Macroecological processes drive spiritual ecosystem services obtained from giant trees

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Abstract

Giant trees that have come to have their own unique identities are often named by local people and can inspire a sense of awe and become objects of faith. Although these giant trees provide various kinds of spiritual ecosystem services that are beneficial to the spiritual well-being of the human society, the drivers of these services remain unclear. Using structural equation modeling with 38,994 giant tree records of 237 species across Japan, this study showed that macroecological processes, such as annual precipitation and temperature, may drive spiritual ecosystem services obtained from giant trees directly and indirectly via tree properties such as sizes and ages.

Main

Giant trees are the largest and longest living organisms on the planet and play an important ecological role in the natural world[1,2]. Moreover, human societies recognize trees that have become relatively large, and position them for their sociocultural significant roles[1,3,4]. For instance, the Celts, Druids, and many other societies in ancient Europe venerated trees, and oak (*Quercus* spp.) and spruce (*Picea* spp.) trees were of special significance in old Germanic rituals, the source of the tradition of the Christmas tree[4]. These trees have come to have their own unique names, and occasionally, they inspire a sense of awe in people, eventually become objects of faith (i.e., animism)[3,5]. In this manner, giant trees have a spiritual connection with local people and encourage social cohesion among them; therefore, attachments to and identification with giant trees by people facilitate their spiritual well-being[1,7,8]. In other words, giant trees provide various spiritual ecosystem services that are beneficial to the spiritual well-being[8] of human societies worldwide[1,3,6]. However, the natural drivers and processes that influence the provision of spiritual ecosystem services have rarely been studied[9] and the mechanisms behind giant trees and their relationship with human society remain unclear as well.

The size and distribution of organisms are influenced by geography and climate, and a main topic in macroecology is describing patterns and revealing background processes[10]. In this context, giant trees are no exception, and their age, size, and other properties are influenced by geography and climate[11]. In addition, previous studies have suggested that trees with extraordinary properties (e.g., large size and old age) tend to be given unique names[1] and are recognized as sacred[4]. Specifically, researchers have argued that human attachment to such "charismatic" organisms has resulted in many individual large old trees being given unique names such as Centurion, Methuselah, and General Sherman[1]. Matui reviewed previous studies and summarized that some Japanese religions are related to the natural environment (e.g., wind festival, thunder faiths, and mountain faiths) and topography (e.g., rivers, lakes, and marshes)[12], and thus, religion is related to climatic and geographical context. I hypothesized that the sizes and distributions of trees and the provision of spiritual ecosystem services are possibly influenced by macroecological processes (e.g., temperature and precipitation) related to the properties of each tree[1,4]. Therefore, these unknown processes could be revealed from a macroecological perspective using appropriate methodology.

Here, I aimed to test whether spiritual ecosystem services provided by giant trees are driven by macroecological processes on a regional scale depending on the properties of each tree. Moreover, I considered the possibility that geographical and climatic factors directly affect spiritual ecosystem services by changing the relationship between giant trees and human society[12]. To test the hypothesis, I compiled a comprehensive dataset of 38,994 individual giant trees with a trunk circumference ≥ 300 cm across the Japanese archipelago. For the analysis, I selected the probabilities of being an object of faith and receiving a unique name as variables related to spiritual ecosystem services; trunk circumference and tree age as variables related to the properties of giant trees; and annual mean temperature, annual precipitation, elevation, and latitude as variables related to macroecological processes. Specific hypotheses were as follows: 1) larger circumference and older age of a tree tend to increase the probability of it being an object of faith and receiving a unique name (i.e., properties of giant trees influence spiritual ecosystem service)[1,4], 2) lower annual mean temperature and higher annual precipitation facilitate larger trunk circumferences and older tree ages (i.e., macroecological processes influence properties of giant trees)[11], and 3) geographical (i.e., latitude and elevation) and climatic (i.e., annual mean temperature and precipitation) conditions alter the probabilities of a tree being an object of faith and receiving a unique name (i.e., macroecological processes influence spiritual ecosystem services)[12]. The overview of the relationships and the general organization of the model is shown in Extended data Fig. 1. For testing these hypotheses, I used piecewise structural equation modeling (SEM)[13] to analyze links among spiritual ecosystem services obtained from giant trees, individual tree properties, and macroecological processes.

The model outline and statistical analysis results are shown in Fig. 1 and Table 1, respectively. The piecewise SEM analysis showed that macroecological variables directly and indirectly affected spiritual ecosystem services obtained from giant trees through other variables (Global goodness-of-fit: Fisher's $C = 6.608$ and two-sided P-value = 0.579, Table 1). Trunk circumference was influenced positively by tree age and annual precipitation, and negatively by latitude, elevation, and annual mean temperature; tree age was negatively influenced by annual mean temperature, and hypothesis 1 was supported. The probabilities of being an object of faith and receiving a unique name were both positively correlated with both trunk circumference and age of giant tree. Therefore, hypothesis 2 was supported. Additionally, the probability of being an object of faith was positively correlated with latitude and negatively correlated with annual mean temperature and annual precipitation. Furthermore, the probability of getting a unique name was positively correlated with latitude, elevation, and annual mean temperature and negatively correlated with annual precipitation, thereby supporting hypothesis 3. Both trunk circumference and tree age were the top two strongly influential explaining variables for both probabilities of being an object of faith and receiving a unique name (Table 1). A positive correlation between both probabilities of being an object of faith and receiving a unique name was observed (Table 1). Annual mean temperature was negatively influenced by both latitude and elevation, and annual precipitation was influenced negatively by latitude and positively by elevation (Table 1).

This study clearly showed that macroecological processes (i.e., geographical and climatic factors) determined patterns of tree properties, and, consequently, the occurrence probability of spiritual ecosystem services provided. Few studies have been conducted on the driving factors of cultural ecosystem services, which include spiritual services[7], because the processes by which nature supplies these services are unknown. Thus, giant tree size is a simple and ideal property for clarifying these mechanisms. Generally, larger and more long-lived giant trees have stronger relationships with human society and, thus, provide a spiritual ecosystem service. The results of this study are totally consistent with the hypotheses.

The results showed that climatic and geographic factors are related to spiritual ecosystem services. The most prominent relationships were that both the probabilities of being an object of faith and receiving a unique name tended to increase with lower annual precipitation (Table 1). The worship of giant trees in Japan is partly related to "pray for rain" (雨乞い; "Amagoi" in Japanese)[14,15] and some trees even have names related to this. Considering these facts, the piecewise SEM results are strongly consistent with previous empirical findings that suggest the probability of having a unique name or being an object of faith increases when precipitation is low[14,15]. Originally, rice cultivation was the foundation of the traditional Japanese society, and the abundance or failure of the rice crop was a matter of the greatest concern that was directly linked to life and death[15]. Among various climatic factors, drought was the strongest causality of a devastating decline in rice yields. Therefore, future changes in rainfall may alter the provision of spiritual services obtained from giant trees.

Results related to elevation showed different relationships with the two types of variables related to spiritual ecosystem services (Table 1 and Fig. 1). Specifically, the probability of receiving a unique name tends to be higher with a higher elevation, but no significant relationship was observed between the probability of being an object of faith and elevation (Table 1 and Fig. 1). Both shrines and temples, including sacred trees, are generally located close to human residential areas (i.e., villages and village mountains) in Japan, with the exception of mountain worship[12]. This is probably owing to easier accessibility, as a remote place is difficult to visit routinely. Similarly, giant trees are unlikely to be objects of faith in remote areas that are difficult to visit, but this was not clear in the result. Contrarily, if giant trees are visible from far off places, human society will give them unique names as a signpost or symbol without having to visit them daily. Moreover, giant trees should be more visible from a long distance at higher elevations, such as on top of a mountain. Therefore, different relationships can be due to differences in provision of two types of spiritual ecosystem services.

Interestingly, species information as a random effect was not selected in all paths (Table 1). Although these results may seem to contradict the view of some previous studies, in which certain species were recognized as sacred trees[4], they are consistent with the findings of other previous studies that trees with extraordinary properties are more likely to be recognized as sacred[1,4]. These two aspects have rarely been considered in a single framework related to spiritual ecosystem services. Therefore, differences in species in providing spiritual ecosystem services are due to size differences as shown by the result of this study (Table 1). However, further studies are required to reveal the importance of species differences with regard to factors other than size and longevity.

This study of giant trees in the Japanese archipelago is the first to clearly demonstrate the relationship between spiritual ecosystem services and underlying macroecological processes, which have been difficult to evaluate quantitatively. Although comprehensively assessing spiritual and religious values across regions and countries is difficult[16], future research on the drivers of non-material ecosystem services, including spiritual services, worldwide is necessary to accumulate knowledge on their similarities and differences and to prevent loss of spiritual ecosystem services, the roles of which in human society are unknown. In addition, although spiritual ecosystem services have been reported worldwide[6,8], their cultural and psychological context are different among regions, countries, and continents[17]. Thus, the cultural and psychological context of each human society will impact the directions, quantities, and qualities of spiritual ecosystem services even if the ecosystem services originate from same natural phenomena as they are based on the relationships between nature and human perception. Therefore, comprehensive approaches including ecological, cultural, and psychological aspects are required to understand spiritual ecosystem services in one framework globally.

Methods

Definition of spiritual ecosystem services

Spiritual ecosystem services belong to the category of cultural ecosystem services[6]. Previous studies have pointed out the fuzzy definition of spiritual ecosystem services as a critical problem[6,16]. In the present study, I define spiritual ecosystem services as ecosystem services that are beneficial to the spiritual well-being of human beings as stated by Irvine et al[8]. Furthermore, they summarized features of spiritual well-being for four relational domains of self, others, environment, and transcendent other(s) to interpret identified literature in terms of the relationships between biodiversity and spiritual well-being[8]. Obviously, provision of spiritual ecosystem services from giant trees can have various routes and it is difficult to identify one or two categories. Some parts of the provision processes of spiritual ecosystem services by giant trees can be recognized as place-based processes[8,18], in which attachment to and place identity are known as measures of spiritual well-being[8]. The relationship between human attachments to giant trees and the trees receiving unique names has been suggested[1]. In addition, the religious part of the provision processes of spiritual ecosystem services by giant trees can foster connections with nature and feelings of transcendence, linking them implicitly to spiritual well-being[8]. Therefore, in the present study, I considered the probabilities of being an object of faith and receiving a unique name as variables related to spiritual ecosystem services.

Data preparation

Animism was a primitive religion in ancient Japan, and sacred trees are frequently found at both shrines and temples and also remote places such as steep mountains in contemporary Japan[5]. Since the fourth National Survey of the Natural Environment in Japan (1988–1991), the Ministry of Environment conducted a survey of giant trees and forests across the Japanese archipelago, which is a long chain of continental islands located off the eastern coast of Asia and recognized as a biodiversity hotspot[19]. Therefore, the data I used for analysis was based on this survey (giant trees database, '巨樹・巨木林データベース' in Japanese; https://kyoju.biodic.go.jp/). A single-trunk tree was considered giant when its trunk circumference exceeded 300 cm[14,20]. If a tree had multiple trunks originating from the same root system, individual trunk circumferences were measured and combined, and the tree was considered giant when the total circumference exceeded 300 cm. In the original dataset, the location of each giant tree was identified by its address in Japan. Based on these addresses, I geocoded the location of each giant tree using the Google Maps Geocoding API (https://developers.google.com/maps/documentation/geocoding). However, records with only prefectural information were excluded from the main analysis because the resolution was insufficient. Based on both latitude and longitude, the elevation of each location was determined by the Google Maps Elevation API (https://developers.google.com/maps/documentation/elevation/overview). For climatic variables, I used annual mean temperature and precipitation at the 1-km grid scale from Mesh Climate Data 2010 (Japan Meteorological Agency, http://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-G02.html). The 1-km grids have 30-s latitude and 45-s longitude grid cells (the Japanese Standard Third Mesh). The package "jpmesh" (version 2.1.0)[21] was used in R software to convert the location of each giant tree to an identity number of the Japanese Standard Third Mesh. I linked the location of each giant tree with climatic variables using the mesh identity number.

Data filtering

Based on information in the giant trees database, I summarized presence/absence of both faith and unique name for each tree, because the original dataset included more detailed information for some individuals (e.g., presence/absence of ritual and taboo). The records targeting only individual giant trees were selected; thus, those targeting a row of trees or a forest area were not considered. The range of trunk circumferences was 300–3,000 cm. Tree ages were approximated based on local and traditional knowledge on giant trees, and they were categorized into four ranks: 1) ≤ 99 years, 2) > 100 and ≤ 199 years, 3) > 200 and ≤ 299 years, and 4) > 300 years, as reported by the observed person of the records in the giant trees database[14]. The original records use the Japanese name for each tree; therefore, I converted the Japanese names to scientific names using a checklist of Japanese plant names[22] and linked them with a plant family. Unmatched individuals at the species level were removed prior to statistical analysis. For individuals with overlapping data, complementary data were combined into one species, while duplicate data about presence/absence mismatches were assumed to be present, and newer data were prioritized. In addition, missing data (NA values) were deleted list-wise. Finally, the dataset, containing 38,994 complete records of individual giant trees, comprising 237 species, was compiled and used for the following statistical analysis.

Piecewise SEM statistical analysis

To explore direct and indirect relationships among spiritual ecosystem services obtained from giant trees and macroecological processes, I performed the analysis using the "piecewiseSEM" package (version 2.1.2) in R[13]. The SEMs included probabilities of being an object of faith and receiving a unique name as variables related to spiritual ecosystem services, trunk circumference and tree age as variables related to properties of giant trees, and annual mean temperature, annual precipitation, elevation, and latitude as macroecological variables. First, I constructed a model that included all hypothesized paths between macroecological processes, properties of giant trees, and spiritual ecosystem services (Extended data Fig. 1). The model was continuously updated by removing and adding potential paths until both of the following criteria were satisfied: 1) no significant relationship in Shipley's test of directed separation, and 2) no non-significant paths in the model. After finishing the updates, I compared models with and without the plant species information of each giant tree as a random effect for the response variables (i.e., trunk circumference, tree age, faith, and unique name) using Akaike's Information Criterion. As a result, only paths with trunk circumference as explanatory variable were included with the plant species as a random effect. After determining the best model, I conducted a goodness-of-fit evaluation for piecewise SEM based on Fisher's C and chi-square tests ($P > 0.05$). The final model satisfied the criteria for adequate model fit with Fisher's C = 6.608 and P = 0.579 (Table 1). The result is consistent in the case of changing the taxonomic resolution from species to family because the model without random effects was finally selected.

Data availability: Giant tree data were downloaded from the giant trees database in Japanese (https://kyoju.biodic.go.jp/) on November 19, 2022. Climate data were downloaded from Mesh Climate Data 2010 (Japan Meteorological Agency, http://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-G02.html). The compiled dataset will be available in Figshare after acceptance of the manuscript.

Code availability: The code for the piecewise structural equation modeling (SEM) statistical analysis will be available in figshare after acceptance of the manuscript.

Author contributions statement

R.N. conceived the study, analyzed the empirical data, and wrote the manuscript.

Acknowledgments

I thank Dr. Yo Nakawake for suggestions on literature related to cultural studies. RN was supported by the Japan Society for the Promotion of Science (22K15188) and the National Institute for Environmental Studies, Japan.

Competing interests statement

The author declares no conflict of interest.

Table 1. Global goodness-of-fit of the final model is an overview of piecewise structural equation modeling (SEM)[13] results with Fisher's $C = 6.608$ and two-sided P-value = 0.579 on eight degrees of freedom, satisfying the criteria of adequate fit. Abbreviations: LAT, latitude; ELV, elevation; AMT, annual mean temperature; AP, annual precipitation; TC, trunk circumference; AGE, tree ages; FAI, probability of being an object of faith; NAM, probability of receiving a unique name.

Response	**Explanatory variable**	**Standardized coefficient (*r*)**	**Coefficient**	**Degrees of freedom**	**two-sided *P*-value**
Causal effect					
AMT	LAT	–0.7327	–0.8528	38991	<0.0001
AMT	ELE	–0.6532	–0.0060	38991	<0.0001
AP	LAT	–0.3881	–89.9245	38991	<0.0001
AP	ELV	0.1879	0.3441	38991	<0.0001
TC	LAT	–0.1183	–7.9795	38988	<0.0001
TC	ELV	–0.0660	–0.0352	38988	<0.0001
TC	AMT	–0.0975	–5.6519	38988	<0.0001
TC	AP	0.0485	0.0141	38988	<0.0001
TC	AGE	0.2509	47.4205	38988	<0.0001
AGE*	AMT	–	–0.0124	38992	<0.0001
FAI	LAT	–0.0760	–0.0622	38988	<0.0001
FAI	TC	0.1474	0.0018	38988	<0.0001
FAI	AGE	0.2202	0.5045	38988	<0.0001
FAI	AMT	–0.0304	–0.0214	38988	0.0007
FAI	AP	–0.0301	–0.0001	38988	<0.0001

NAM	LAT	0.1879	0.1693	38987	<0.0001
NAM	ELE	0.1746	0.0012	38987	<0.0001
NAM	TC	0.3481	0.0046	38987	<0.0001
NAM	AGE	0.2273	0.5737	38987	<0.0001
NAM	AMT	0.1284	0.0994	38987	<0.0001
NAM	AP	–0.1100	–0.0004	38987	<0.0001
Covariance					
FAI	NAM	0.0832	0.0832	38994	<0.0001
AMT	AP	–0.1354	–0.1354	38994	<0.0001

*The standardized coefficient could not be calculated due to analytical limitation.

Figure legend

Figure 1. Relationship diagram of piecewise structural equation modeling (SEM) explaining links among macroecological processes, giant trees, and spiritual ecosystem services. Green and red arrows indicate significant positive and negative correlations, respectively. Path thickness indicates the strength (absolute value) of the standardized coefficients at three levels: ≤ 0.3, > 0.3, and > 0.6. Abbreviations: LAT, latitude; ELV, elevation; AMT, annual mean temperature; AP, annual precipitation; TC, trunk circumference; AGE, tree age; FAI, probability of being an object of faith; NAM, probability of receiving a unique name. The path between annual mean temperature and tree age is shown as a dashed line because the standardized coefficient could not be calculated due to analytical limitation.

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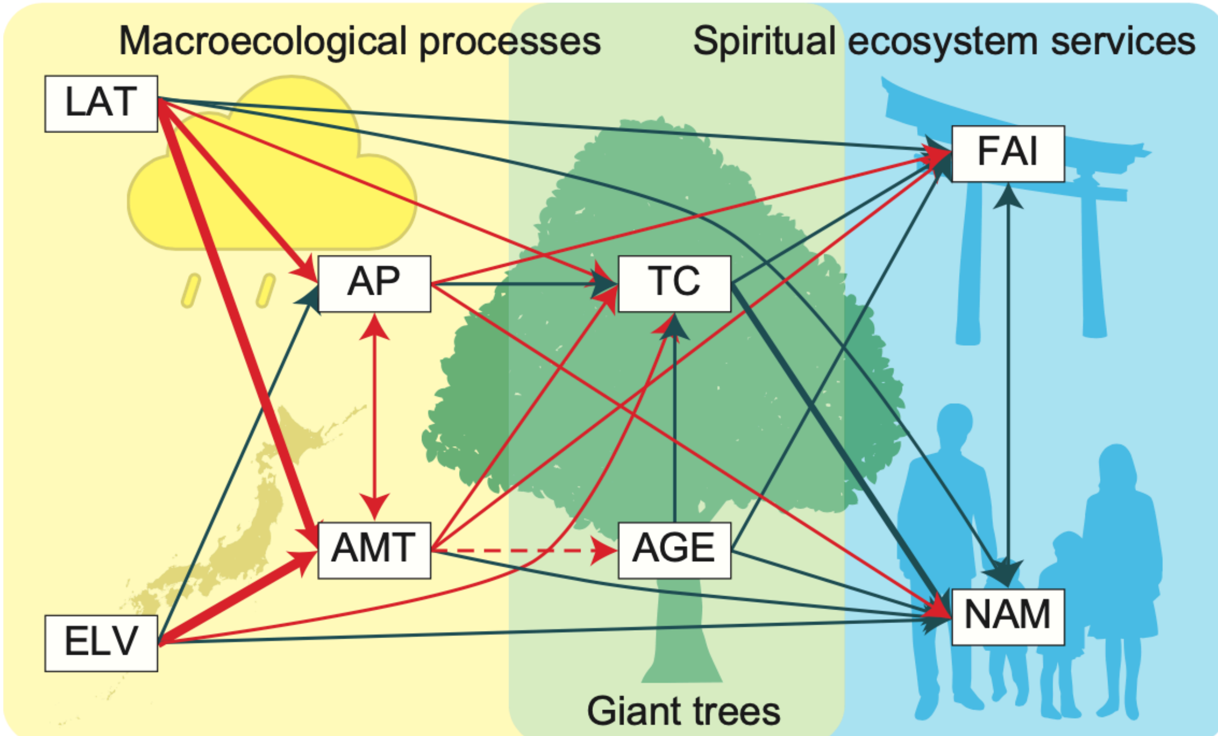
Figure 1


Macroecological processes
Spiritual ecosystem services
LAT
FAI
AP
TC
AMT
AGE
ELV
NAM
Giant trees

Extended data Figure 1. Initial model structure for piecewise SEM analysis.