Comparison of Extrapolation and Interpolation Methods for Estimating Daily Photosynthetically Active Radiation (PAR)
——A Case Study of the Poyang Lake National Nature Reserve, China

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Abstract Measurements of photosynthetically active radiation (PAR), which are indispensable for simulating plant growth and productivity, are generally very scarce. This study aimed to compare two extrapolation and one interpolation methods for estimating daily PAR reaching the earth surface within the Poyang Lake national nature reserve, China. The daily global solar radiation records at Nanchang meteorological station and daily sunshine duration measurements at nine meteorological stations around Poyang Lake were obtained to achieve the objective. Two extrapolation methods of PARs using recorded and estimated global solar radiation at Nanchang station and three stations (Yongxiu, Xingzi and Duchang) near the nature reserve were carried out, respectively, and a spatial interpolation method combining triangulated irregular network (TIN) and inverse distance weighting (IDW) was implemented to estimate daily PAR. The performance evaluation of the three methods using the PARs measured at Dahuchi Conservation Station (day number of measurement = 105 days) revealed that: (1) the spatial interpolation method achieved the best PAR estimation ($R^2 = 0.89$, s.e. = 0.99, $F = 830.02$, $P < 0.001$); (2) the extrapolation method from Nanchang station obtained an unbiased result ($R^2 = 0.88$, s.e. = 0.99, $F = 745.29$, $P < 0.001$); however, (3) the extrapolation methods from Yongxiu, Xingzi and Duchang stations were not suitable for this specific site for their biased estimations. Considering the assumptions and principles supporting the extrapolation and interpolation methods, the authors conclude that the spatial interpolation method produces more reliable results than the extrapolation methods and holds the greatest potential in all tested methods, and more PAR measurements should be recorded to evaluate the seasonal, yearly and spatial stabilities of these models for their application to the whole nature reserve of Poyang Lake.

Keywords photosynthetically active radiation (PAR); extrapolation; interpolation; triangulated irregular network (TIN); inverse distance weighting (IDW)

CLC number P208

► Received on May 22, 2010.
► Supported by the National Natural Science Foundation of China (No. 40971191); the Scientific Research Starting Foundation of Ministry of Education of China for Returned Overseas Chinese Scholars, the Special Foundation of Ministry of Finance of China for Nonprofit Research of Forestry Industry (No. 200904001); the International Institute for Geo-information Science and Earth Observation (ITC), the Netherlands.
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Introduction

Photosynthetically active radiation (PAR), or the solar energy over the spectrum of 400-700 nm, is an important factor determining the growth and productivity of plants.\[1\] Because of this, PAR is frequently used as an input variable in plant growth and productivity simulation models.[2-4] Therefore, long-term and accurate PAR records are necessary for implementing these models. However, such records are generally very scarce because PAR is not measured routinely.

Various methods have been proposed to estimate PAR for locations which lack measurements. One of the commonly used methods is to derive PAR from the measured global solar radiation because PAR is a fraction of this radiation. The PAR proportion in global solar radiation varies from 35% to 50% depending on weather and climatic conditions.[5-7] However, accurate records of global solar radiation reaching the earth surface are only available from a few sites because of the high costs of the required instruments and their maintenance and calibration.\[8\] Therefore, various physical, statistical or stochastic methods have been used to estimate global solar radiation.

Physical methods comprise radiative transfer models that consider physical interactions between solar radiation and atmosphere, such as Rayleigh scattering, radiative absorption by ozone and water vapour, and aerosol extinction.[9,10] Such methods are difficult to be used by non-experts for their complexities.[11] Statistical methods are based on empirical relations between the transmittance of incident solar radiation and meteorological variables.[12] They derive radiations from the routinely measured meteorological variables such as sunshine duration,[9,13] cloud cover,[8,14] temperature,[15,16] precipitation,[12] air humidity,[17] or their combinations.[18,19] Stochastic methods[20,21] incorporate the aspects of physical and statistical methods, and are more flexible in combination with stochastic processes such as cloud movement.[22] They could be helpful in exploring possible or theoretical model scenarios over a long time period,[23] but cannot generate the data matching the actual weather conditions for a particular time period.[12]

Two methods are generally employed to estimate the radiations at unobserved locations from those at observed sites, such as meteorological stations. The extrapolation method regards the recorded or calculated radiation at a nearby site as the value at an unobserved site if the distance between the two sites falls below a certain value.[8,24] When a network of meteorological stations exists, spatial interpolation methods, such as geometric interpolation and geostatistics method, can be used. For example, Barr et al.[25] used inverse-distance-squared weighting (a geometric interpolation method) and Kriging (a geostatistics method) methods to estimate solar radiation on the Canadian prairies, Rehman and Ghori[26] and Tiba[27] applied Kriging to derive the spatial distribution of radiation in the Saudi Arabia and the Brazilian Northeast, respectively, and Miller et al.[28] applied six spatial interpolation methods (e.g., Inverse Distance Weighting (IDW), Radial Basis Functions, and Kriging) to generate a parameter value of the Johnson–Woodward model and tested its spatial applicability for estimating solar radiation from the sunshine duration record.

There is an increasing interest for model productivities of aquatic ecosystems. However, the availability of PAR or associated records is even sparser in such environments than terrestrial environments. Moreover, aquatic environments might have different weather conditions from the surrounding terrestrial environments. It remains questionable, therefore, whether extrapolation or interpolation from nearby land-based meteorological stations results in accurate PAR estimations over lake environments.

This study aimed to compare two extrapolation and one interpolation methods for estimating daily PAR reaching the earth surface within the Poyang Lake national nature reserve, China from the global solar radiation and sunshine duration recorded at the nearby meteorological stations.

1 Materials and methods

1.1 Study area

Poyang Lake national nature reserve (Fig.1) is situated at 115°55′-116°03′E and 29°05′-29° 15′N in the northwest of Poyang Lake, and has a generally flat terrain with several hills about 50 meters high.[29] Poyang Lake (including the nature reserve) has a rich
biodiversity with 102 species of aquatic plants and 122 species of fishes, and it is one of the biggest bird conservation areas in the world, hosting millions of birds from over 300 species.\textsuperscript{[29]} The lake is particularly important to the conservation of the endangered Siberian crane,\textsuperscript{[30]} as more than 95% of its world population winter here.\textsuperscript{[29]} The PAR estimation over this region is important for understanding the lake ecosystem, including the underwater PAR and the growth of one submerged aquatic macrophyte species, Vallisneria spiralis L., the tuber of which is the main food of the wintering Siberian crane.

1.2 Meteorological data

Nine meteorological stations are distributed around Poyang Lake (Fig.1). Daily sunshine duration is measured routinely in these stations, while daily global solar radiation is only recorded at Nanchang station. We obtained the daily sunshine duration measurements at the nine stations and the daily global radiation records at Nanchang station for the time period of 2001-2006. These data were measured and recorded according to the Chinese meteorological standards.

In addition, PAR at the building top of Dahuchi Conservation Station (Fig.1), which just lies at the edge of Lake Dahuchi, was recorded at five minute intervals from 6 July to 12 August and from 6 September to 10 November 2006 with a LI-190SA quantum sensor and a LI-1400 data logger (http://www.licor.com) to evaluate the performances of the extrapolation and interpolation methods described below.

1.3 Extrapolation and interpolation methods

We first estimated daily PAR in the nature reserve using the following three methods:

1) Extrapolating from measured global solar radiation

2) The nature reserve is located about 55-75 km from the Nanchang station, which is the closest meteorological station to the nature reserve with global solar radiation records. Given this distance and the contrast between lake and terrestrial environments, we consider that the radiation records at Nanchang
station might not reflect the radiation variation over the nature reserve. We supposed a PAR fraction of 45% in global solar radiation\textsuperscript{[5,6]} and used this proportion to estimate daily PAR from daily global solar radiation at Nanchang station (Eq.(1)). The estimated daily PAR was then extrapolated to the nature reserve.

\[
PAR = R \times 0.45 \tag{1}
\]

where \(PAR\) and \(R\) represent the daily PAR and daily global solar radiation reaching the earth surface, respectively.

(2) Extrapolating from estimated global solar radiation

Three meteorological stations (Xingzi, Yongxiu and Duchang) are closer to the nature reserve than the Nanchang station (Fig.1). The solar radiations at the three stations might more reasonably reflect those in the nature reserve. However, the radiation measurements are missing at the three stations. Because of the missing global solar radiation and existing sunshine duration records, Chen’s model\textsuperscript{[31]} (Eq.(2)), which explained 92\% of the variation of the global solar radiation using sunshine duration at 86 meteorological stations in China, was applied to estimate global solar radiations at the three stations from the measured sunshine durations after model evaluation.

\[
R = R_{ext} \times (0.001 \times \Phi + 2.41 \times 10^{-5} \times H + 0.109
+ 1.029 \times \frac{S}{S_{ext}} - 1.216 \times (\frac{S}{S_{ext}})^2 + 0.787 \times (\frac{S}{S_{ext}})^3) \tag{2}
\]

where \(S\) is the daily sunshine duration on the earth surface, \(\Phi\) and \(H\) represent the latitude and altitude of the meteorological station, respectively, and \(R_{ext}\) and \(S_{ext}\) denote the extra atmosphere global solar radiation and maximum sunshine duration\textsuperscript{[32,33]}

We first evaluated Chen’s model using the sunshine duration and solar radiation records from 2001 to 2006 at Nanchang station, and the evaluation revealed a highly significant correlation between the estimated and measured radiations \((R^2 = 0.92, F = 26959.28, n = 2191, P < 0.0001)\). The model was then applied to estimate daily global solar radiations from sunshine durations, and daily PARs were derived with Eq.(1) at the three stations. Finally, the derived daily PARs at the three stations were extrapolated to the nature reserve, respectively.

(3) Interpolating from estimated global solar radiations

Spatial interpolation derives spatially continuous estimation of meteorological data from spatially discrete locations within a network of meteorological stations.\textsuperscript{[34]} We thus explored whether this method could provide a more accurate result compared with the extrapolation methods. We first estimated the daily global solar radiations and PARs at the meteorological stations using Eqs. (2) and (1), respectively. Then, a triangulated irregular network (TIN)\textsuperscript{[35]} with nine meteorological stations as TIN nodes was created by using ArcGIS Software (http://www.esri.com), and IDW method\textsuperscript{[36]} (Eq. (3)) was applied to estimate the PAR at a given location within each triangle from the estimated PARs at the three stations forming the triangle.

\[
PAR = \frac{PAR_1}{dis_{i1}^2} + \frac{PAR_2}{dis_{i2}^2} + \frac{PAR_3}{dis_{i3}^2} \times \left(\frac{1}{dis_{i1}^2} + \frac{1}{dis_{i2}^2} + \frac{1}{dis_{i3}^2}\right) \tag{3}
\]

where \(PAR_i\) is the PAR on the earth surface at a given location \(i\), \(PAR_1\), \(PAR_2\) and \(PAR_3\) are the PARs at nodes (meteorological stations) 1, 2 and 3 forming a TIN triangle, and \(dis_{i1}\), \(dis_{i2}\) and \(dis_{i3}\) are distances from location \(i\) to the three nodes, respectively.

Then we used the daily PAR measured at the Dahuchi Conservation Station to evaluate the performances of the above-mentioned methods. Agreement between the measured and estimated values was described by the intercept, slope and coefficient of determination \((R^2)\) of the reduced major axis (RMA) regression\textsuperscript{[37]} line of the measured against estimated values, and estimation standard error (s.e.). The differences of correlation coefficients derived from \(R^2\) for all pairs of regressions were tested, the null hypothesis tests of intercept equal to zero and slope equal to one were carried out, and the standard errors of the estimations were compared. Based on these tests and comparisons, we evaluated the performances of these methods and further suggested the optimal method for estimating daily PAR in the nature reserve.

Finally, the daily PAR in Lake Dahuchi within the nature reserve was estimated by using the optimal method and its seasonal pattern was summarized briefly.
2 Experiments

The TIN based on the nine meteorological stations around Poyang Lake covers the whole nature reserve. The Dahuchi Conservation Station lies in the triangle with Xingzi, Duchang and Yongxiu stations as nodes.

The scatter plots (Fig.2) of the PARs measured at Dahuchi Conservation Station against those estimated through extrapolation and interpolation methods show good agreements.

Table 1: Statistics describing the reduced major axis (RMA) regressions of PAR at Dahuchi Conservation Station against those estimated through extrapolation of global solar radiation

|   | R²   | s.e. | F      | P     |
|---|------|------|--------|-------|
| (a) | 0.88 | 0.99 | 745.29 | < 0.001 |
| (b) | 0.80 | 1.27 | 429.32 | < 0.001 |
| (c) | 0.87 | 1.04 | 669.76 | < 0.001 |
| (d) | 0.89 | 0.93 | 868.43 | < 0.001 |
| (e) | 0.89 | 0.94 | 830.02 | < 0.001 |

Table 2: Difference tests (P value) of correlation coefficients derived from $R^2$ for all pair of regressions

|   | (b) | (c) | (d) | (e) |
|---|-----|-----|-----|-----|
| (a) | 0.0471 | 0.7750 | 0.7573 | 0.7573 |
| (b) | 0.0886 | 0.0221 | 0.0221 |
| (c) | – | 0.5521 | 0.5521 |
| (d) | – | – | 1 |

The null hypothesis tests of intercept equal to zero and slope equal to one for the RMA regression lines reveal that the intercepts for Duchang (d) differs significantly from zero and the slopes for Yongxiu (c) and Duchang (d) are significantly different from one at a significant level of 0.01, which indicates that the extrapolations from Yongxiu (c) and Duchang (d) stations achieve biased PAR estimations.

Of the two unbiased models, the interpolation method (e) holds a lower standard error (s.e. = 0.94), than the extrapolation method from Nanchang station (A, s.e. = 0.99).

Synthetically comparing and analyzing the intercept, slope, coefficient of determination and standard error of all estimations, we considered that the spatial interpolation method (e) achieved the best PAR estimation at Dahuchi Conservation Station, the PAR extrapolation from Nanchang station (a) obtained an unbiased result, and the extrapolations from Yongxiu (c), Xingzi (b) and Duchang (d) stations were less appropriate because of their biased estimations.

Fig. 3 shows the daily PARs in Lake Dahuchi from 2001 to 2006 based on spatial interpolation method (e). The figure reveals seasonal variation in daily PAR with higher values in summer than in winter, with day-to-day variation superimposed.

Fig. 2: Scatter plots of daily photosynthetically active radiation (PAR, MJ m$^{-2}$ day$^{-1}$) measured (Y axis) from 6 July to 12 August and from 6 September to 10 November 2006 at Dahuchi Conservation Station against those estimated (X axis) through extrapolation of the global solar radiation measured at Nanchang (a) and estimated at Xingzi (b), Yongxiu (c) and Duchang (d), and interpolation of PARs estimated at these three meteorological stations (e) ($n = 105$ days)
Table 3  Null hypothesis tests of intercept equal to zero and slope equal to one for the reduced major axis (RMA) regressions between the measured and estimated PAR

|       | Intercept | Slope       |
|-------|-----------|-------------|
|       | $a \pm s.e.$ | $t$ | $P$ | $b \pm s.e.$ | $t$ | $P$ |
| (a)   | 0.1771±0.2293 | 0.7723 | 0.4417 | 0.9190±0.0316 | 2.5633 | 0.0118 |
| (b)   | 0.4912±0.2806 | 1.7505 | 0.0830 | 0.9694±0.0425 | 0.7200 | 0.4731 |
| (c)   | 0.4664±0.2339 | 1.9940 | 0.0488 | 0.8971±0.0327 | 3.1468 | 0.0022 |
| (d)   | 0.5585±0.2059 | 2.7125 | 0.0078 | 0.8640±0.0281 | 4.8399 | 0.0000 |
| (a)   | 0.3966±0.2169 | 1.8285 | 0.0703 | 0.9236±0.0309 | 2.4725 | 0.0150 |

Fig. 3  Daily PAR estimated using spatial interpolation method in Lake Dahuchi

3 Discussion

We reported that the extrapolation of solar radiation measured at Nanchang station explained 88% of the variation of PAR at Dahuchi Conservation Station. The relative short distance (about 55 km) between Nanchang station and the Dahuchi Conservation Station possibly contributes to their similarity in solar radiations. This result is contrary to our assumption that the radiation record at Nanchang station might not realistically reflect the variation of radiation in the nature reserve. However, it corresponds to the result of Hunt et al.,[8] who reported that it would be preferable to use the measured data from a neighbouring station if the distance between sites was less than 390 km. Nevertheless, this does not mean that the other parts in the nature reserve could also obtain a similar result, because the Dahuchi Conservation Station is closer to Nanchang station compared with other parts (Fig.1), and the estimation accuracy might decline with the increasing distance to the meteorological station.[19,24,38]

We supposed that extrapolation from meteorological stations closer to the nature reserve might achieve better PAR estimates compared with that from the Nanchang station. However, we found that the extrapolations from Xingzi, Yongxiu and Duchang stations did not result in better estimations than from Nanchang. Moreover, the extrapolation results from different stations showed high differences. However, we argue that such comparison cannot be used to draw a conclusion that the PAR at Nanchang station describes the solar conditions in our study area better than that at Xingzi, Yongxiu or Duchang stations. We consider that the accuracy of the solar radiation model (Eq.2) might affect the PAR estimations at these stations, which further influences the accuracies of extrapolation methods. Meanwhile, the spatial variability of solar radiation in our study area induced by local environments could also contribute to these relatively lower accuracies.

The TIN and IDW-based spatial interpolation method obtained the best PAR estimation in all tested methods. TIN restricts which three meteorological stations might mainly affect the radiation at a given point considering the spatial distribution of all stations, while IDW is based on the spatial correlation of variables and predicts the values of variables at unobserved locations from those at observed locations. The combination of TIN and IDW thus achieved more accurate PAR estimation compared with the extrapolation method, which only uses the data from one station. Therefore, considering the assumptions and principles supporting these methods, we consider that the interpolation method could produce a more reliable result than the extrapolation methods in the nature reserve.

Several extrapolation and interpolation methods from nearby land-based meteorological stations were
compared for PAR estimations over lake environments. We found that the PARs derived from the extrapolation at the Nanchang station and from the interpolation with TIN and IDW method showed significant correlations with those at Dahuchi Conservation Station and achieved unbiased PAR estimations, which indicates that the extrapolation or interpolation methods from nearby land-based meteorological stations can be used for PAR estimations at Dahuchi Conservation Station. However, these results do not imply that the extrapolation or interpolation methods from nearby land-based meteorological stations result in accurate PAR estimations because of the differences in weather conditions between lakes and their surrounding terrestrial environments, especially for large water bodies like Poyang Lake. Further detailed evaluations of these methods for their application to the whole nature reserve or Poyang Lake should be carried out.

One general limitation of TIN-based interpolation is that the points on the shared edge of two adjacent triangles have two interpolated values, which are calculated from two triangles respectively. The mean of the two interpolated values was calculated as the final value, which might overcome this limitation of the suggested method.

Only the PAR measurements at Dahuchi Conservation Station in a limited time period (105 days) in the summer, autumn and winter of 2007 were recorded to evaluate the performances of the extrapolation and interpolation methods. We acknowledge that such evaluation holds certain limitations considering the account of evaluation sites and the time period of PAR measurements. Therefore, we suggest that further evaluations should be made to evaluate the seasonal, yearly and spatial stabilities of these models.

4 Conclusion

The principal results obtained can be summarized as follows:

(1) The spatial interpolation method obtained the best estimation of daily PAR at Dahuchi Conservation Station, and holds the greatest potential in all tested methods to be applied in the whole nature reserve after further evaluations.

(2) The extrapolation method from directly measured solar radiation at Nanchang station explains 88% of variation of daily PAR at Dahuchi Conservation Station, and achieved an unbiased result. However, the estimation accuracy for other parts within the nature reserve might decline with the increasing distance to Nanchang station.

(3) More PAR measurements should be recorded to evaluate the seasonal, yearly and spatial stabilities of these models for their application to the whole nature reserve or Poyang Lake.

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