for predicting the cost of forest biomass in various locations across Japan, where forest biomass costs have not been analyzed because of lack of data.

要旨

森林バイオマスは代替エネルギー源になり得るとともに、その利用は森林生態系の保全や森林吸収源の増加につながる可能性がある。これらは、経済学では正の外部性と位置付けられ、森林バイオマスの供給ポテンシャル、森林バイオマス利用の社会・環境的影響の分析を促してきた。しかし、ほぼ全ての先行研究は、多様な場所での森林バイオマス利用費用を固定的な費用として推定しているとともに、その推定結果が大きく異なっていることから、森林バイオマス利用費用はケース・バイ・ケースであり、分析に意味がないとのイメージさえ生み出してきた。このことは、森林バイオマスのポテンシャルの正確な推定を阻んできたといえる。

本研究は、森林バイオマスの利用費用を、固定的な費用ではなく、ベイズ・メタ分析により、分布として推定する考え方を提案し、例として日本での森林バイオマスの収集費用を推定する。森林バイオマスの利用費用を分布で分析することにより、現在の費用情報をより正確にアップデートできる。また、データ不足から森林バイオマスの利用費用が分析されていない日本の多様な地域での森林バイオマスの利用費用を予測するためにも、重要な情報になり得る。

1. Importance of estimating the costs of forest biomass utilization as distribution costs

The utilization of forest biomass, such as low-quality logs and residues from cutting and thinning, has positive social and environmental impacts. Forest biomass can serve as a promising alternative energy source, and its use could lead to the conservation of forest ecosystems and strengthen the carbon sequestration potential of forests. In economics, these are referred to as positive externalities, and have generated considerable interest in the capacity of forest biomass utilization (i.e., the supply potential of forest biomass) and its socio-environmental impacts (Buongiorno et al., 2003; Çoban and Eker, 2014; Ince and Buongiorno, 2007; Lauri et al., 2017; Moiseyev et al., 2011; Raunikar et al., 2010; Wit and Faaij, 2010).

Economic analyses of forest residue-based biomass usage have been limited until recently, and most have focused on cost analysis, as many developed countries have faced high costs for forest wood biomass utilization (Accastello et al., 2017; Bjornstad, 2005; Hudson and Hudson, 2000; Joutz, 1992; Nakahata et al., 2019; Yoshioka et al., 2011)[i]. However, the number of recent studies is still scant, and few international studies have briefly analyzed the costs of forest biomass utilization in Japan.

Kamimura et al. (2011) estimated long-term supply curves of forest biomass in Japan. This study estimated the marginal cost of forest biomass as 14,000 JPY/ton, which is the payment received by the supplier of forest biomass without profits. The analyzed supply curves were derived using the unit fixed costs of biomass collection and transportation, and the costs of 12 cases conducted in a feasibility study project in 2007 were referenced. Yamaguchi et al. (2014) also analyzed the total supply costs of forest biomass to estimate the annual supply potential and availability of forest biomass in a Japanese prefecture. They used the unit costs of labor and machines.

These studies from Japan are complex and case-specific because the cost of forest biomass utilization varies depending on the following: area-specific forest topography, forest management practices, investment in machines, e.g., new residue compaction systems (Hudson and Hudson, 2000), the scale of the operation (Nakajima and Sawa, 2011), logistics factors such as whether and how long and wide forest roads are prepared (Sawaguchi, 1996a, 1996b), and the amount of biomass collected and transported. The limitation of previous studies was that they assumed fixed coefficients for the unit harvesting cost and unit transportation cost variables. In fact, the heterogeneity of costs greatly influences the results of realistic analyses of forest biomass potential, and could be the reason for the limited number of studies on supply curve analyses of forest biomass. The distribution of varying costs in the Bayesian framework rather than fixed values could be a step forward.

Matsuoka et al. (2021) and Battuvshin et al. (2020) estimated the medians and ranges of harvesting costs for different forest operation systems, including felling, bunching/winching/yarding, processing, forwarding, and strip road networks. The results of Matsuoka et al. (2021) were consistent with those of Battuvshin et al. (2020). The estimates as ranges of values are more informative than the fixed cost approach; however, studies included costs for strip-road construction, which is a significant improvement, but rendered them rather incomparable to other studies.

The present study aimed to estimate forest biomass utilization in Japan as variable costs rather than fixed costs by estimating harvesting costs using a Bayesian multilevel meta-analysis.

Through a comprehensive search of the database, we collected 51 study points from Japanese journal articles and gray literature, in which researchers or implementers analyzed the supply costs of forest biomass. These studies do not estimate opportunity costs as exact as economic costs; however, meta-analyses using these studies are expected to be informative and possible.

This cost is not an equilibrium point, which is the last unit of marginal cost, where profits are zero but could be lower than the market price (profits are positive) or higher than the market price (profits are negative). However, this study provides an accurate update of forest biomass cost to estimate the supply potential of forest biomass, similar to the study conducted by Kamimura et al. (2011). In addition, the estimation of the cost of forest biomass usage as a distribution would be informative for predicting the cost of forest biomass in various locations across Japan, where forest biomass costs have not been analyzed because of lack of data.

2. Utilization and costs of forest biomass

Japan is a forest-rich country, and thus, forest biomass such as charcoal and firewood have been the major energy sources in the past; currently, there is a renewed interest in using forest biomass for energy usage. Forest biomass is utilized for energy first by harvesting (sometimes including cutting), transporting and chipping, and sometimes making pellets. The cost of utilization of forest biomass is the sum of the costs of these individual processes.

It has been argued that the potential of forest biomass for energy usage is limited in Japan, mainly because of its high cost. However, the cost of forest biomass remains unknown in many areas. For example, there is no peer-reviewed analysis of the cost of forest biomass in the Ehime Prefecture. In addition, in areas where analysis has been conducted, there have been diverse results regarding the costs of forest biomass usage, which have often contented practices with the treatment of costs as unclear and intractable.

3. Definition, material, and methodology

Definition of wood biomass

Based on international literature on the wood economy, forest wood biomass or primary wood products are usually defined as roundwood (e.g., pulplog, sawlog, other industrial roundwood, and fuelwood) and logging residues. Logging residues include branches, stumps, and harvest losses (stemwood that is unsuitable for material use).

Material

A comprehensive search for relevant journal papers published after 2000 and written in both Japanese and English was conducted on Google Scholar, using keywords such as cost, supply, economics, wood, forest, and biomass. A web search on Yahoo and Google was also conducted to find relevant gray literature.

The literature collected in this study is presented in Table 1. There were 51 data points, including 26 from journal papers and 25 from gray literature, from 31 different studies. The average cost of harvesting forest biomass and its standard errors were 5308 JPY/wet ton [ii] and 2955 JPY/wet ton, respectively. Sixteen percent of the data points included transportation costs in the cost estimates and twelve percent utilized the market price for cost estimates. The average amount of biomass was 708 wet tons. Fifty-nine percent of the data points used yarders or forwarders for harvesting. Most of the studies were conducted in the Chugoku (28%) and Chubu (18%) areas on the main island of Japan. The average publication year was 2011. Forty-nine percent of the data points were published in the gray literature. All cost estimates in the studies were fixed-point estimates and no standard error values were reported.

Methodology: a Bayesian multilevel meta-analysis

Many previous studies have estimated the cost of forest wood biomass under different assumptions in terms of location, years of measurement, breakdown of costs, amount of forest biomass collected, and harvesting technologies. Some studies have utilized market prices rather than costs. These population- and between-study (group-level) differences should be reflected in the analysis. Meta-analyses (Hartung et al., 2008) enable formal mathematical combinations of information to merge individual data into a joint result (Röver, 2017).

In meta-analyses, independent primary studies, instead of individual data, form the fundamental units of analysis (Harrer et al., 2021). We used a random-effects pooling model (Cuijpers, 2016) of the meta-analysis by assuming that the population effect size is normally distributed (Schwarzer et al., 2015) and estimated the mean and variance of this distribution of true effect sizes. The random-effects model focuses on small studies when pooling the overall effects in a meta-analysis (Schwarzer et al., 2015).

In particular, this study used a Bayesian multilevel model with standard errors for the meta-analysis (Bürkner, 2018; Harrer et al., 2021; Higgins et al., 2009). In the model, the response cost through the linear combination η of predictors is transformed by the inverse link function f, assuming a certain distribution D ('family') for *Cost*.

$$Cost\ i \sim D\,(f\,(\eta\ i),\ \theta\,)$$

Table 1. Studies analyzed for the Bayesian multilevel meta-analysis

Data point	Study	Cost (JPY/wet ton)	Transportation cost=1	Market price=1	Biomass (wet ton)	Yarder/Forwarder	Area: Hokkaido =1	Area: Chugoku =1	Area: Shikoku =1	Area: Chubu =1	Area: Kyusyu =1	Publish Year	Gray =1
	Mean	5,308	0.157	0.118	708	0.588	0.078	0.275	0.098	0.176	0.059	2011	0.490
	Standard deviation	2,955	0.367	0.325	668	0.497	0.272	0.451	0.300	0.385	0.238	2.575	0.505
	Max	12,000	1	1	2,274	1	1	1	1	1	1	2017	1
	Min	575	0	0	13	0	0	0	0	0	0	2004	0
1	1	4286	0	0	NA	1	0	0	0	0	0	2012	0
2	1	3660	0	0	NA	1	0	0	0	0	0	2012	0
3	1	4286	0	0	NA	1	0	0	0	0	0	2012	0
4	1	2081	0	0	NA	1	0	0	0	0	0	2012	0
5	2	4500	1	1	NA	0	0	1	0	0	0	2017	0
6	2	5000	1	1	NA	0	0	1	0	0	0	2017	0
7	3	5282	1	1	NA	0	0	0	0	0	0	2009	0
8	4	4366	0	0	NA	0	0	0	0	0	0	2009	0
9	5	9495	0	0	NA	0	0	1	0	0	0	2004	0
10	6	1200	1	0	NA	0	0	0	1	0	0	2016	0
11	7	7000	1	1	NA	0	0	0	0	1	0	2017	0
12	8	4255	1	0	NA	0	0	1	0	0	0	2012	0
13	8	10800	0	0	NA	0	0	0	0	1	0	2012	0
14	9	4813	0	0	NA	0	1	0	0	0	0	2008	0
15	9	3052	0	0	NA	0	1	0	0	0	0	2008	0
16	10	2690	0	0	511	1	0	0	0	1	0	2011	0
17	10	3081	0	0	511	1	0	0	0	1	0	2011	0
18	11	1761	0	0	682	1	0	1	0	0	0	2012	0
19	12	2000	0	0	NA	1	0	1	0	0	0	2011	0
20	12	900	0	0	NA	1	0	1	0	0	0	2011	0
21	13	12000	1	0	NA	1	0	0	0	0	0	2009	0
22	14	800	0	0	NA	1	0	0	1	0	0	2015	0
23	15	6667	1	0	426	1	0	0	0	0	0	2016	0
24	16	5925	0	0	NA	1	0	0	0	1	0	2007	0
25	17	4919	0	0	405	1	0	0	0	0	0	2011	1
26	17	4482	0	0	698	1	0	0	0	0	0	2011	1
27	18	4079	0	0	149	1	0	0	1	0	0	2011	1
28	19	575	0	0	1,891	1	0	0	0	1	0	2011	1
29	19	824	0	0	1,874	1	0	0	0	1	0	2011	1
30	20	4895	0	0	1,741	0	0	1	0	0	0	2011	1
31	20	4989	0	0	1,113	1	0	1	0	0	0	2011	1
32	20	4895	0	0	288	1	0	1	0	0	0	2011	1
33	20	5235	0	0	993	0	0	1	0	0	0	2011	1
34	21	8067	0	0	13	1	0	0	0	1	0	2010	1
35	22	8334	0	0	826	1	0	1	0	0	0	2010	1
36	22	6573	0	0	707	1	0	1	0	0	0	2010	1
37	22	2934	0	0	186	1	0	1	0	0	0	2010	1
38	23	4135	0	0	34	1	0	0	0	0	1	2010	1
39	24	7175	0	0	2,192	1	0	0	0	0	0	2010	1
40	24	5493	0	0	2,274	0	0	0	0	0	0	2010	1
41	25	5282	0	0	68	0	0	0	0	1	0	2010	1
42	26	8738	0	0	865	0	0	0	0	0	0	2010	1
43	26	11374	0	0	483	0	0	0	0	0	0	2010	1
44	27	9813	0	0	245	1	0	0	0	0	1	2010	1
45	27	4543	0	0	38	1	0	0	0	0	1	2010	1
46	28	7614	0	0	219	0	1	0	0	0	0	2010	1
47	28	3112	0	0	345	0	1	0	0	0	0	2010	1
48	29	10799	0	0	545	1	0	0	1	0	0	2010	1
49	29	9584	0	0	204	1	0	0	1	0	0	2010	1
50	30	3000	0	1	NA	0	0	0	0	0	0	2015	0
51	31	9347	0	1	NA	0	0	0	0	0	0	2016	0

Where θ is a family specific parameter, which is the standard deviation σ of the normal distribution in our model. The linear predictor is expressed as follows:

$$\eta = X\beta + Zu$$

Where β (fixed effects) and u (random effects) are coefficients at the population and group levels, respectively, and X and Z are the corresponding design matrices. In our model, both X and Z were intercepts (both population- and group-level effects include intercept) [iii]. One of the largest between-study (group-level) differences for intercept was generated by the different measurement units of costs among the studies (JPY/ton or JPY/m^3) and the conversion rates between tons and m^3. We used a conversion rate of 0.85 ton/m^3, which was the average conversion rate of four cases in a feasibility project. The mean and standard error of the costs in the sample were used as priors for the population-level coefficients for the intercept. However, some researchers have argued that a conversion rate as small as 0.35 ton/m^3 should be used (Kamimura et al., 2011), and between-study heterogeneity was adjusted by adding the corresponding error to the standard deviation of the group-level effect of the intercept coefficient. The Bayesian model has several practical advantages over frequentist approaches (Harrer et al. 2021; Röver 2017;). In particular, the Bayesian model produces full posterior distributions for parameters, which calculate the exact probability of whether the parameters are smaller or larger than specified values. The brms package (Bürkner, 2017) was used to fit our model. The brms package implements Bayesian multilevel models in **R** using a probabilistic programming language, Stan.

4. Results

Five thousand iterations and 2500 warmups were set in the Bayesian multilevel meta-analysis. The Rhat values were 1.00 for the standard deviation of both intercepts (group-level and population-level effect) suggest that posteriors converged. The estimate of the population-level intercept was 5360, and the credible interval for intercept was 4343 – 6357, meaning that at 95% probability, the coefficient of intercept was in the range of 4343 – 6357. The standard deviation of the group-level intercept was estimated to be 2218, which was much larger than the estimated error of the population-level intercept, which was 511.

5. Discussion and conclusion

Heterogeneity between studies: the group-level standard error of the cost of harvesting was much larger than the population-level deviation. The reasons for the divergence between studies were unclear; however, more recently published studies had a slight tendency toward lower costs.

The implications of the present study are limited to the long term. For example, harvesting costs could differ in the middle run if discarded forest biomass has been corrected and new biomass can only be harvested after logging. Harvesting costs could also differ in the long run if forest management changes or if new forest roads are constructed. However, this Bayesian meta-analysis could serve as a more accurate basis for future estimations of the forest biomass potential in Japan. In addition, we propose cost estimation as a distribution rather than a fixed cost, which could provide a more accurate manifestation of inherently diverse costs in different areas. Moreover, such an estimation can be used to estimate the cost of forest biomass usage, although no cost estimation has been made because of lack of data.

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Endnotes

i　In Japan, a large amount of artificial forest planted in the 1960's is becoming ready for harvesting, but the operational costs for forest management is high, and sustainable forest management has become a challenge (Yukutake and Yoshimoto, 2001). In this backdrop, forest biomass has not been well utilized and is often left in forests (Kamimura et al., 2011).

ii　Whether wet ton or dry ton were used as a unit was not articulated in most of the studies; however, if there were no expiations, the unit was assumed to be wet ton unless expiations about drying biomass was not mentioned in the studies.

iii　Our meta-analysis included different assumptions as explanatory dummy variables for population-level effects. At first, in X we included the variables "Transport" (cost estimates include transportation cost), "Market" (market prices are used as costs of biomass), "YarderForwarder"(yarder and/or forwarder was used for harvesting), "Hokkaido" (forest biomass was harvested in Hokkaido), "Chugoku" (harvested in Chugoku), "Shikoku" (harvested in Shikoku), "Chubu" (harvested in Chubu), "Kyusyu" (harvested in Kyusyu), "Publish" (published year of journal articles), and "Gray" (published year of gray literature) as well as Intercept. We utilized weakly informative priors for population-level coefficients, which reflected prior information on their signs by setting the locations and scales of normal distribution if signs were expected based on the literature. However, when all the explanatory variables (X and Z) were included in the estimation, all coefficients ranged from negative to positive values, which means they were insignificant. In contrast, when a linear regression model including all the explanatory variables was estimated, Intercept, "Publish," and "Gray" were significant. However, no coefficients of a Bayesian model that included only these three variables were on the same signs in the 95% credible interval, which means that no coefficients were significant at the 95% level, although Intercept and "Publish" were comparatively more significant than "Gray." When a study was published a year later, there was a slight tendency for the harvest cost to be 129 JPY/wet ton lower. Therefore, Intercept (and its group-level deviation) only model was estimated using Bayesian multilevel meta-analysis.