Journal of Environmental Sciences (China), Vol. 2, No. 4, pp 95–109, 1990 ISSN 1001–0742

Radiative dryness index and potential productivity of vegetation in China

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(Received September 26, 1990)

Abstract—The Chikugo Model is used to estimate radiative dryness indexes (RDI) and net primary productivity (NPP) of vegetation zones in China by calculating climatic parameters. That provides the water-heat equilibrium condition, potential primary production for natural vegetation in various vegetation zones, and their geographical distribution pattern. That could be used as the basis for study the effect of global climate change on ecosystems.

Keywords: Chikugo Model; radiative dryness index; net primary productivity.

The fixed solar energy in the dry matter produced by plants through photosynthesis is the basis for all living beings and their functions in the earth. The net primary productivity (NPP, t.DM/ha. yr) of vegetation is basically determined by the solar energy irradiated on plants, as well the soil moisture at the rhizosphere. Therefore, the net primary productivity could be calculated by means of correlation analysis between climatological factors (mainly solar radiation, atmospheric temperature, and precipitation) and dry matter production of plants. That would be significant for determining the potential productivity of the zonal landscape, making full use of climatic and land resources, increasing and giving full play to primary productivity of plants.

H. Lieth (1972) and H. Lieth et E. O. Box (1972) had estimated the primary productivity worldwidely. The Miami Model and Thornthwaite Memorial Model have been used to calculate the NPP of plants basing on mean annual temperature, precipitation, and potential evapotranspiration (PET). The latter one, i.e. the method using PET is considered as the more accurate one, because it has been involved the evapotranspriration process which is closely related with photosynthesis and combined temperature and precipitation factors together. N. A. Efimova's method and its result (1977) for calculating the productivity of plants through radiative factors also brought great attention.

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I. M. Budyko (1956, 1984) and J. E. Bierhuizen et R. O. Slatyer (1965) advanced a physical approach to determine gas exchange between vegetation and surface atmosphere through radiation equilibrium. Basing on Budyko's equation, Zenbei Uchijima and Hiroshi Seino (1985) found the correlation between radiation and radiative dryness indexes as follows:

$NPP = alpha \times Rn = Ao \times Rn/d\ (1+Beta)$,

where:

Rn: net radiation (kcal/ha)

Alpha: constant ratio=Ao/d (1+Beta)

Ao: experimental constant of gas exchange between vegetation and atmosphere

d: water vapor deficit (mb)

Beta: Bowen ratio

d(1+Beta): climatic dryness index

It is thus evident that NPP keeps in proportion with net radiation (Rn), and decreases with the increasing of climatic dryness index. Basing on worldwide data, Uchijima and Seino (1985) developed the Chikugo Model for estimating the NPP of vegetation from climatological data.

$$NPP = 0.29[\exp(-0.216RDI^2)Rn],$$

where:

RDI: radiative dryness index (RDI=Rn/lr),

l: latent heat of evaporation of water (kcal/g)

r: precipitation (mm)

The climatological factors used for calculating Rn and RDI are: solar radiation on the top of atmosphere, duration of possible sunsh albedo, temperature, humidity, and precipitation. NPP in above equation is a function of annual net radiation (Rn) and radiative dryness index (RDI). The ratio of NPP and Rn is strongly affected by RDI.

Correlating Rn, RDI, and NPP calculated from Chikugo Model with the vegetation zonation of Budyko's radiation equilibrium model, it is thus clear that the vegetation zones and their productivities are highly correlated with solar radiation and radiative dryness indexes (Fig. 1 and 2). NPP in the forest zones where dryness indexes are 0.3–1.0 is higher than other vegetation zones because of the fitness between radiation and climatic moisture conditions. In the moist forest zones, the tropical rainforest has the highest NPP, 25–30 T.DM/ha.Yr. NPP decreases accordingly along with the reduction of radiation. It is 10–15 T.DM in the temperate deciduous broadleaved forest zone, 5–10 T.DM in the temperate coniferous forest zone, and less than 5 T.DM in the cold-temperate coniferous forest zone. NPP significantly decreases in tundra zone because of deficit of radiation and in desert zone because of viciously combination of high temperature and limited water supply there.

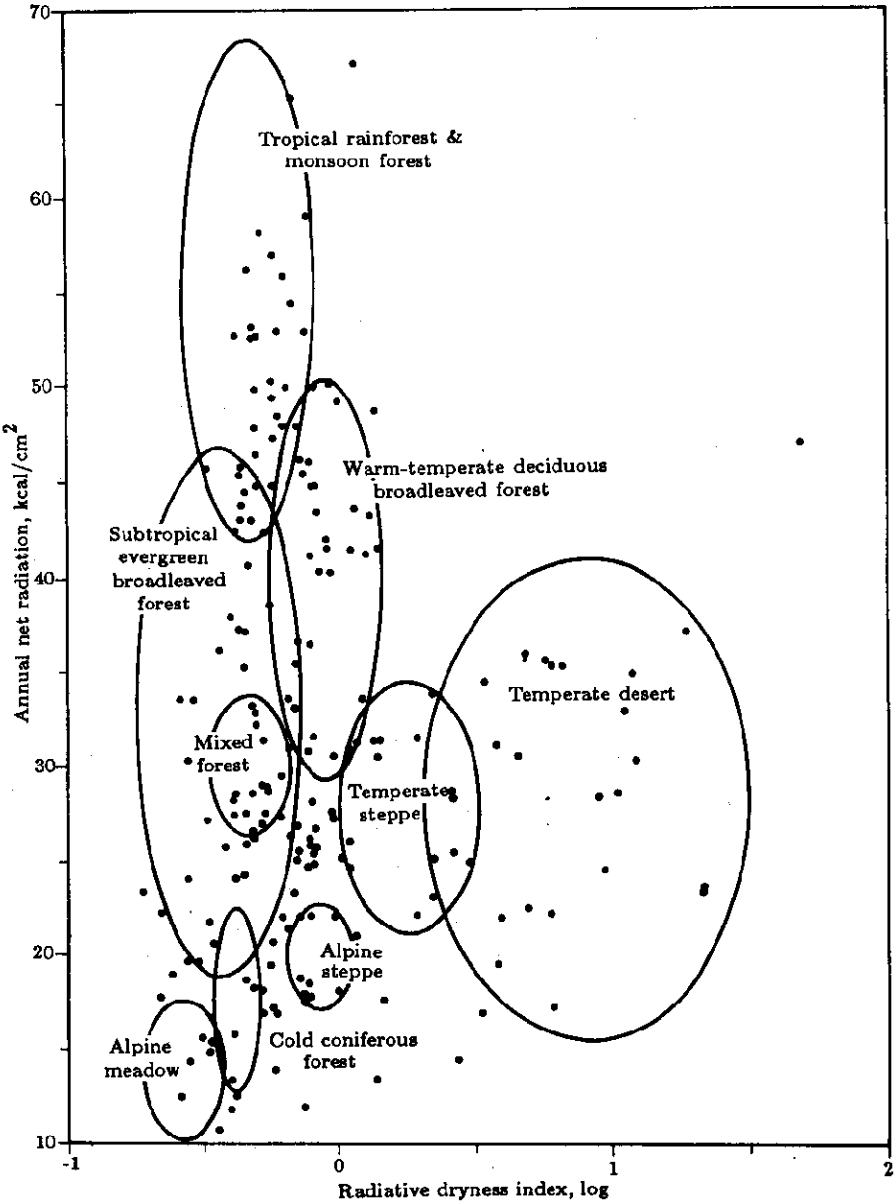

Fig. 1 Zonal vegetation in accordance with Rn and RDI in China

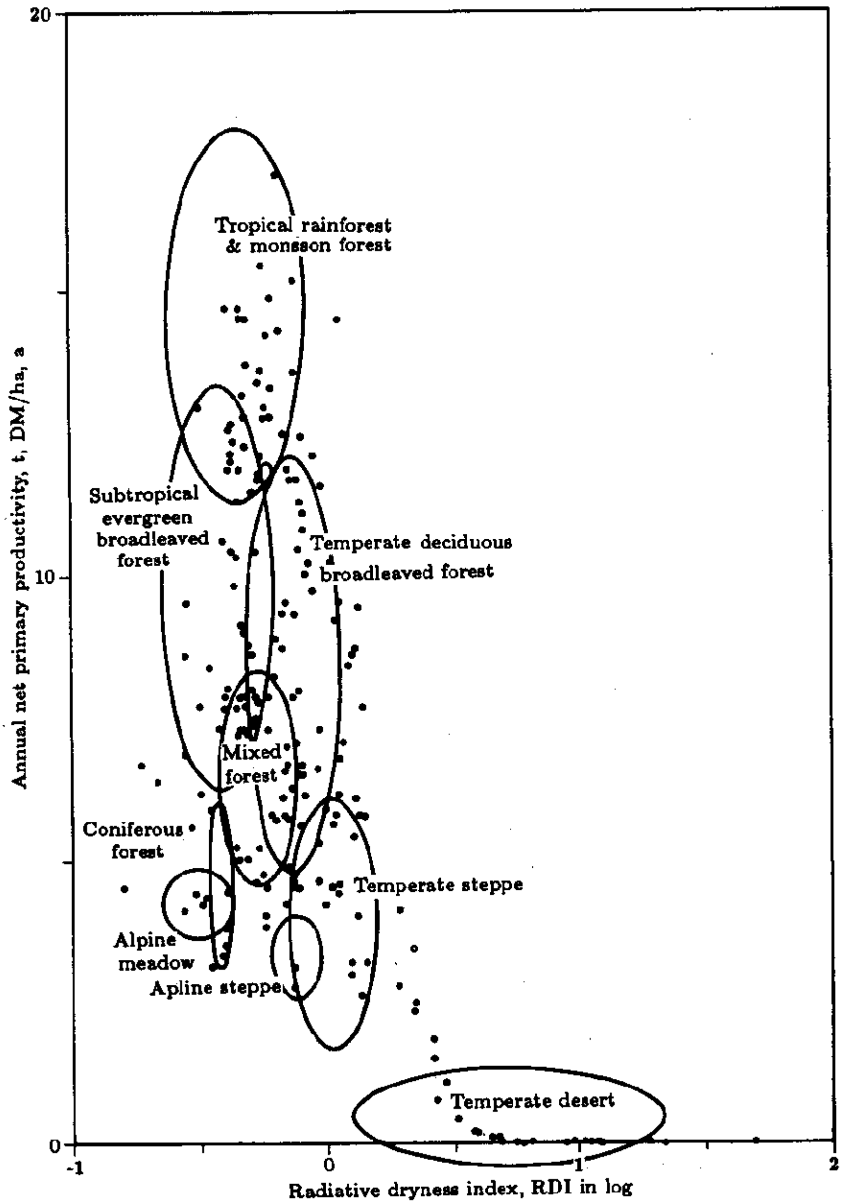

Fig. 2 Zonal vegetation in accordance with NPP and RDI in China

The general distribution pattern of potential total solar radiation (St), net radiation (Rn), radiative dryness index (RDI), and net primary productivity (NPP) in China is as follows (Table 1).

Table 1 Radiative dryness index (RDI) and net primary productivity (NPP) of vegetation zones in China (according to Budyko and Uchijima's methods)

I. Cold-temperate coniferous forest zone					
IA. Southern montane subzone					
	N	Mean	Stdev	Min	Max
LAT	6	51.685	1.153	50.400	53.470
LONG	6	123.94	1.83	121.47	126.65
ALT	6	405.0	191.0	177.4	732.6
St	6	3.6517	0.1040	3.5100	3.8100
Spar	6	1.7617	0.0412	1.7100	1.8300
Rn	6	16.15	4.58	10.90	22.20
SumT	6	1648	275	1235	2045
RDI	6	0.6000	0.1705	0.4000	0.8000
e%	6	0.2283	0.0523	0.1700	0.3000
NPP	6	4.267	1.046	3.000	5.600
II. Temperate mixed coniferous-broadleaved forest zone					
	N	Mean	Stdev	Min	Max
LAT	42	44.392	2.649	40.050	50.250
LONG	42	127.36	2.43	123.78	132.97
ALT	42	249.6	154.1	15.1	774.2
St	42	4.1402	0.1447	3.8600	4.4600
Spar	42	1.9914	0.0643	1.8500	2.1200
Rn	42	27.738	3.123	23.300	37.900
SumT	42	2604.3	363.7	1915.0	3363.0
RDI	42	0.7229	0.1355	0.4800	0.9700
e%	42	0.34000	0.03357	0.30000	0.46000
NPP	42	7.169	0.869	6.000	10.100
III. Warm-temperate deciduous broadleaved forest zone					
	N	Mean	Stdev	Min	Max
LAT	92	37.233	2.613	32.930	42.420
LONG	92	117.02	3.85	107.13	123.43
ALT	92	185.6	270.9	2.0	978.9
St	92	4.3324	0.3001	3.5600	4.7600
Spar	92	2.0792	0.1230	1.7600	2.2500
Rn	92	42.747	6.224	25.300	54.300
SumT	92	4050.6	513.4	2909.0	4891.0
RDI	92	1.1091	0.2040	0.6500	1.8300
e%	92	0.42891	0.06687	0.26000	0.58000
NPP	92	9.427	1.460	5.900	12.700

Table 1 (continued)

IV. Substropical evergreen broadleaved forest zone

IVA. Eastern subzone

	N	Mean	Stdev	Min	Max
LAT	184	28.453	2.863	22.350	33.870
LONG	184	113.38	5.09	103.00	122.82
ALT	184	213.6	232.5	1.2	1071.2
St	184	3.5214	0.4522	2.3900	4.4300
Spar	184	1.7452	0.1971	1.2400	2.1400
Rn	184	39.821	8.484	17.500	59.200
SumT	184	5575.8	833.7	3668.0	7938.0
RDI	184	0.5286	0.1501	0.2200	0.9400
e%	184	0.59707	0.05975	0.41000	0.71000
NPP	184	10.783	2.156	5.000	15.200

IVB. Western subzone

	N	Mean	Stdev	Min	Max
LAT	33	26.100	1.597	23.380	29.350
LONG	33	102.11	1.90	98.48	105.18
ALT	33	1706.9	426.7	759.9	2666.6
St	33	2.8273	0.2365	2.3300	3.3000
Spar	33	1.4470	0.1037	1.2300	1.6300
Rn	33	24.615	5.610	15.500	39.300
SumT	33	4690	1238	2569	7996
RDI	33	0.4412	0.1701	0.1600	1.1000
e%	33	0.46697	0.05497	0.36000	0.58000
NPP	33	6.767	1.314	4.400	9.400

IVC. Arid-warm valley xeroshrub vegetation region

	N	Mean
LAT	1	23.570
LONG	1	102.15
ALT	1	396.60
St	1	4.1800
Spar	1	2.0200
Rn	1	57.600
SumT	1	8709.0
RDI	1	1.2600
e%	1	0.56000
NPP	1	11.900

Table 1 (continued)

V. Tropical rainforest & monsoon forest zone

VA. Eastern subzone

	N	Mean	Stdev	Min	Max
LAT	26	21.061	1.748	16.830	23.620
LONG	26	110.46	2.35	106.75	116.30
ALT	26	48.6	59.3	4.6	250.9
St	26	4.0554	0.4064	3.4200	5.2800
Spar	26	1.9750	0.1718	1.7100	2.4900
Rn	26	54.65	8.45	43.00	81.10
SumT	26	7942	1560	831	9672
RDI	26	0.5831	0.1954	0.2600	1.1600
e%	26	0.70500	0.02789	0.62000	0.75000
NPP	26	14.546	1.675	12.100	19.500

VB. Western subzone

	N	Mean	Stdev	Min	Max
LAT	6	22.790	1.003	21.480	24.020
LONG	6	101.57	3.01	97.83	105.95
ALT	6	566.9	239.7	136.7	793.3
St	6	3.692	0.440	2.930	4.100
Spar	6	1.8233	0.1866	1.5000	2.0000
Rn	6	45.33	8.58	29.80	53.00
SumT	6	7514	783	6049	8246
RDI	6	0.5367	0.1411	0.3600	0.7600
e%	6	0.6483	0.0479	0.5600	0.7000
NPP	6	12.267	2.053	8.400	14.200

VI. Temperate steppe zone

VIA. Eastern subzone

	N	Mean	Stdev	Min	Max
LAT	65	41.842	4.388	35.370	50.220
LONG	65	114.48	7.24	102.85	125.90
ALT	65	902.9	534.7	114.9	1917.0
St	65	3.8643	0.4831	3.0800	4.7200
Spar	65	1.8765	0.1908	1.5500	2.2200
Rn	65	25.525	5.648	15.100	35.400
SumT	65	2706.8	465.3	1646.0	3503.0
RDI	65	1.2255	0.4925	0.5300	2.9700
e%	65	0.26446	0.5932	0.05000	0.36000
NPP	65	5.182	1.313	1.100	7.100

Table 1 (continued)

VIB. Western subzone					
	N	Mean	Stdev	Min	Max
LAT	4	47.153	0.511	46.670	47.730
LONG	4	87.51	2.20	85.72	90.38
ALT	4	1057	252	735	1292
St	4	3.648	0.285	3.330	4.020
Spar	4	1.7800	0.1152	1.6500	1.9300
Rn	4	21.90	4.90	16.60	28.40
SumT	4	2272	365	1984	2795
RDI	4	2.170	0.324	1.950	2.640
e%	4	0.1200	0.0245	0.0900	0.1500
NPP	4	2.250	0.420	1.800	2.800

VII. Temperate desert zone					
	N	Mean	Stdev	Min	Max
LAT	48	40.918	2.778	36.300	48.050
LONG	48	90.97	9.17	75.98	107.40
ALT	48	1113.2	484.0	34.5	3191.1
St	48	3.6877	0.4337	2.8400	4.5000
Spar	48	1.7979	0.1793	1.4300	2.1200
Rn	48	27.66	7.01	15.60	47.00
SumT	48	3600	705	1189	5391
RDI	48	9.58	8.62	1.34	48.66
e%	48	0.02187	0.04954	0.00000	0.20000
NPP	48	0.387	0.861	0.000	3.400

VIIB. Zaidam desert subzone					
	N	Mean	Stdev	Min	Max
LAT	11	37.575	0.901	36.420	38.830
LONG	11	97.097	2.619	93.170	100.250
ALT	11	3004.2	226.6	2733.0	3360.7
St	11	3.5900	0.1394	3.3000	3.7900
Spar	11	1.7900	0.0640	1.6600	1.8900
Rn	11	16.65	4.14	8.20	22.80
SumT	11	1122	688	97	2010
RDI	11	5.11	5.73	0.35	17.01
e %	11	0.0991	0.0978	0.0000	0.2500
NPP	11	1.800	1.791	0.000	4.800

Table 1 (continued)

VIII. Tibetan high-cold vegetation district

VIIIA. High-cold meadow-scrub subzone

	N	Mean	Stdev	Min	Max
LAT	26	33.440	1.067	31.480	35.270
LONG	26	98.858	3.378	91.100	102.970
ALT	26	3792.3	474.9	2915.7	4800.0
St	26	3.7800	0.4033	2.9300	4.4500
Spar	26	1.8912	0.1809	1.5000	2.1800
Rn	26	16.558	1.970	13.500	19.900
SumT	26	354.6	397.9	0.0	1512.0
RDI	26	0.5396	0.1723	0.3100	1.0000
e%	26	0.23423	0.02730	0.18000	0.27000
NPP	26	4.4731	0.4468	3.7000	5.3000

VIIIB. High-cold steppe subzone

	N	Mean	Stdev	Min	Max
LAT	6	33.935	2.253	30.950	36.270
LONG	6	94.13	5.05	88.63	100.62
ALT	6	4113	817	2835	4700
St	6	4.238	0.450	3.550	4.540
Spar	6	2.0933	0.2031	1.7800	2.2300
Rn	6	20.13	2.93	15.30	24.30
SumT	6	368	561	0	1419
RDI	6	1.1300	0.1620	0.9500	1.3600
e%	6	0.2050	0.0339	0.1600	0.2500
NPP	6	4.383	0.407	3.600	4.700

VIIIC. Southern Tibetan temperate steppe-shrubland subzone

	N	Mean	Stdev	Min	Max
LAT	4	29.400	0.199	29.250	29.670
LONG	4	90.487	1.257	88.880	91.770
ALT	4	3711.4	134.9	3551.7	3836.0
St	4	4.195	0.209	4.010	4.490
Spar	4	2.0675	0.0929	1.9900	2.2000
Rn	4	36.500	1.374	35.000	38.200
SumT	4	2001	227	1802	2263
RDI	4	1.555	0.249	1.360	1.920
e%	4	0.2950	0.0451	0.2300	0.3300
NPP	4	6.275	1.005	4.800	7.000

1. The highest point of calculated potential annual total solar radiation (St, GJ/M2) is 5.28 at the Nansha Islands in the tropical South China Sea. Other two high points are 4.72 on the Loess Plateau in the southern part of steppe zone and 4.76 in North China's deciduous broadleaved forest zone. The St is also high in southern Xinjiang's desert zone—4.5 and on the Tibetan Plateau—more than 4.5. The lowest point of St is located in the rainy subtropical zone, where the average of St is 2.8–3.5 and the lowest point is 2.3.

2. Calculated annual net radiation (Rn, kcal/cm^2) generally increases southwards (Fig.3). The average of Rn is 45–55 and the highest is more than 80 in China's Tropics. The lowest Rn exists in the northernmost cold-temperate coniferous forest zone, it averages 16 there and the lowest point is 11. The average is 42 in deciduous broadleaved forest zone and it is lower in the rainy and cloudy subtropical evergreen broadleaved forest zone. But, Rn is as high as 58 in the western subtropical arid-warm valley region. Rn is low, only 16, in the eastern high-cold meadow subzone of the Tibetan Plateau. It is higher—20 in the central high-cold steppe subzone and the highest point, 35-38 on the Plateau is in its southern valley's temperate steppe subzone.

3. The radiative dryness indexes (RDI) highly accord with vegetation zones (Fig.4). It is 0.6 in the cold-temperate coniferous forest zone and 0.72 in the temperate mixed coniferous-broadleaved forest zone. Even the highest RDI in the above mentioned zones is not over 1.0. But, the RDI is quite high in the warm-temperate deciduous broadleaved forest zone. Its average is higher than 1.0 and the highest one could reach to 1.8 or even more. That indicates the aridness is extremely high there because it is heavily affected by the continental Mongoli-Siberian high pressure anticyclonic center and strongly depressed by steppe zone from the north. In fact, a large part of deciduous broadleaved forest zone in China has been seriously steppolized or it should partially belong to steppe zone. The RDI of subtropical forest zone is generally 0.4–0.5, but it is as high as 1.26 in the western dry-hot valleys. The RDI of tropical forest zone averages 0.5–0.6, usually not over 1.0. Temperate steppe zone has average RDI in 1.2 (eastern part) and 2.2 (western part). Average RDI in temperate desert zone is 9.6, the highest one could be up to 48.7. The RDI of the Tibetan Plateau is 0.54 in eastern high-cold meadow subzone, 1.13 in high-cold steppe zone, and 1.56 in southern Tibetan temperate shrub-steppe subzone. The RDI in western and northern plateau desert subzones could be higher than 3–4.

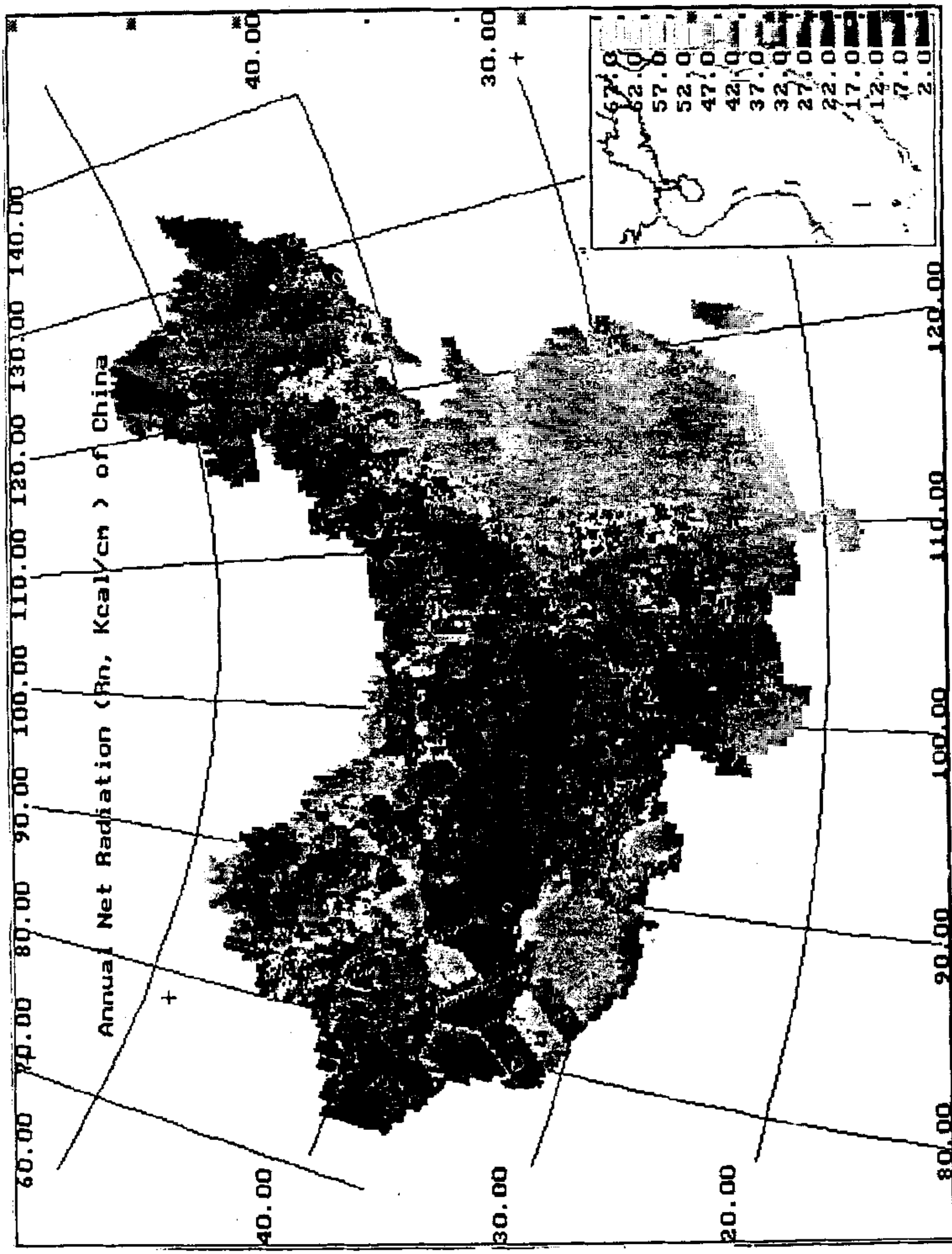

Fig. 3 Distribution of Rn in China

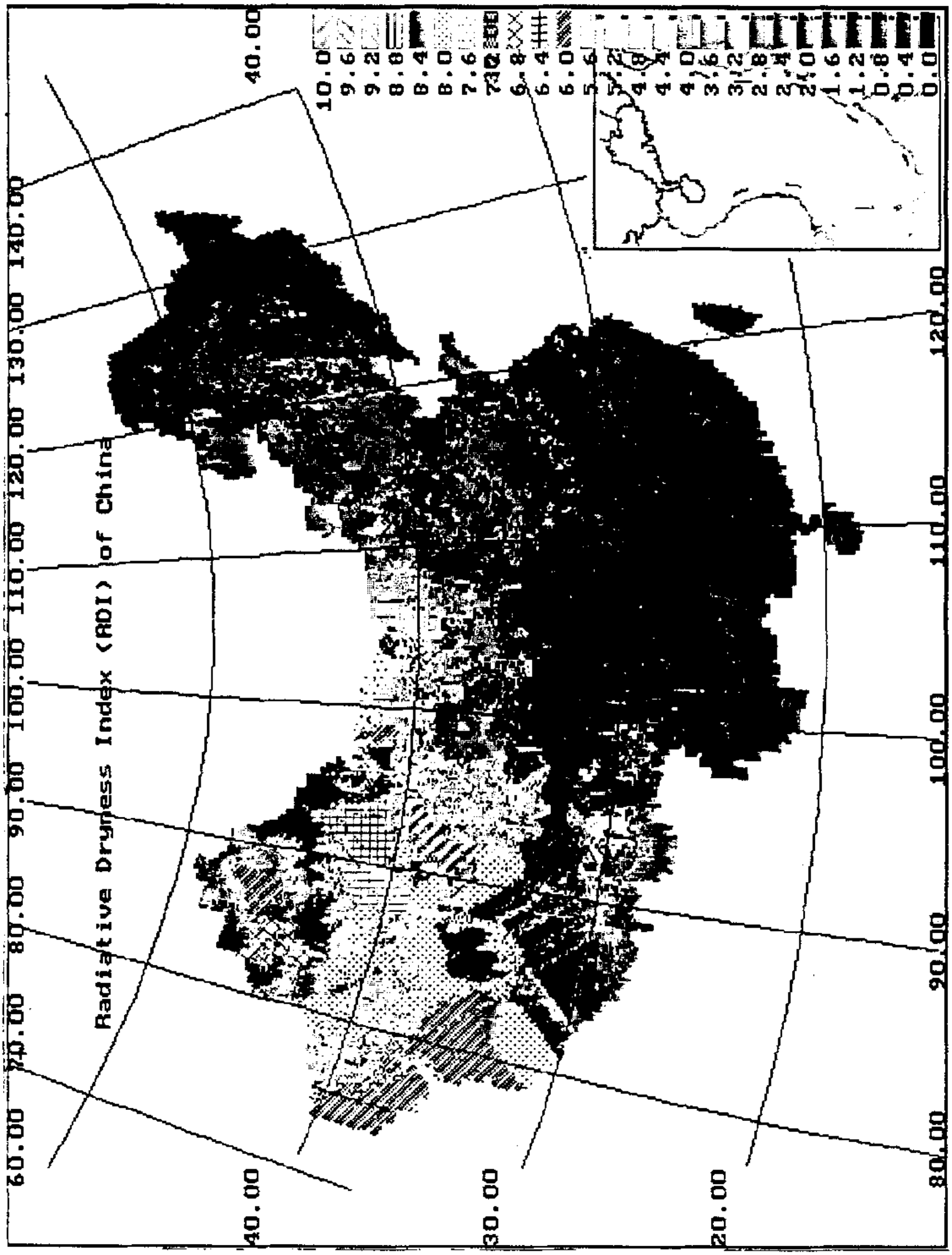

Fig.4 Distribution of RDI in China

Because of the high correlation between RDI and vegetation zones, it should be considered as a signification index for ecological and vegetation regionalization. Especially for the region where the primary vegetation had been completely destroyed or changed, RDI seems a dependable parameter for determining the potential vegetation types.

4. The gradient of calculated potential net primary productivity (NPP, T. DM/Ha. Yr) of forest zones prominently increases from the north to the south. It is 4.3 in cold-temperate coniferous forest zone, 7.2 in temperate mixed coniferous-broadleaved forest zone, 9.4 in warm-temperate deciduous broadleaved forest zone, 10.8 in subtropical evergreen broadleaved forest zone, and 12.3 in tropical rainforest and monsoon forest zone. The highest NPP is 19.5 on an island in the tropical South China Sea. Comparing with other tropical forest area in the world, China's terrestrial tropics is very limited in area and much lower in NPP. The northern Tropics of China separates into 4 disconnected regions along the southern coast of China and is strongly affected by the northern continental and cold airflow during the winter time for lack of orographic barriers on the eastern Asian plain to block the high pressure dry and cold current.

The average NPP is 5.2 in temperate steppe zone, 0.4 in temperate desert zone, and less than 0.1 or 0 for the most part of extremely arid desert area in northwestern China. It is 4.5 in the high-cold meadow subzone on the eastern Tibetan Plateau, 4.4 in the high-cold steppe subzone for the most part on the central plateau, and 6.3 in the warmer southern Tibetan temperate shrub-steppe subzone. There is no calculation of NPP for the western and northern parts of the plateau because of lacking records in these areas. But, it should be less than 1 in the western desert subzone and less than 0.1 or 0 in the northern Qiangtang's high-cold desert subzone.

5. The energy efficiency(%) of net primary production of vegetation (e%) on annual global solar radiation basis is calculated from a total global solar radiation (St), NPP, and caloric content for plant (woody) dry matter (4.7 kcal/g). It is generally between 0.2–0.7 in China's forest zones. The highest e% in the tropical forest area is 0.75 and the lowest one is 0.17 in the northernmost coniferous forest area. The e% of the arid zones is much lower, 0.1–0.36 in the steppe zone, 0–0.25 in the desert, and 0.2–0.3 on the Tibetan Plateau.

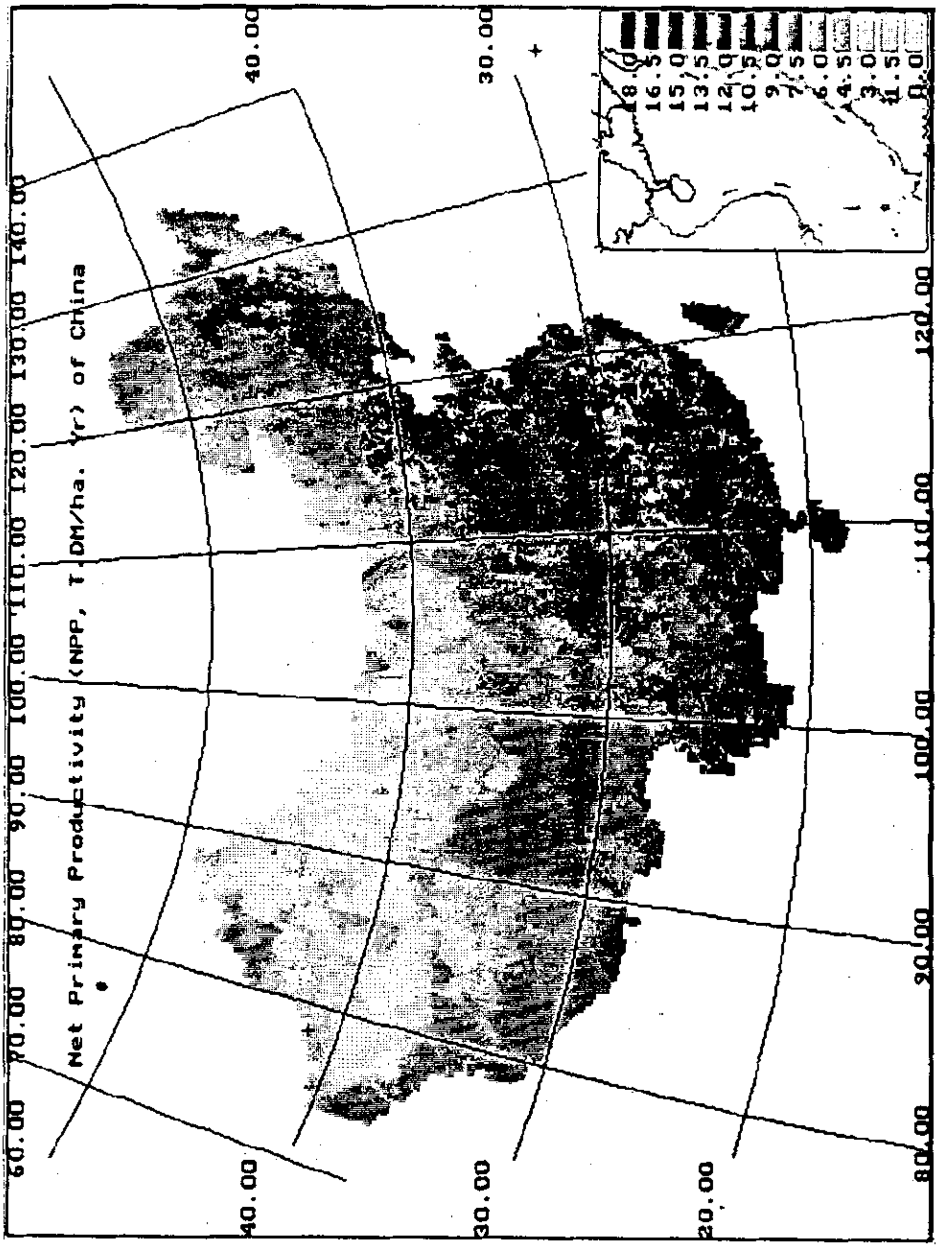

Fig.5 Distribution of NPP in China

CONCLUSION

According to the above-mentioned analysis of vegetation-climate correlation, the climatic potential productivity of China's vegetation zones is given. It is thus clear that the main limit factors of primary production in China are deficit in water supply, insufficient moistureheat equilibrium, and low temperature (even for the Tropics) in the winter. The one of the key methods to increase primary production in the forest zones is to improve the energy efficiency of the net primary production (e%). That could be reached mostly by restoration and optimization of community structure, such as, multilayered and diversified (mixed) plantation temporally and spatially could result obvious ecologieconomic gain by increasing solar energy efficiency and primary production, improving community stability, controlling water and soil erosion, reducting damages of diseases and insect pests and so on. Although the NPP is quite low in northern China's temperate steppe and desert zones, it is rational management, conservation, and improvement, such as, appropriate and limited cultivation, grazzing, and utilization, controlling desertification, establishing local optimized agroforestry systems and so on. Under the condition of suitable combination of high solar energy and abundant water supply (by irrigation) in oases or ecotone between oases and desert, highly productive artificial grassland or tree-crops plantation could be established with 10–15 T.DM of NPP.

The calculation of RDI, NPP, and e% for vegetation zones also could be used to estimate or simulate the pattern of vegetation succession and change of NPP under global climate change by the "greenhouse effect".

Acknowledgements—The material on which this paper is based was from the Eco-climatological Database in the Laboratory of Quantitative Vegetation Ecology, Institute of Botany, Chinese Academy of Sciences. We would like to thank the staff of the Lab, Zhao Shuyu, Guo Yuke, and Zhao Shiyong, for their effort and help to establish the database.

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