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Distribution of Agroclimatic Resources in Yunnan, China

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Introduction

Yunnan Province is situated in South-western part of the People's Republic of China, lat. 21° 08′ N to 29° 15′ N and long. 97° 31′ E to 106° 12′ E, covering an area of 38 × 10^4 km^2. This province has been much noted as a center of 'laurel forest culture'[15] and as the origin of various crops[6,16] and domestic animals[3], presenting what is called 'Eastern crescent'. Even now, various kinds of animals and plants live in this province, and this is the reason why Yunnan Province has been considered as a vast treasure-house of the genetic resources.

The genetic diversity is founded primarily on the net primary productivity, which is to be determined chiefly by the amount of climatic resources[9]. Therefore, the genetic diversity in a certain place can be estimated, to some extent, by assessing the climatic resources in that place[9]. And, because the distribution of animals and plants is a reflex of adaptation of each species to environments in each habitat, by examining the climatic conditions under which the animals and plants live, their physiological and ecological properties can roughly be estimated. In addition, in agriculture, climatic informations have been adopted frequently as effective marks to estimate the proper land and the right growing season.

Yunnan Province has a quite complicated configuration of the ground, as shown in such topographical characteristics as rivers running among the mountains and the remarkable difference between high and low lands. Therefore, the distribution of climate is very complicated, too. Now, in Japan whose configuration of the ground is quite complicated as in Yunnan Province, numerous mesh climate maps have been drawn up, and effective utilization of local climatic resources has been under planning[8]. However, in Yunnan, such an attempt has never been done. In the present paper, we attemped to draw up a mesh climate map in Yunnan Province.

Materials and Methods

1. Climatic data and the method of analysis

Climatic data were dependent on ① data of air temperature in China, 1960-1970[11], ② data of precipitation in China, 1960-1970[12] ③ annual report of land surface weather in China, 1971-1979, 1981, 1984 and 1986[10] (the above-mentioned data were summed up as DATA 1) ④ divi-

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sion of crop cultures in Yunnan Province (summed up as DATA 2)[1]. DATA 1 contains data of air temperature, humidity, precipitation, sunshine, evaporation and wind etc. fixed in the main meteorological observing stations of China, although the number of observing stations in Yunnan was only nine. DATA 2 contains more strictly climatic data (air temperature, precipitation, and sunshine etc.) in Yunnan, but the statistical duration is unclear. In addition, because the latter introduced climatic data from the relationship with crop cultivation, there were places where only the data noted during the crop cultivation period, June-September, was described. In such places, the annual amount of precipitation (Pa) was assessed in the following equation.

$$Pa = 1.542\,Pd - 50.282 \quad (R^2=0.967) \qquad \text{Eq. (1)}$$

where, Pa and Pd are the amount of precipitation in a year and are noted from June to September, respectively. Eq.(1) was introduced as a result of analysis of regression from data of 22 weather stations where both Pa and Pd were given. The climatic characteristic in Yunnan consisting in the fact that the terminal amount of precipitation from May to October amounts to 85% or more than that of Pa, makes the application of Eq.(1) possible.

Although the duration of sunshine is an important index by itself showing whether light environment is proper or improper, in this paper, the conversion of that into solar radiation was tried in the following procedures, on account of some merits that the latter is given as unit of energy and is easy to be connected with agricultural prductivity etc[7].. Firstly, concerning 33 meteorological observing stations from Hokkaido to Okinawa of Japan, the ratio of annual integrated solar radiation (R) to annual duration of sunshine (S) was calculated, and the relationships between R/S ratio and latitude, longitude and altitude were examined successively. But, because no clear relationships among them could be found, 2.5MJ/hour, or the mean value of R/S in Japan, was applied in Yunnan, too. That is to say that, annual duration of sunshine multiplied by 2.5 MJ/hour makes annual solar radiation. The authors regarded it as basical 'annual solar radiation'. Secondly, the relationship between basical 'annual solar radiation' (Rb) and the actual one (Ra) was examined, using 4 data of annual solar radiation in Yunnan, given in DATA 2. The Ra could be assessed in the following equation.

$$Ra = 0.655Rb + 2054.73 \quad (R^2=0.999) \qquad \text{Eq. (2)}$$

2. Geographical informations and the method of analysis

The geographical informations in the main meteorological observing stations of China could be picked up from DATA 1, but those of the place described in DATA 2 were invariably unclear with the exception of altitude. The latitude and longitude of such places were measured from 'Operational Navigation Chart (H-9, H-10, J-9, J-10, 1:1,000,000, 1980)' (DATA 3). In addition, altitude in the lattice point of 10′ intervals was also measured from DATA 3. Basically, the altitude was determined as the value of contour line close to the lattice point, though it was done as mean of two contour lines in the case when the interval of contour line was wide or the lattice point was fixed between the two contour lines. Although the interval of contour line differed in charts or in altitudes, there was no help for it, as the authors were prevented from obtaining any detailed informations concerning DATA 3.

3. Agroclimatic evaluation of the net primary productivity

In this paper, we attempted to evaluate the agroclimatic resources by agroclimatologically assessing the net primary productivity (NPP). NPP (tonDM$\cdot$ha$^{-1}\cdot$year^{-1}) can be estimated agroclimatologically in accordance with Miami[5] and Chikugo[14] models. According to Miami model[5], it can be calculated in the following two equations.

$$\text{NPP} = 30/[1+\exp(1.315-0.119T)] \qquad \text{Eq. (3)}$$
$$\text{NPP} = 30[1-\exp(-0.000664P)] \qquad \text{Eq. (4)}$$

In Eqs. (3) and (4), T and P are the annual mean temperature and the annual amount of precipitation in a certain place, respectively. Therefore, in Miami model, two NPPs are introduced from Eqs. (3) and (4), but the lower value of the two are given as NPP in the place. On the other hand, according to Chikugo model[14], NPP is accessed in the following equation.

$$\text{NPP} = 0.29[\exp\{-0.216\,(\text{RDI})^2\}]\text{Rn} \qquad \text{Eq.(5)}$$

In Eq. (5), RDI and Rn are the annual radiative dryness index and the annual net radiation, respectively. Net radiation is a measure of energy characterizing the intensity of biophysical processes on the Earth. In order to evaluate the monthly mean net radiation ($R_{n,i}$, $\text{cal}\cdot\text{cm}^{-2}\cdot\text{day}^{-1}$, Seino and Uchijima[7] adopted the following empirical equation due to Chang[2].

$$R_{n,i} = (1-\rho_i)S_{t,i} - \sigma\, T_{a,i}^4[286.18+202.6B_i-(45.24+10.92B_i)\sqrt{e_{a,i}}] \qquad \text{Eq. (6)}$$

where ρ_i is albedo (0.0 − 1.0) of underlying surface, $S_{t,i}$ is the global solar radiation ($\text{cal}\cdot\text{cm}^{-2}\cdot\text{day}^{-1}$, σ is the Stefan-Bolzmann constant ($8.26 \times 10^{-11}\text{cal}\cdot\text{cm}^{-2}\cdot\text{min}^{-1}\cdot\text{K}^{-1}$), $T_{a,i}$ is the monthly mean temperature, B_i is the ratio of the global solar radiation to the solar radiation on the upper boundary of atmosphere and $e_{a,i}$ is the atmospheric vapor pressure (hPa). Subscript i shows the month number. However, as we could not get complete monthly data, the annual mean net radiation was calculated in directly substituting annual data into Eq.(6). In addition, Seino and Uchijima[7] regarded ρ_i as 0.15 in no snow cover period and as 0.65 in snow cover period, but we assumed that ρ_i was uniformly 0.2 because there was no data for snow cover period. e_a was estimated in the following equation in accordance with the method of Seino and Uchijima[7].

$$e_a = 4.54\exp(0.068T_a) \qquad \text{Eq. (7)}$$

We adopted the lower value of the two NPPs calculated from Miami and Chikugo models, because there was a possibility that Rn from Eq.(6) was overestimated as compared with the actual one, a drop in ρ_i during the snow cover period was neglected.

Results and Discussion

1. Geographical features of Yunnan

Yunnan shows a considerable difference varying from 76.4 to 6,740 meters in its undulations[1]. And, the land measuring between 1,000 and 3,500 meters in altitude covers 77% of the provincial area[1]. Besides, the percentage of highlands beyond 3,500 meters amounts to 13[1]. While the percentage of lowlands below 1,000 meters is only 10[1].

Fig.1 is a mesh map showing the mean altitude in 30′-mesh. On the whole, the altitude, in Yunnan, tends to become higher with the increasing in latitude, excepting the northeast district. The highland in the northwest side is adjacent to the Tibet-Plateau.

2. Temperature environment

The air temperature also changes remarkably with latitude, because of a change in global solar radiation brought about with latitude, dropping out at about 0.55°C as the altitude becomes higher by the measure of 100 meters[4]. In addition, because the climatic characteristics are also to be affected by the geographical positions, for example, whether it is situated in the east or in the west of the continent, the longitude is also an important climatic factor[4]. In Yunnan and its outskirts, between the annual mean air temperature (${}_aT_m$), and latitude (ψ), longitude (δ) and altitude (H), there was a relationship expressed in the following equation:

$$ {}_{a}T_{m} = a + b \cdot \sin^2 \psi + c \cdot \delta + d \cdot H \qquad \text{Eq. (8)} $$

In Eq.(8), a, b, c and d are parameters (Table 1). The parameters differed in the data used, but the basic relationship never differed. This equation indicates that the mean air temperature becomes higher as latitude and longitude become smaller and as altitude becomes lower, and that such a tendency is common to Yunnan and its peripheral regions. Now, the climatic classifications in Yunnan Province are dependent primarily on the altitude and secondarily on the fact whether it is situated in the West or in the East of Mt. Airao[1]. According to Eq.(8), they are corresponded to the 4th and the 3rd terms, respectively, but it was assumed that latitude,

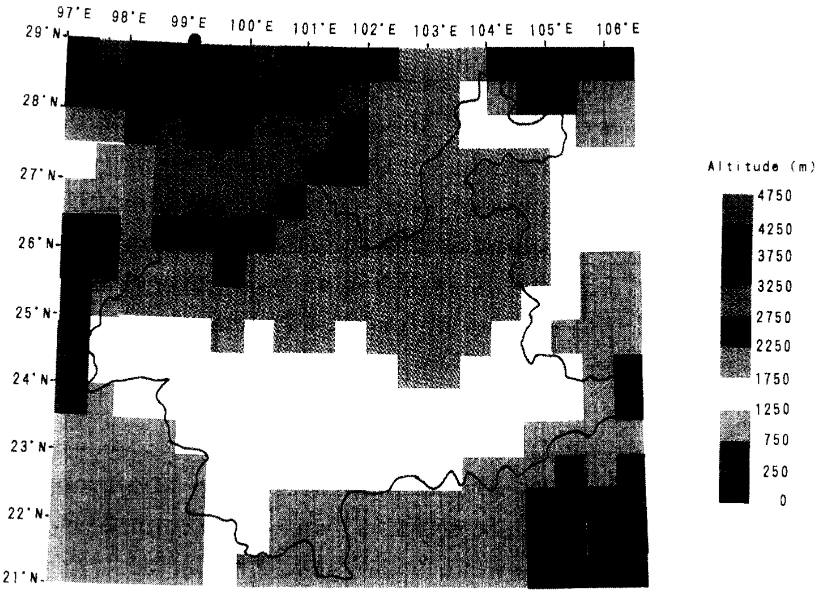

Fig. 1. A mesh map showing the configulation of the ground in and around Yunnan Province.

Table 1. The values of parameter when the annual mean temperature (${}_{a}T_{m}$) and available accumulated temperature (ΣT_{10} and ΣT_{18}) were expressed in the following equation,
$y = a + b \cdot \sin^2 \psi + c \cdot \delta + d \cdot H$
coefficient of determination (R^2) and the number of data used (n)

	a	b	c	d	R^2	n	
${}_{a}T_{m}$	28.99	−46.10	0	−0.00337	0.950	44*1	(0.872, n=83)
	51.13	−39.71	−0.2132	−0.00425	0.960	44*1	(0.896, n=83)
	31.78	−52.83	0	−0.00407	0.872	83*2	
	60.51	−49.84	−0.2806	−0.00443	0.901	83*2	
ΣT_{10}	37493	−16437	−258.15	−1.8899	0.860	32*2	
ΣT_{18}	33483	−15942	−229.05	−2.9357	0.946	25*2	

ψ, δ and H indicate latitude (rad.), longitude (°) and altitude (m).
*1 shows the result based on DATA 1.
*2 shows the result based on DATA 2.
Value in parentheses shows coefficient of determination when left equation was applied onto 83 meteorological observing stations of Yunnan Province.

as compared with longitude, controlled the distribution of annual mean air temperature, because Eq.(8) could be applied satisfactorily even if the 3rd term was neglected (Table 1). Fig.2 shows mesh map of annual mean air temperature calculated by substituting geographical informations shown in Fig.1 for Eq.(8). On the whole, $_aT_m$ tended to become higher in the lower latitude excepting the northeast area. It was also observed that $_aT_m$ in the greater part of Yunnan ranged from 12.5 to 17.5°C, though $_aT_m$ in the northwest mountain and that in the south lowland districts were counted lower than 10°C and higher than 20°C, respectively.

The available accumulated temperature (ΣT_{10} and ΣT_{18}) was also related to ψ, δ and H in the same way as in case of $_aT_m$ (Table 1). Fig.3 shows a mesh map of ΣT_{10}. Yunnan has gradually fallen into the five agricultural devisions, i.e., Central Dian (I), South Dian (II),

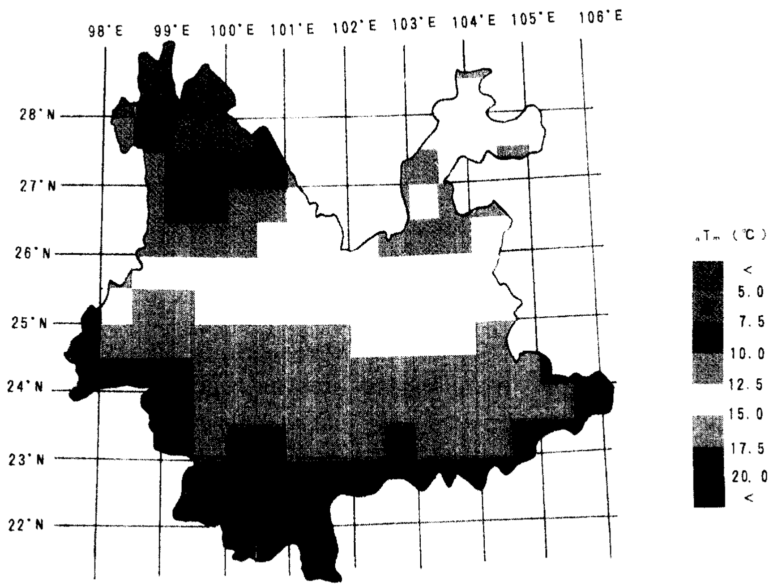

Fig. 2. A mesh map of annual mean temperature ($_aT_m$) in Yunnan Province.

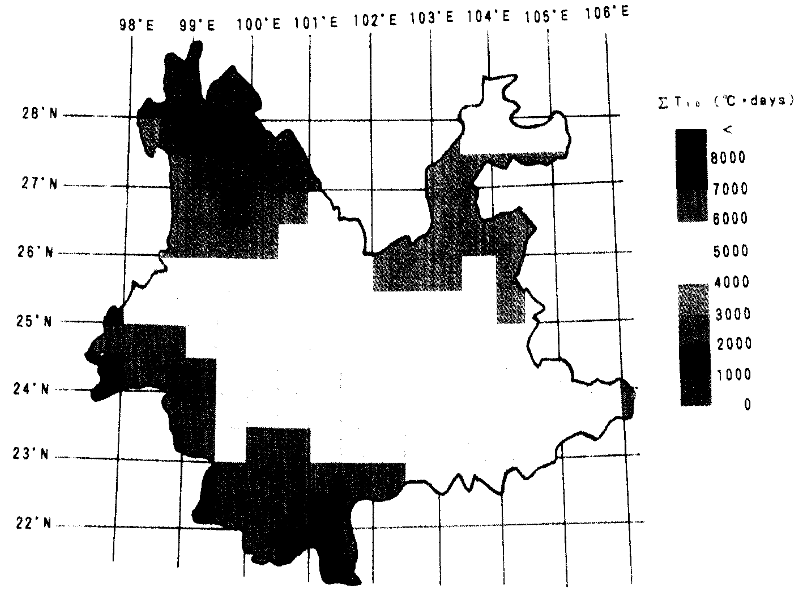

Fig. 3. A mesh map of available accumulated temperature (ΣT_{10}) in Yunnan Province.

South remote region (Ⅲ), Northeast Dian (Ⅳ) and Northwest Dian (Ⅴ)[1]. Ⅰ−, Ⅱ−, Ⅲ−, Ⅳ− and Ⅴ−Devisions corresponded nearly to the central region having 4,000-5,000 degree day, the south region having 5,000-6,000 degree day, the south remote region having greater than 6,000 degree day, the northeast region having 3,000-5,000 degree day and the northwest region having less than 4,000 degree day, respectively.

On the other hand, USDA (U.S. the Department of Agriculture) has accepted 2,600-3,800 degree day in ΣT_{10} as optimum temperatures in rice culture[13]. The temperature condition in the greater part of Yunnan satisfies the above-mentioned demand, but it is said that cool summer damage often occurs[1]. In 1995, the result, examined by the senior author using 23 panicles of paddy gathered at the suburbs of Kunming, showed that 40% of total grains were sterile ones. Judging from some growing circumstances, it was assumed that rice plants sustained cool summer damage in this year. Fig.4 shows changes in monthly mean air temperature in Kunming (25°01′N, 102°41′E, 1,892m) and in Asahikawa (43°46′N, 142°22′E, 119m) lying in the north limit of rice culture in Japan. In winter season, the air temperature is much higer in Kunming than in Asahikawa, but, in summer season, the difference is relatively small. Especially, in July and August, it is somewhat higher in Asahikawa. This period corresponds to the term when rice plant attains from reduction division stage to the heading stage. And, these are the growing stages most sensitive to cool temperature. In this meaning, it may be concluded that Kunming nearly equals to marginal land for rice culture. 'ΣT_{10} is sufficient, nonetheless partial insufficiency of temperature happens.' This seems to be a fatality in the highland agriculture under tropic or subtropic climates. In Yunnan, in order to solve such a difficult problem, ΣT_{18} was accepted as a criterion for estimating as the right land[1]. ΣT_{18}, in Yunnan, ranged from the count greater than 5,000 degree day to the count lower than 0 degree day (as a calculated value). The greater parts of the Northeast Dian and of the Northwest Dian did not satisfy 1,000 degree day in ΣT_{18} which has been fixed to be a low temperature limit of rice culture[1] (unshown), but, rice culture is being done even in such districts[1]. This disagreement suggests that 1,000 degree day in ΣT_{18} has not always been regarded as a

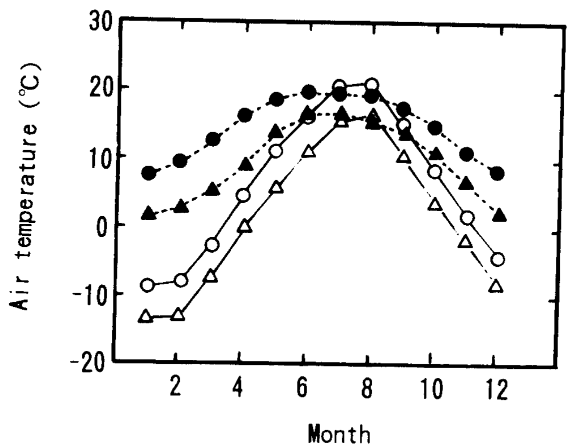

Fig. 4. Changes in monthly mean and minimum temperature in Kunming (25°01′N, 102°41′E, 1,892m) and Asahikawa (43°46′N, 142°22′E, 119m) Solid and open circles indicate mean temperature, and solid and open triangles indicate minimum temperatures in Kunming and Asahikawa, respectively.

necessary condition, or that certain places where ΣT_{18} exceeds 1,000 degree day exist in the district. However, the details are unclear.

3. Raifall resource

The relationship between the annual amount of precipitation (P), and ψ, δ and H was examined, basing on 44 observing data obtained in Yunnan and its outskirts. The result gives the two following equations.

$$\left.\begin{aligned} P &= 3425.7 - 2944.5\sin^2\psi - 0.1701H \quad (R^2=0.761) \\ P &= 846.3 - 3559.5\sin^2\psi + 11.34\,\delta - 0.1222H \quad (R^2=0.765) \end{aligned}\right\} \quad \text{Eq. (9)}$$

These equations indicate that the rainfall becomes smaller as latitude and altitude become larger and that it tends to be larger in the east than in the west side. However, even when Eq.(9) was applied to 80 spots inside Yunnan Province, no correlation between the calculated and the observed values was found at all ($R^2=0.082$). Fig.5 is a rainfall chart drawn, basing on 80 observing values inside Yunnan. On the whole, the rainfall tends to become smaller toward the north, being in agreement nearly with Eq.(9). Even in such a tendency, there are some areas supplid with much rain in the south and the east districts and there is one area with relatively little rain, situated around 26°N and 100°E. The former is situated around slanting surface toward highlands through a raivine, and the latter is sited around the rear (lee side) of Mt. Wuliang. It seems to be an evidence of the fact that complicated configuration of the ground inside Yunnan disturbs considerably the regularity in the rainfall distribution in southwest China.

Accordingly, some topographical data detected from Fig. 1 were given in order to enhance the accuracy of the estimated rainfall.

$$P=7000-2187.5\sin^2\psi-52.3\,\delta-0.199H+92.35m_1-0.504d_1+2.23m_2+0.113d_2-0.052d_3 \quad (R^2=0.451,\ n=80) \quad \text{Eq. (10)}$$

In Eq.(10), m_1 is the percentage of meshes less than 1,000m in altitude for 25 meshes around target mesh (including target mesh)(%), m_2 is the percentage of meshes less than altitude in

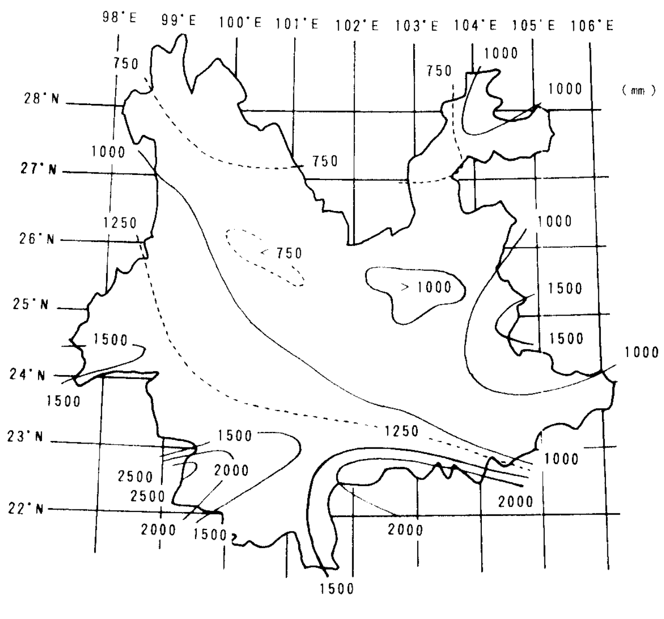

Fig. 5. Distribution map of the annual amount of precipitation in Yunnan Province.

target mesh (of 24 meshes encircling target mesh)(%), d_1 is the difference between the mean altitude of target mesh and altitude at the meteorological observing station in target mesh (m), d_2 is the difference in altitude between the highest mesh (of 24 meshes encircling target mesh) and target mesh (m), and d_3 is the difference in altitude between the lowest mesh (of 24 meshes encircling target mesh) and target mesh (m), respectively. Fig.6 is a mesh map of annual amount of precipitation calculated from Eq.(10). In this case, d_1 gave 0. Some characteristics consisting of the fact that the rainfall tends to become smaller toward the northeast and that there are some areas with much rain in the south districts, are caught relatively well in Fig.6.

4. Radiation environment

Fig.7 is an isoquant map of annual total solar radiation. The greater part of Yunnan has the count ranging from 5 to 6 $GJ \cdot m^{-2}$, and there is one area having the count less than 4$GJ \cdot m^{-2}$ in the northeast side, and there is one area having more than 6$GJ \cdot m^{-2}$ sited around 25-27°N and 100-102°E, respectively.

Owing to the fact that the parameters same as those in Eq.(10) were introduced, the following equation was established.

$$S_t = 10876 - 18123\sin^2\phi - 39.3\delta + 1.289H - 1.478m_1 - 0.0297d_1 - 3.63m_2 + 0.355d_2 - 0.592d_3$$

$$(R^2 = 0.833,\ n = 59) \quad \text{Eq. (11)}$$

Fig.8 is a mesh map of annual total solar radiation (S_t) calculated from Eq.(11). Fig.8 catches relatively well rough characteristics shown in Fig.7. However, Eq.(11) rates the values in the northwest mountain district considerably high.

The annual net radiation (R_n) ranged from 98.5 to 32.7 $kcal \cdot cm^{-2}$ in Yunnan (unshown). But, the count of 98.5 $kcal \cdot cm^{-2}$ in the northwest mountain district seems to be apparently an overestimated one. And, the error is to be on a problem of accuracy of Eq.(11). It may be said that R_n in Yunnan ranged between 50 and 70 $kcal \cdot cm^{-2}$., with the exception that there is a district showing extremely low R_n in the northeast of Yunnan.

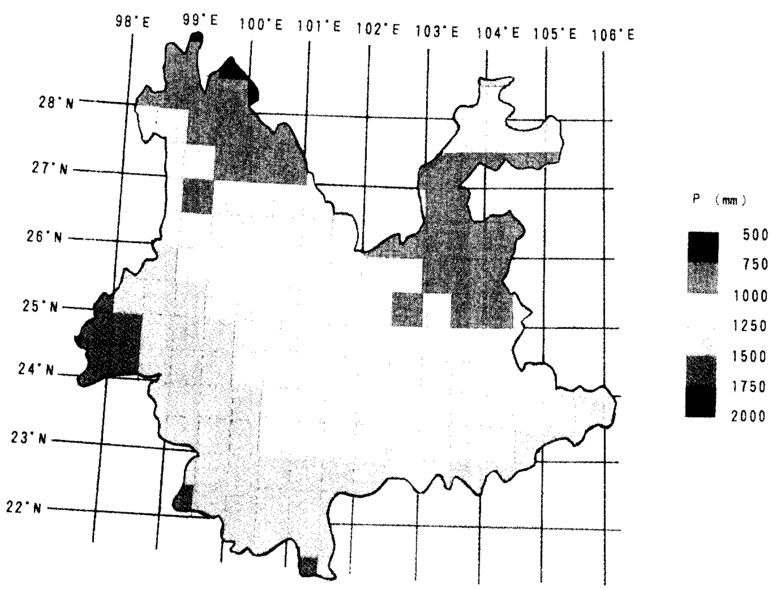

Fig. 6. A mesh map showing distribution of the annual amount of precipitation (P) in Yunnan Province.

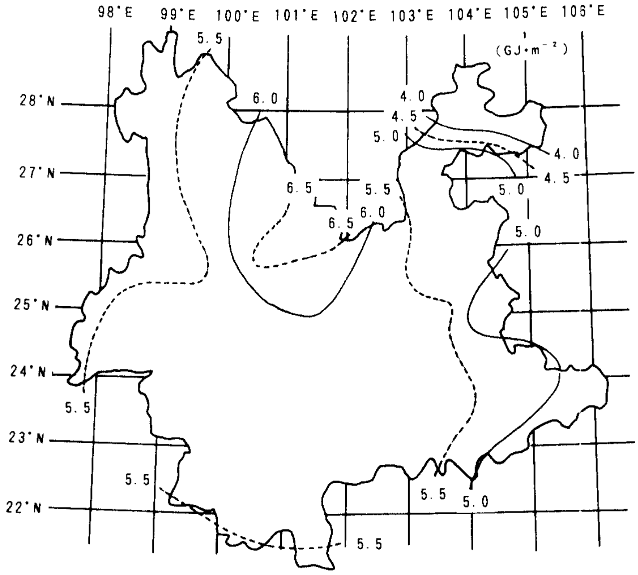

Fig. 7. Distribution map of the annual total solar radiation in Yunnan Province.

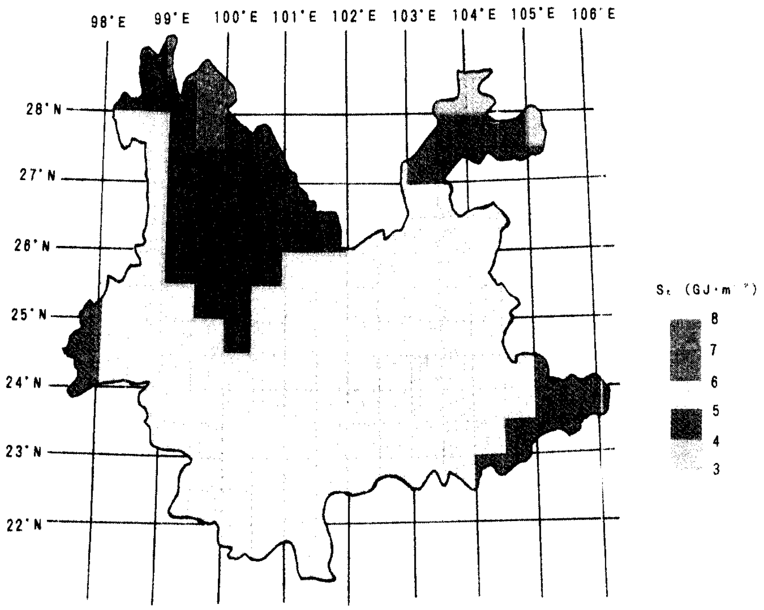

Fig. 8. A mesh map showing distribution of the annual total solar radiation (S_t) in Yunnan Province.

5. Net primary productivity

Fig.9 shows a mesh map of NPP in Yunnan Province. The NPP in Yunnan ranged between 5.8 and 17.9 ton·ha^{-1}·year^{-1}, and the greater part of Yunnan is in possession of NPP ranging from 12.5 to 17.5 ton·ha^{-1}·year^{-1}. This level agreed nearly with the NPP near Yunnan in the global distribution map of NPP, drawn by Seino and Uchijima[9]. According to them, the land area with the NPP above 10ton·ha^{-1}·year^{-1} was only 36.6% of the entire land area[9]. In this meaning, the NPP distribution shown in Fig.9 is an evidence showing the fact that Yunnan has high agroclimatic fertility, biological diversity and activity of ecosystems in the province. On

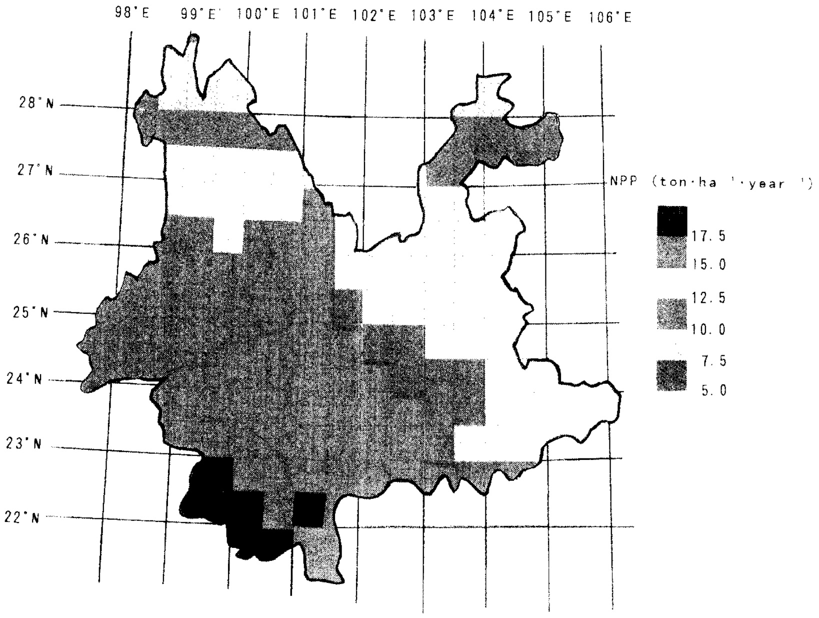

Fig. 9. A mesh map of NPP distribution in Yunnan Province.

the other hand, it was assumed that low productivity in the northwest district depended mainly on the low temperature or the high radiative dryness index, and the low NPP in north-east was due mainly to low net radiation.

Concluding remarks

The distributions of agroclimatic resources in Yunnan Province were examined. Now, the climatic classification in Yunnan was attempted, basing mainly on altitude, and from the present results it was demonstrated that the distribution of climatic elements in Yunnan Province was affected by various geographical factors. The annual air temperature or the available accumulated temperature could be approximated by the simple factors, i.e., latitude, longitude and altitude (See Eq.(8)). And, the annual amount of precipitation and annual total solar radiation could also be approximated satisfactorily by adding the above factors to some topographical factors, i.e., the percentage of meshes less than 1,000m in altitude for 25 meshes around target mesh (including target mesh), the percentage of meshes less than altitude in target mesh (of 24 meshes encircling target mesh), the difference between the mean altitude of target mesh and the altitude at weather observing station in target mesh, the difference in altitude between the highest mesh (of 24 meshes encircling target mesh) and the target mesh, and the difference in altitude between the lowest mesh (of 24 meshes encircling target mesh) and the target mesh (See Eqs.(10) and (11)), though those were rough data read from navigation charts. In addition, some mesh maps based on those results were drawn. These contained some errors, but were agreed relatively well with the actual distribution.

Perhaps, it may be expected that the accuracy of the estimated values might be improved still more by introducing other more detailed geographical informations. Such an attempt must be useful in discovering the climatic resources unexplored. There were two obstacles in enhancing the estimated accuracy. One was the fact that detailed geographical informations could not be obtained or had not been drawn up, and the second was the fact that there was only a few meteorological observing stations for the extensive area of Yunnan, and that the data were too partial to cover the living areas as far as we were concerned. In order to draw up finer and more accurate mesh maps, the constructions of digital national land informations and of observational networks as those in AMeDAS of Japan will be necessary in Yunnan.

The NPP calculated from Eqs.(3)-(5) seems to be an index showing climatic fertility. Therefore, it was expected that NPP might be connected closely with yielding productivity in the arable land[7], but it was left as a subject for further discussion.

Summary

The distributions of agroclimatic resources in Yunnan Province were examined. Both the annual mean temperature and the available accumulated temperature were related to latitude (ψ), longitude (δ) and altitude (H) in the following equation.

$$Y = a + b\cdot\sin^2\psi + c\cdot\delta + d\cdot H \quad (a,b,c,d\text{: parameters})$$

The five agricultural divisions in Yunnan corresponded nearly to the distribution chart of ΣT_{10}. In 1995, an occurrence of cool summer damage was observed in Kunming. Judging from the change in monthly mean temperature, it was assumed that Kunming equaled nearly to the marginal land for rice culture.

The annual amount of precipitation and annual solar radiation were expressed in the following equation.

$$Y = a\cdot\sin^2\psi + b\cdot\delta + c\cdot H + d\cdot m_1 + e\cdot d_1 + f\cdot m_2 + g\cdot d_2 + h\cdot d_3$$

where, a,b,c,d,e,f,g and h are parameters, m_1 is the percentage of meshes less than 1,000m in altitude for 25 meshes around target mesh (including target mesh)(%), m_2 the percentage of meshes less than altitude in the target mesh (of 24 meshes encircling the target mesh)(%), d_1 is the difference between the mean altitude of target mesh and the altitude at the meteorological observing station in the target mesh (m), d_2 is the difference in altitude between the highest mesh (of 24 meshes encircling the target mesh) and the target mesh (m), and d_3 is the difference in altitude between the lowest mesh (of 24 meshes encircling the target mesh) and the target mesh (m), respectively. The mesh map drawn up by using above equation was close to the actual distribution chart. The result was an evidence showing that the distribution of climatic elements in Yunnan Province was affected considerably by various geographical factors.

The NPP in Yunnan ranged from 5.8 in the Northeast to 17.9 $\text{ton}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ in the South, and the greater part of Yunnan had NPP between 12.5 and 17.5 $\text{ton}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$.

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