Article

Spatial Estimation of Sika Deer Population Density Distribution

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ABSTRACT

We estimated the spatial distribution of the sika deer (*Cervus nippon*) population density in areas around Mt. Hiko in Fukuoka Prefecture, Japan. The data comprised pellet counts in 86 plots from February to April 1999 and from November 1999 to March 2000. Taking this to correspond to the population density in the plots, the sika deer population density was mapped using a kriging interpolator. Five semivariograms were examined in a geographic information system (GIS): spherical, circular, exponential, Gaussian, and linear with sill models. We used the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) to select the appropriate semivariogram model. The spherical model produced the smallest values in both the AIC and BIC. The ordinary kriging interpolator with the spherical model provided the deer population density at intervals of 50m. Four distinct high-density areas, in which the deer density exceeded 30/km², were found around Mt. Kosho and Mt. Hiko. Using independent data for the damage caused by deer and the map of the sika deer density, we estimated the deer densities in all plots where the damage by deer had been checked, and determined the relation between population density and the degree of browsing damage, which is most serious in Fukuoka Prefecture. As the sika deer population density increases, the proportion of damaged plots increases. Of plots with the density exceeding 40 deer/km², browsing damage occurred in 83%. This method provides insight into the density of deer over a broad region and, in combination with the information about deer damage, can be applied to give the probability of deer damage.

Keywords: browsing damage, distribution map, population density, sika deer (*Cervus nippon*)

INTRODUCTION

Damage to planted forests by wildlife has become a serious problem in Japan. Damage by Sika deer alone has accounted for 50% of the damage to forests in the last 10 years (Forest Agency of Japan, 2003). Sika deer cause damage by browsing, stripping bark, and fraying trees with their antlers. The resulting damage has been considerable in the Kyushu, Kanto, and Chugoku districts of Japan since the late 1980s (MIURA, 1999).

To address the problem of sika deer damage in plantation

forests, the Government of Japan amended the Wildlife Protection and Hunting Law in 1999. A new planning system, the Specified Wildlife Conservation and Management Plan, aims to sustain long-term stable wildlife populations and to promote co-existence between humans and wildlife (KAMIKAWA, 1999; Wildlife Management Workshop of Japan, 2001).

Although browsing damage by sika deer to planted seedlings has been reported in various regions of Japan (LI *et al.*, 1996; Japan Wildlife Research Center, 1998; TOKIDA, 1998; UHEYAMA, 1998; OI *et al.*, 2001; MURAKAMI *et al.*, 2004), few reports have examined the relation between the sika deer density and the extent of the degree of damage. The obvious way to study the relationship is to measure the sika deer density and degree of damage in the same plots. But there is a problem. In Japan, especially western Japan, the pellet-count method is widely used to estimate the sika deer population density. This method assumes that all pellets are decomposed mainly by dung beetles. However, ENDO (2001) found that fecal pellets on bare fields disappeared abruptly in all seasons due to rainfall. Estimates on bare fields may therefore underestimate the true density. IKEDA (2005) also stated that bare fields and young plantations are unsuitable for sika deer

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population surveys. Estimation of the density in an open environment from the density in neighboring forested habitats is not a resolved.

To tackle this issue, we applied an interpolation method of the Geographical Information System (GIS) to our data to map the sika deer population density. We then estimated the deer density distribution on young plantations and analyzed the relation between the density and browsing damage.

MATERIALS AND METHODS

Study Area

The study areas include recognized sika deer habitats surrounding Mt. Hiko in Fukuoka Prefecture, Japan (Fig. 1).

The area was approximately 1130.3km². The deer range was determined from a questionnaire conducted in 1995 by the government of Fukuoka Prefecture, which hunters were asked about hunting places and signs of sika deer, such as footprints (IKEDA, 2001).

The area ranges in elevation from 0-1200m above sea level. The boundary between Fukuoka Prefecture and Oita Prefecture is the Hiko Mountains, a cordillera centered on Mt. Hiko. In winter, the peak of Mt. Hiko is often covered by snow to a depth of more than 50cm. Below 750m the vegetation is evergreen broad-leaved forest; above 750m there is a zone of deciduous broad-leaved forest.

Fig. 2 shows the vegetation in the study area. The data derive from the 5th National Survey of the Nature Conservation Bureau (1999), running from 1994 to 1998.

Fig. 1 Study area around Mt. Hiko in Fukuoka Prefecture, Japan. (A) Solid lines show the borders between Japanese prefectures (Kyushu district is the gray zone.) (B) Kyushu district. Solid lines show the borders between prefectures. The study area is the gray zone. (C) Fukuoka Prefecture. Solid lines show the borders between prefectures, and the study area is indicated by the gray zone.

Table 1 Overview of the sika deer population density survey and the damage survey

	Sika deer population density survey	Damage survey
Survey year	from fiscal 1998 to 1999	from fiscal 1997 to 1999
Number of survey plots	86 plots	1144 plots (1142 plots were available*)
Method establishing of survey plot	set up randomly in the third area mesh (about 1 kilometer square)	planted forest up to 5 years after planting
Inquirer	Researcher	prefectural official or forest owners' cooperative staff

* 2 plots were out of the study area.

Plantations of Sugi (*Cryptomeria japonica* D. Don) and Hinoki (*Chamaecyparis obtuse* Endl.) occupy 53.3% of the forest. Pine (*Pinus densiflora* Siebold et Zucc. or *Pinus thunbergii* Parl.) covered 6.7%. Broad-leaved forest and grassland, including orchard, bamboo forest, covered 11.2%. Urban land was taken to include residential neighborhoods, playgrounds, industrial areas, dry fields and rice paddies, and comprised 28.7%. The area of cut-over land was 0.01%.

Estimation of Sika Deer Population Density

The sika deer population density was surveyed according

to pellet-count, from February to April 1999 and from November 1999 to March 2000. The survey plots were chosen randomly in Basic Grid Squares, according to Announcement No.143 of the Administrative Management Agency of Japan on July, 12, 1973. The survey plot was located at least one plot on each municipality in this study area (IKEDA 2001). Based on the Basic Grid Squares, 86 plots around Mt. Hiko were selected for the deer population survey, as outlined in Table 1. Fig. 3 shows the sika deer survey plots.

In forest in Kyushu district, evergreen trees grow naturally and visibility is poor. It is impractical to count the number of sika deer among mixed evergreen trees. A pellet-

Fig. 3 Distribution of sika deer population density survey plots. Black circles show sika deer population density survey plots. The subdivided area bounded by the heavy line indicates the study area. The fine grid inside the study area indicates Basic Grid Squares (Third Area Partition). Parallel thin lines outside the study area show the Secondary Area Partition. Boundaries between municipalities are also shown.

count method was therefore used to estimate the sika deer population density.

In the pellet count method used in this study, three surveyors were allocated at intervals of 10 meters in the survey plot. The surveyors placed 1m-square-shaped frames at 10-meter intervals, and counted the number of sika deer pellets retaining their original shapes in the frame after taking out the litter layer. They moved linearly, and counted the number of pellets in a 1m-square-shaped frame every 10 meters. NISHISHITA (1999) recommended that the survey area should exceed 110m², to reduce errors in pellet counts to small levels. The number of 1m-square areas at a survey plot therefore exceeded 110.

The density was calculated using the formula derived by IWAMOTO *et al.* (2000):

$$N = \frac{f}{\beta \left(\sum_{t=1}^T h_t e^{-\sum_{i=1}^t c_i} \right)}$$

where:

N is sika deer population density (deer / km²)
 f is number of pellets found in the survey

β is rate at which pellets were found

T is backdating period (month)

h_t is number of pellets defecated by one deer t months ago

c_i is disappearance rate of pellets deposited t months ago and exposed over i months

IWAMOTO *et al.* (2000) state that the disappearance rate (c_i) can be calculated from the atmospheric temperature in a plot when the rate was not measured directly. Backdating period of T was 100 months (IWAMOTO *et al.*, 2000). The temperature of the survey plot was estimated using an adjustment value of -0.6°C per 100 m of vertical elevation from the temperature recorded at the nearest meteorological station.

Sika Deer Damage Survey

The deer damage survey in Fukuoka Prefecture was conducted in private forests from 1997 to 1999, focusing on the area around Mt. Hiko. The survey was conducted during weeding operations (involving plantation stands up to 5 years old); and it recorded data such as plant species, years after planting, type of damage, proportion of damaged

Fig. 4 Sika deer damage survey plots (black squares). The area framed by the heavy line indicates the study area. The large grid shows the Secondary Area Partition. Boundaries between municipalities are also shown.

trees, damage intensity on each plantation tree, and the presence/absence of damage prevention measures (*e.g.* fences and repellents). Table 1 gives an overview of the deer damage survey. The damage survey plots are shown in Fig. 4.

Method of Estimation of the Sika Deer Population Density

YABE *et al.* (2001) estimated that the home range of a single sika deer in the central mountains of Kyushu Island varied between 34-201 ha, which is less than elsewhere in Japan (YABE, 1995; OCHIAI *et al.*, 1996; TADO *et al.*, 1997; MAEJI *et al.*, 2000). ENDO *et al.* (1996) stated that mean home range sizes ranged from 3.0 to 3.6 ha on Nozaki Island in the Goto Archipelago, Nagasaki Prefecture. Based on the study on Nozaki Island, the home range in southern Japan might be smaller than in other districts of Japan, although this result might be due to the spatial restriction on the island and the high productivity of *Zoysia*-type grasslands (SHIGEMATSU *et al.*, 1994). This small home range indicates that the deer in this region are sedentary and their density structure is relatively stable, as seen in the population in Miyazaki Prefecture (Japan Wildlife Research Center, 1998).

Since the population density survey plots were discrete,

we applied the ordinary kriging interpolator to our database of population density survey locations and population densities (WACKERNAGEL, 1995; MASE *et al.*, 2001). This method was used to interpolate data from discrete survey plots into a map of the whole habitat. The kriging interpolator uses parameter estimation based on the semivariogram model. The semivariogram is a statistic used to understand the relation between distance and the variance of the distance for the data.

The interpolation interval was 50m, which represents the approximate edge distance of a well-rounded forest compartment in Fukuoka Prefecture (Forest Planning Department of the Forest Erosion Control Division of Fukuoka Prefecture, 2001). For the spatial data analyses (*e.g.*, drawing the population density distribution maps), we used ArcView 3.2a (ESRI Inc.) and Spatial Analyst (an extension of ArcView). For statistics analyses, SPSS (SPSS Inc.) was used.

RESULTS

Estimating the Distribution of the Sika Deer Population

The semivariogram is calculated from the sika deer population density database according to the following

equation.

$$r(h) = \frac{1}{2n} \sum_{i=1}^n (Z(x_i) - Z(x_i + h))^2 \quad [1]$$

where :

h is an arbitrary distance (referred to as the 'lag' in online manual in the GIS software)

n is the number of pairs of sample points (in particular, the sika deer population density survey plots) separated by h

Z is the attribute value (in particular, sika deer population density)

$r(h)$ is the calculated value of the semivariogram at distance h

MASE *et al.* (2001) called the Eq. [1] the empirical semivariogram.

The value of h is referred to as the lag for the kriging interpolator. In this study, h was 4399m, which was the maximum distance between a pair of the nearest sika deer population density survey plots. The reason why h was the maximum distance between a pair of the nearest density survey plots was $n > 0$ on Eq. [1].

The semivariogram calculated with Eq. [1] is modeled by fitting a theoretical function. In GIS software, spherical, circular, exponential, Gaussian, and linear with sill models were used to model the semivariogram. Below are the equations of the semivariogram models (MASE *et al.*, 2001).

Spherical model

$$r(h;\theta) = \begin{cases} \theta_0 + \theta_1 \left[\frac{3h}{2\theta_2} - \frac{1}{2} \left(\frac{h}{\theta_2} \right)^3 \right], & 0 < h \leq \theta_2 \\ \theta_0 + \theta_1, & h > \theta_2 \\ 0, & h = 0 \end{cases}$$

Circular model

$$r(h;\theta) = \begin{cases} \theta_0 + \theta_1 \left[1 - \frac{2}{\pi} \cos^{-1} \left(\frac{h}{\theta_2} \right) + \sqrt{1 - \frac{h^2}{\theta_2^2}} \right], & 0 < h \leq \theta_2 \\ \theta_0 + \theta_1, & h > \theta_2 \\ 0, & h = 0 \end{cases}$$

Exponential model

$$r(h;\theta) = \begin{cases} \theta_0 + \theta_1 \left[1 - \exp \left(\frac{-h}{\theta_2} \right) \right], & h > 0 \\ 0, & h = 0 \end{cases}$$

Gaussian model

$$r(h;\theta) = \begin{cases} \theta_0 + \theta_1 \left[1 - \exp \left(\frac{-h^2}{\theta_2^2} \right) \right], & h > 0 \\ 0, & h = 0 \end{cases}$$

Linear with sill model

$$r(h;\theta) = \begin{cases} \theta_0 + \theta_1 h, & h > 0 \\ 0, & h = 0 \end{cases}$$

Where :

θ denotes model parameters ($\theta = [\theta_0, \theta_1, \theta_2]$)

These models are described (GRAAF *et al.*, 2003):

Spherical model: this calculates the semivariogram as a modified quadratic function for which, at some distance, pairs of points will no longer be auto correlated and the semivariogram reaches an asymptote.

Circular model: uses a circular neighbourhood search model with a particular radius.

Exponential model: the exponential model is similar to the spherical model in that it approaches the asymptote gradually. However, it differs from the spherical model in the rate at which the asymptote is approached and in the fact that the asymptote is never actually reached.

Gaussian model: the gaussian or hyperbolic model is similar to the exponential, but it assumes a gradual rise for the y-intercept.

Linear with sill model: this model is similar to the linear model except that at some distance pairs of points are no longer auto correlated and the semivariogram reaches an asymptote.

To select the appropriate semivariogram model, we used the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). The AIC can be used to select the most appropriate model from a set of models (SAKAMOTO *et al.*, 1983; SUZUKI, 1995). It tends to select the model having the most parameters (FUKUI, 2004). To mitigate this tendency, the BIC was also calculated.

Table 2 shows the AIC and BIC for each model. The spherical model produced the smallest values of both AIC and BIC, so that we adopted this model for execution of the interpolator. Fig. 5 shows the density distribution of the sika deer population using the ordinary kriging interpolator with the spherical model.

Fig. 6 shows a histogram of the deer density. The proportion of the low-density area (0-10 deer/km²) exceeded 50% of the total area. The area below 20 deer/km² was approximately 90%, and the proportion of high-density area, exceeding 30 deer/km², was above 5%.

Table 2 Semivariogram and Information Criterion. AIC denotes Akaike Information Criterion; BIC is Bayesian Information Criterion.

	Spherical model	Circular model	Exponential model	Gaussian model	Linear with sill model
AIC	109.64	109.66	121.38	120.18	109.69
BIC	110.23	110.25	121.97	120.77	110.28

Fig. 5 Kriging interpolation of the sika deer population density using the spherical model. [white] indicates 0-10 deer population density per 1km². [light gray] indicates 10-20 deer/km². [medium gray] indicates 20-30 deer/km². [dark gray] indicates more than 30 deer / km². The area framed by the heavy line is the study area.

Fig. 6 Histogram of the sika deer population density class. The study area was approximately 1130.3km².

Relation between Sika Deer Population Survey Plots and Damage Survey Plots

Sika deer cause damage by browsing, stripping bark, and fraying trees with their antlers. IKEDA (2001) stated that browsing damage is worst in Fukuoka Prefecture. Of the plots where deer damage was recorded, browsing damage was responsible for 95%, whereas the proportion of plots with stripped bark and frayed trees was only 5%.

Table 3 gives on the sika deer damage survey. Sika deer damage was surveyed on 1144 plots. There were 369 damaged plots, which comprised 32.3% of all damage survey plots. In the damage survey, 1087 plots (95.0%) were planted with Sugi (*Cryptomeria japonica* D. Don) or Hinoki (*Chamaecyparis obtuse* Endl.), which is the main planted tree in Japan. Uniform stands planted Sugi or Hinoki comprised 856 (74.8%).

96 plots in the survey were equipped with sika deer damage prevention measures, either sika deer repellent or a guard fence. Data from 44 plots were eliminated from the

Table 3 Overview of sika deer damage survey

	Number of damaged plots			Number of non-damaged plots			sum
	Nonexistence of protection measures	Existence of protection measures	Unknown	Nonexistence of protection measures	Existence of protection measures	Unknown	
Uniform stand							
Sugi (<i>Cryptomeria japonica</i> D. Don)	50	7		103	13	1	174
Hinoki (<i>Chamaecyparis obtusa</i> Endl.)	168	36	1	451	24	2	682
Kunugi (<i>Quercus acutissima</i> Carruth.)	2			24	1		27
Keyaki (<i>Zelkova serrata</i> Makino)	10			2			12
Kaede (<i>Acer palmatum</i> Thunb.)				1			1
Yamazakura (<i>Cerasus jamasakura</i> H. Ohba)	1			1			2
Mixd stand							
Sugi (<i>Cryptomeria japonica</i> D. Don)	64	7		99	4	1	175
Hinoki (<i>Chamaecyparis obtusa</i> Endl.)							
Sugi (<i>Cryptomeria japonica</i> D. Don)	2			1			3
Keyaki (<i>Zelkova serrata</i> Makino)							
Sugi (<i>Cryptomeria japonica</i> D. Don)		2					2
Hinoki (<i>Chamaecyparis obtusa</i> Endl.)							
Keyaki (<i>Zelkova serrata</i> Makino)							
Sugi (<i>Cryptomeria japonica</i> D. Don)	2						2
Keyaki (<i>Zelkova serrata</i> Makino)							
Yamazakura (<i>Cerasus jamasakura</i> H. Ohda)							
Sugi (<i>Cryptomeria japonica</i> D. Don)	1			14			15
Hinoki (<i>Chamaecyparis obtusa</i> Endl.)							
Kunugi (<i>Quercus acutissima</i> Carruth.)							
Sugi (<i>Cryptomeria japonica</i> D. Don)	8			4			12
Hinoki (<i>Chamaecyparis obtusa</i> Endl.)							
Yashabushi (<i>Alnus firma</i> Siebold et Zucc.)							
Hinoki (<i>Chamaecyparis obtusa</i> Endl.)				3			3
Icho (<i>Ginkgo biloba</i> L.)							
Hinoki (<i>Chamaecyparis obtusa</i> Endl.)				1			1
Enju (<i>Sophora japonica</i> L.)							
Hinoki (<i>Chamaecyparis obtusa</i> Endl.)				9			9
Kunugi (<i>Quercus acutissima</i> Carruth.)							
Hinoki (<i>Chamaecyparis obtusa</i> Endl.)	6						6
Keyaki (<i>Zelkova serrata</i> Makino)							
Hinoki (<i>Chamaecyparis obtusa</i> Endl.)					1		1
Sendan (<i>Melia azedarach</i> L.)							
Hinoki (<i>Chamaecyparis obtusa</i> Endl.)				1			1
Yamazakura (<i>Cerasus jamasakura</i> H. Ohba)							
Hinoki (<i>Chamaecyparis obtusa</i> Endl.)					1		1
Sendan (<i>Melia azedarach</i> L.)							
Keyaki (<i>Zelkova serrata</i> Makino)							
Icho (<i>Ginkgo biloba</i> L.)							
Yamazakura (<i>Cerasus jamasakura</i> H. Ohba)				1			1
Kunugi (<i>Quercus acutissima</i> Carruth.)							
Keyaki (<i>Zelkova serrata</i> Makino)				2			2
Icho (<i>Ginkgo biloba</i> L.)							
Keyaki (<i>Zelkova serrata</i> Makino)				3			3
Yamazakura (<i>Cerasus jamasakura</i> H. Ohba)							
Keyaki (<i>Zelkova serrata</i> Makino)and so on	1						1
Unknown Species	1			7			8
Sun	316	52	1	727	44	4	1144

analysis because protection measures were believed to be responsible for the lack of damage. Consequently, 1100 damage survey plots were used in our analysis.

The sika deer density and damage survey plots were plotted on a topographical map (Fig. 7). This map was based on Fig. 3 and Fig. 4. The sika deer population density survey and damage survey were conducted independently. As stated above, the obvious way to study the relation between the sika deer population density and damage is to measure the sika deer density and degree of damage on the same plots. But a problem is that pellets may decompose differently on bare fields and young plantations (ENDO, 2001, IKEDA, 2005). In addition, the survey timings were different (Table 1). We therefore confirmed the relation between sika deer population density and sika deer damage spatially.

The locations of the population density plots and damage survey plots were treated as point objects. We used a version of the nearest-neighbor distance method to calculate distances between point objects representing the locations of the population density plots and the deer-damaged plots. OKABE *et al.* (2000) described the nearest-neighbor distance method as a way to examine the effect of physical objects located in a region upon the distribution of point-like elements over that

region. We used only population density plots in which the deer density was nonzero. The average of the nearest distances was obtained. The average nearest distance from undamaged plots was also calculated (Table 4). The average values were then subjected to *t*-tests.

There were 362 damaged and 731 undamaged plots. The average distance from the population density plots to the damaged plots was ~200m shorter than the average distance to the undamaged plots. This difference was statistically significant ($p < 0.01$).

Relation between Sika Deer Population Density and Damaged Survey Plots

The *t*-tests showed that the sika deer density survey and the damage survey were correlated. Estimates of deer densities in plots found to be damaged can therefore be used to infer the sika deer density (Fig. 8). Following a computation of the densities in damaged and undamaged plots, the proportion of damaged plots at each increment of 5 deer/km² is shown as a histogram (Fig. 9). Above 20 deer/km² the proportion of damaged plots often exceeded 50%.

Fig. 10 shows the relation between the proportion of

Fig. 7 Distribution of sika deer population density census plots and damage survey plots in the study area. Black circles show sika deer population density survey plots. Squares show sika deer damage survey plots. The study area is framed by the heavy line.

Table 4 Distance from sika deer density survey plot to the nearest damage survey plot.

	damaged plots	undamaged plots
Total distance to nearest density survey plot (m)	556595.0	1274933.8
Number of plots	362	731
Average distance to nearest density survey plot (m/plot)	1537.6	1744.1

Fig. 8 Sika deer population density overlaid on the damaged survey plots. Circles show damage survey plots damaged by sika deer. indicates 0-10 deer population density per 1km². indicates 10-20 deer / km². indicates 20-30 deer / km². indicates more than 30 deer / km².

Fig. 9 Fraction of sika deer browsing damage for each population density class. The total number of available damage survey plots in the study area was 1,100, of which 369 were damaged plots and 731 were undamaged plots without protective measures such as a guard fence.

Fig. 10 Fraction of damaged plots on each 5 deer/km² class of sika deer population density according to the extent of damaged plantation tree numbers in the plot. indicates the fraction of plot numbers with less than 30% of trees damaged (limited damage). indicates the fraction of plot numbers with between 30% and 70% of trees damaged (spread damage). indicates the fraction of plot numbers with more than 70% of trees damaged (extensive damage). indicates the fraction of plot numbers with unknown extent of tree damage.

damaged plots at each 5 deer/km² increment, according to the extent of damaged plantation tree numbers in the damaged plot. The extent of the damage was subdivided into four categories according to the fraction of damaged trees: less than 30% (hereafter referred to as “limited damage”), between 30% and 70% (“spread damage”), more than 70% (“extensive damage”) and unknown extent. Below 10 deer/km² in Fig. 10, the proportion with limited damage was greater than 50%. Not surprisingly, it tended to decrease as the sika deer density increased.

DISCUSSION

Previous reports (Environment Agency of Japan, 1989, 1994, 2000; IKEDA, 2001, 2005; Japan Wildlife Research Center, 1998) evaluated the deer density only at points in the survey plots, because there was no method for estimating the density, where no survey had been conducted. This was a severe limitation.

Other reports have shown the density distribution on a

grid map with squares more than 1km in size (IKEDA, 2001, 2005; Japan Wildlife Research Center, 1998; Nature Conservation Bureau, 1999). In these reports, squares for which there was no information from sika deer population density surveys were shown as ‘population unknown’ or blank, although square was included in the sika deer habitat.

It is possible to estimate the sika deer population density throughout the habitat by smoothing the point data. The map of sika deer population density in Fig. 5 is derived without conducting a sika deer population density survey.

In Miyazaki Prefecture, an isogram map of the sika deer population density was drawn in 1998 (Japan Wildlife Research Center, 1998). The same report concluded that the population needed to be managed on each sika deer habitat. This suggests that to estimate the deer density accurately requires a large number of survey plots. Although we do not discuss how many plots would be required here, we believe the distribution we obtain is reasonable because the plots are distributed throughout the study area at mean intervals of 2150m (minimum 754m - maximum 4399m). Additionally,

referred to the same report, this study area surveyed giving a questionnaire about sika deer to hunters.

The selection of the lag size h in Eq. [1] might have important effects on the empirical semivariogram. ESRI (2001) stated that "When samples were located on a sampling grid, the grid spacing was usually a good indicator for lag size. However, if the data is acquired using an irregular or random sampling scheme, the selection of a suitable lag size is not so straightforward." In Fig 3, the sika deer population density survey plots are not evenly distributed. ESRI (2001) described an empirical method for deciding the lag by multiplying the lag size times by the number of lags, which should be about half of the largest distance between all points. But we could not find an objective method for choosing the lag in previous references. In this study, calculation of lag value adopted as computation method on the maximum distance between a pair of the nearest sika deer population density survey plots. The reason why h was the maximum distance between a pair of the nearest density survey plots was $n > 0$ on Eq. [1].

To validate the matching between the observed values from sika deer population density survey and the estimated values using the kriging interpolator, residuals analysis was conducted. A histogram of the residuals is shown in Fig. 11. The mean of residuals was -0.0032 (standard deviation : 0.31997), the maximum value of the residuals was 1.2032, and the minimum was -1.2036. In Fig. 11, 58% of all the survey plots were between -0.1 and 0.1 residuals. Given these results, the

sika deer population density calculated with the kriging interpolator is estimated accurately. So, in the area surrounding the sika deer population density survey, the accuracy of the sika deer population density might be high. But there were not many survey plots on the peripheral part of the study area. To evaluate the population density distribution with more accuracy than at present, the survey plots should be located evenly.

In Fig. 9, as the sika deer population density increases, the damage proportion generally also increases. Browsing damage occurred in 83% of plots with more than 40 deer/km². Even when the population density exceeded 10 deer/km², the proportion of damaged plots reached about 50%. This shows that preventative measures against deer damage, such as constructing a guard fence, should be conducted before planting trees given this density of deer.

The Environment Agency of Japan (1989, 1994, 2000), and HINO *et al.* (2003) reported acute destruction of natural vegetation in forests where the deer density exceeds 30.0 deer/km². Although recognition of natural forests which have taken a heavy impact of deer is usually difficult, the likely areas can easily be calculated using this approach. The areas in which the density exceeded 30.0 deer/km² in this study are located east and west of Mt. Kosho, on the southwest of Mt. Hiko, and 13km north of Mt. Hiko, totaling 59.1km². In these areas, there is a high risk of destruction of natural vegetation by sika deer.

Fig. 11. Histogram of residuals between sika deer population density with the pellet count method and the population density estimated by the kriging interpolator.

CONCLUSIONS

This study presents a method for producing a distribution map of the sika deer density from point data for the sika deer population survey taken over a wide area. The map assists in recognizing the high deer density area and analyzing the deer damage. Although the necessary conditions for inferring the sika deer density map should be examined more closely, the present techniques are applicable in other regions, especially in western Japan.

The present study area comprised sika deer habitats surrounding Mt. Hiko in Fukuoka Prefecture. The sika deer range extends to neighboring Oita Prefecture. The sika deer population density surrounding Mt. Hiko might therefore be analyzed if data on the deer in Oita Prefecture are included.

Sika deer caused browsing damage at fairly low population densities. Fig. 9 shows that there were still many undamaged plots in low density areas. Browsing damage is primarily related to the deer density, but other factors such as topography may be considered. More detailed analyses of damage occurrence, including probability distributions for damage, should be considered in future studies.

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