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Analysis of the relationship between electromagnetic radiation characteristics and urban functions in highly populated urban areas

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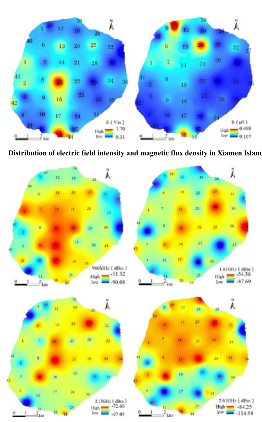
HIGHLIGHTS

- Relationship between EME characteristics and urban functions based on Geographical detector.
- Magnetic flux density had a positive correlation with residential area
- Mobile phone radiation power is positively related to the Edu function area.
- EME is positively related to the distribution of EMR sources.

GRAPHICAL ABSTRACT



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ABSTRACT

The electromagnetic environment (EME) in cities is becoming increasingly complex, and the resulting potential health hazards have attracted widespread attention. Large-scale field observations and monitoring of electromagnetic fields were performed in Xiamen Island over the past six years. The results show that the integrated electric field intensity in Xiamen Island ranged from 0.32 V/m to 1.70 V/m, while the integrated magnetic flux density ranged from 0.11 μT to 0.50 μT; where more electric power facilities and electronic equipment are present in the island, the electric and magnetic field strengths are higher; the radiation power of 2nd Generation mobile communication (2G) is higher than that of 3rd Generation mobile communication (3G) and 4th Generation mobile communication (4G), the coverage of the 3G signal was more uniform than the others and the 4G communication signal's coverage is still developing. The relationship between the EME characteristics and urban functions has been analyzed in this study. Results showed that electric field intensity had no correlation with urban functional areas, magnetic flux density had a positive correlation with residential area ($q = 0.29$); 2G and 4G radiation power are positively related to the educational (Edu) function area (960 MHz $q = 0.22$, 1.8 GHz $q = 0.47$, 2.61 GHz $q = 0.28$); there was a positive relationship between 2G (1.8 GHz) radiation

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power and residential area (q = 0.2). We concluded that there is a strong link between the Xiamen Island's EME and the distribution of electromagnetic radiation (EMR) sources, the denser and wider distributed EMR sources lead to a more complicated urban EME.

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1. Introduction

The number of artificial sources of EMR in modern society has increased tremendously because of the current demands for electricity, telecommunication services, and electronic devices. Mobile phones are one of the prodigious outputs of wireless technologies, and the dependency on mobile phones is growing at an alarming pace. The potential health hazards of man-made electromagnetic fields have become a hot research topic since the late 18th century and have attracted special attention over the last 30 years. The effects of electromagnetic field exposure on reproductive health, cancer development, central nervous system, cardiovascular system, immune function, human behavior, sleep pattern, and energy metabolism have been investigated in many studies (Pourlis, 2009; Shi et al., 2015; Duhaini, 2016; D'Angelo et al., 2015; Kesari et al., 2013; Vijayalaxmi, 2016), but the effect of EMR on the public and the ecological environment is still uncertain.

To understand the characteristics of the urban EME and provide data support for the study of the health effects of the EME, the urban EME was monitored and analyzed by scientists. Bolte investigated the exposure level and spatial and temporal variances during 39 daily activities in 12 frequency bands used in mobile telecommunication and broadcasting (Bolte and Eikelboom, 2012). Urbinello used the portable exposure meters for comparing mobile phone base station radiation in different types of areas in the cities of Basel and Amsterdam (Urbinello et al., 2014). Sagar have conducted radiofrequency electromagnetic field (RF-EMF) measurements by walking through 51 different outdoor microenvironments from 20 different municipalities in Switzerland (Sagar et al., 2016). Long-term electromagnetic field measurement and assessment for a shopping mall were studied by Engiz (Engiz and Kurnaz, 2017). Long term variations measurement of electromagnetic field exposures in Alcalá de Henares (Spain) were studied by Sánchez-Montero (Sánchez-Montero et al., 2017). Result showed that the main contribution to the environmental exposure is from mobile terminal use (37.5%) (Bolte and Eikelboom, 2012), the highest mean exposure depends on the activities taking place in high human density areas (Bolte and Eikelboom, 2012; Engiz and Kurnaz, 2017); electromagnetic environmental surveys using a portable device yields highly repeatable measurements (Urbinello et al., 2014; Sagar et al., 2016); in the city areas where the population density has remained unaltered, lower exposure levels have been measured, conversely, new urban and industrial developments have demanded new resources, which have possibly contributed to the observed increase in the measured electric field levels within these areas (Sánchez-Montero et al., 2017).

In the previous paragraph, we discussed some studies of urban EME monitoring. However, there are few studies on a relationship between EME characteristics and urban development, human activities, urban functions. Urban function is an essential characteristic of a city that may show certain regularities because of the comprehensive influence of natural and human factors, such as local city form, industrial structure, and urban population. The city functional area is the carrier of a city's function, while the urban functional area comprises interconnected elements in a certain spatial space that perform various urban functions yet dominates a certain city function. Urban functional areas can be divided into business, residential, cultural and educational, and industrial areas.

In order to explore the relationship between EME characteristics and urban functions, in this paper, we systematically monitored and analyzed EME in Xiamen Island tried to establish a relationship between EME characteristics and urban functions based on Geographical detector.

2. Materials and methods

2.1. Equipment

① The PMM 8053B EMR analyzer, low frequency probe EHP 50 (5 Hz–100 kHz, 0.01 V/m–100 kV/m, 10 nT–10 mT) and Radio frequency (RF) probe EP 300 (100 kHz–3 GHz, 0.3–300 V/m) produced by Narda, Germany.

② The portable frequency analyzer N9344C (frequency sweep range 9 kHz–3 GHz, resolution 100 kHz) produced by Agilent, U.S. is used for electromagnetic frequency spectrum monitoring and analysis. ETS-Lindgren's Model 3184 Mini-Bicon Antenna was used in spectrum scanning.

Every year the instruments are calibrated by Guangzhou GRG Metrology & Test CO. LTD.

2.2. Methods of field test

According to the Xiamen city map, Xiamen Island (including Siming and Huli districts) is divided into 2 km × 2 km grid partitions, 44 monitoring sites were selected as shown in Fig. 1. Use GPS to record coordinate positions at each monitoring site.

At each monitoring site: the electric field intensity was measured at 1.7 m from the ground using PMM8053B EMR analyzer and radio frequency probe EP 300, the PMM8053B EMR analyzer measures electric field intensity once per second, the average value after 6 min of continuous measurement was obtained.

The magnetic flux density was measured at 1.7 m from the ground using PMM8053B EMR analyzer and low frequency probe EHP 50, the PMM8053B EMR analyzer measures magnetic flux density once per second, the average value after 6 min of continuous measurement was obtained.

The Agilent portable spectrum analyzer N9344C and ETS-Lindgren's Model 3184 Mini-Bicon Antenna were used to scan and analyze the 1 MHz–3 GHz electromagnetic spectrum, set the step by 1 kHz, sweep time 10 ms, and the entire scan duration was 110 s. Only the broadband spectrum scanning RF radiation power of 1 MHz–3 GHz was performed, and the subtle features of the 2G, 3G and 4G signal were not distinguished.

From October 2010 to August 2015, the electric field intensity and magnetic flux density measurement were performed at the same location in different seasons each year (the total time for each measurement is 12 min).

From June 2012 to August 2015, 1 MHz–3 GHz electromagnetic spectrum scan measurement was performed at the same location in different seasons each year (the total time for each measurement is approximately 2 min).

2.3. Evaluation standard

According to ICNIRP guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz), reference levels for general public exposure to time-varying electric and magnetic fields (unperturbed rms values) is showed below (Table 1):

In China frequency 50 Hz was used in power line, so reference levels for general public exposure to time-varying electric fields intensity and magnetic flux density are 5000 V/m and 100 μT respectively.

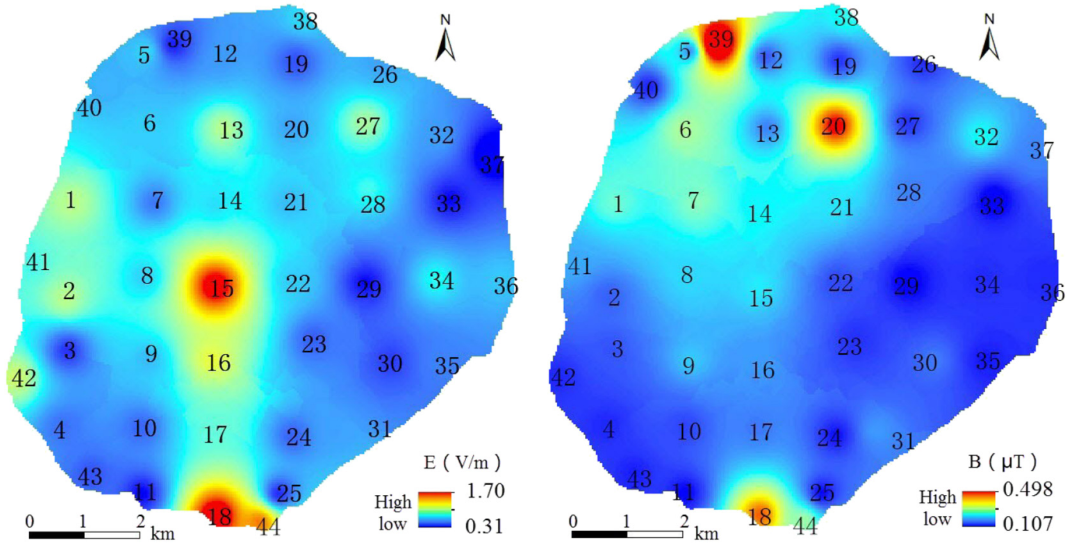

Fig. 1. Distribution of electric field intensity and magnetic flux density in Xiamen Island.

2.4. Data analysis

The geographical detector model (GDM) is a spatial analysis model based on the theory of spatial differentiation. GDM is freely available from http://www.geodetector.org/. The model uses the "factor force" as a measure index to effectively detect and identify correlation between a geographical attribute and its explanatory factor (Wang et al., 2010). By calculating and comparing the q-values of each single factor and the q-values of the superposition of two factors, the geographical detector can determine whether there are interactions between the two factors, as well as the strength, direction, linearity or nonlinearity of the interaction (Wang and Xu, 2017). In the model, the explanatory factors are the category variables rather than the actual value, which effectively overcomes the limitation that the traditional statistical analysis method handles category variables (Hu et al., 2011). Therefore, it can quickly and objectively detect correlation between spatial elements, and has been widely used in many fields of environmental research (Li et al., 2013). Geographical detector consists of four types: risk detector, factor detector, ecological detector and interaction detector (Wang and Xu, 2017). In this paper we used the factor detector to find if the geographical attribute of electromagnetic fields strength is influenced by urban functional areas (Residential area, Commercial area, Ecological area etc.).

Factor detector (Wang and Xu, 2017): factor X detects the spatial differentiation of Y, measured by q value, and the expression is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where N and σ^2 stand for the number of units and the variance of Y in study area, respectively; the population Y is composed of L strata ($h = 1, 2, \ldots, L$), N_h and σ_h^2 stand for the number of units and the variance of Y in stratum h, respectively. The value range of q is [0, 1]. The bigger q-statistic, the stronger impact of urban functional areas on EME. In this paper, we set the significant level of q as 0.2.

More information about GDM can be found on the website http://www.geodetector.org/.

2.5. Figure creation

The average of these annual electric field intensity, magnetic flux density and mobile phone RF radiant power were calculated by using Microsoft Excel.

Figs. 1 and 2 were created by ArcGIS 10.0 (Environmental Systems Resource Institute, ArcMap Release 10.0, ESRI, Redlands, California).

Table 1
Evaluation standard.

Frequency range	E-field strength (V/ m)	H-field strength ($A\,m^{-1}$)	B-field (μT)	Equivalent plane wave power density Seq ($W\,m^{-2}$)
Up to 1 Hz	–	3.2×10^4	4×10^4	–
1–8 Hz	10,000	$3.2 \times 10^4/f^2$	$4 \times 10^4/f^2$	–
8–25 Hz	10,000	4000/f	5000/f	–
0.025–0.8 kHz	250/f	4/f	5/f	–
0.8–3 kHz	250/f	5	6.25	–
3–150 kHz	87	5	6.25	–
0.15–1 MHz	87	0.73/f	0.92/f	–
1–10 MHz	$87/f^{1/2}$	0.73/f	0.92/f	–
10–400 MHz	28	0.073	0.092	2
400–2000 MHz	$1.375f^{1/2}$	$0.0037/f^{1/2}$	$0.0046/f^{1/2}$	f/200
2–300 GHz	61	0.16	0.20	10

Note:
① f as indicated in the frequency range column.
② Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.
③ For frequencies between 100 kHz and 10 GHz, Seq, E2, H2, and B2 are to averaged over any 6-min period.

Based on acquired geographic data, ArcGIS can plot the figures based on data with geographical characteristics effectively. Both EME and urban functional area have typical spatial characteristics while ArcGIS is a strong spatial data analysis tool. Therefore, based on ARCIS' spatial data analysis ability and its extended spatial analysis models, the correlation between EMR characteristics and urban functional areas could be precisely detected.

Fig. 1 shows the distribution of electric field intensities and magnetic flux density across each point in Xiamen Island.

Fig. 2 shows the distribution of mobile phone RF radiant power across each point in Xiamen Island.

3. Results

3.1. Distribution of electric field intensity and magnetic flux density in Xiamen Island

As shown in Fig. 1, points 18, 15, 44, 16, and 42 have the highest averaged electric field intensity, with point 18 having the maximal averaged electric field intensity of 1.70 V/m. By contrast, points 37, 11, 29, 33, and 39 have the lowest averaged electric field intensity, with point 37 having the minimal averaged electric field intensity of 0.32 V/m.

Points 39, 20, 18, 6, and 44 have the highest averaged magnetic flux density, with point 39 having the maximal averaged magnetic flux density of 0.50 μT. On the contrary, points 33, 29, 11, 25, and 24 have the lowest averaged magnetic flux density, with point 33 having the minimal averaged magnetic flux density of 0.11 μT.

The relationship between urban functional areas and EME was analyzed based on the results of a Geographical detector. Functional areas had no correlation with electric field intensity (q value is shown in Table 2). Residential area had a positive correlation with magnetic flux density ($q = 0.29$) and a linear correlation with magnetic flux density ($R^2 = 0.428$) (Table 2).

3.2. Analysis of distribution of mobile phone RF radiant power

As shown in Fig. 2, points 17, 16, 15, 22, and 1 are the top five sites for 2G 960 MHz radiant power, points 36, 28, 15, 27 and 14 are the top five sites for 2G 1.83 GHz radiant power, points 15, 27, 9, 14, and 44 are the top five sites for 3G 2.13 GHz radiant power, and points 22, 9, 27, 38, and 15 are the top five sites for 4G 2.61 GHz radiant power.

The relationship between functional areas and mobile phone RF radiant power was examined based on the results of the Geographical detector (Table 3). Mobile phone RF radiant power (2G and 4G) was positively related to educational areas (960 MHz $q = 0.22$, 1.8 GHz $q = 0.47$,

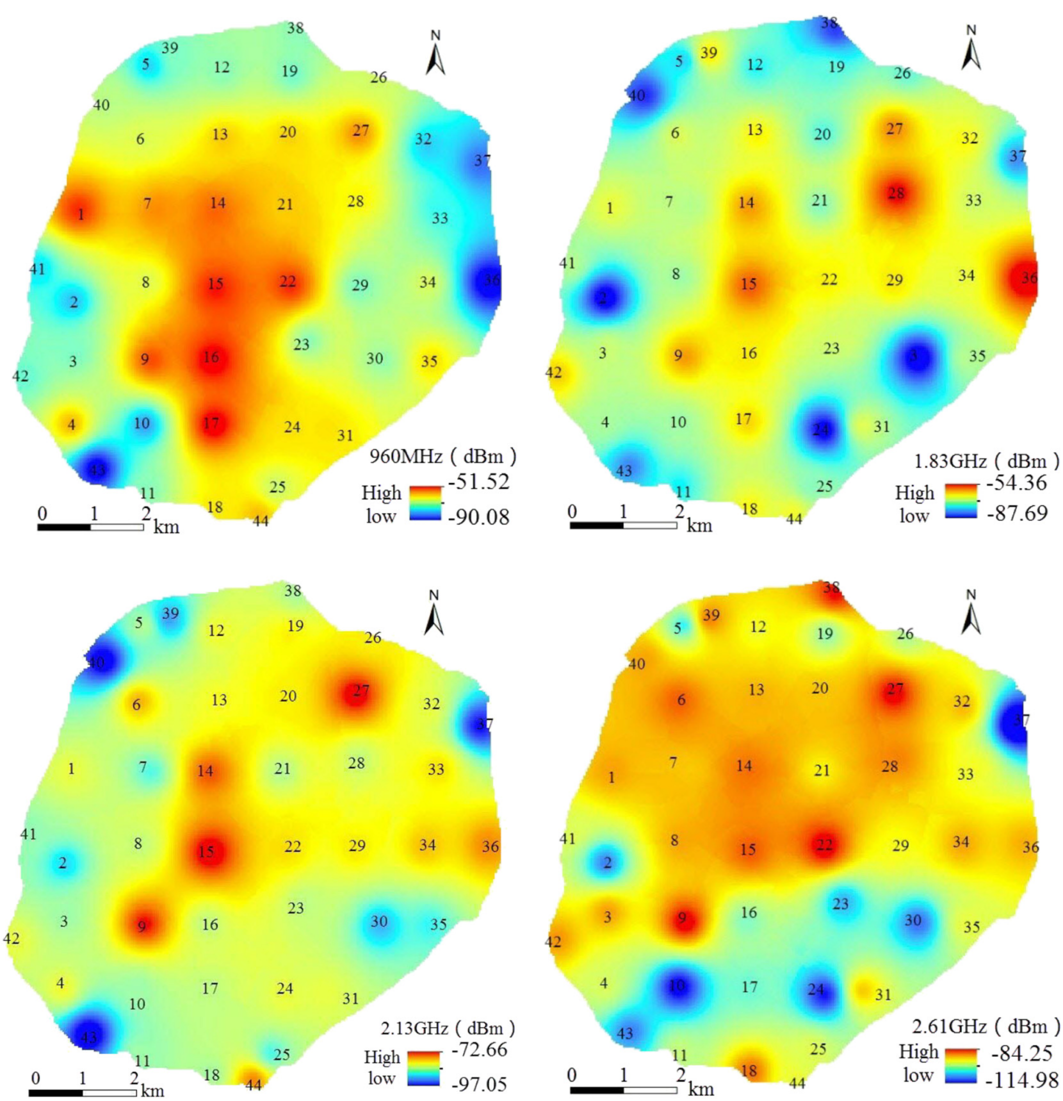

Fig. 2. Distribution of mobile phone RF radiant power in Xiamen Island.

Table 2
The relationship between functional areas and EME.

Functional areas	E q statistic	Functional areas	B q statistic
Residential area	0.11	Residential area	0.29
Commercial area	0.041	Commercial area	0.06
Educational area	0.021	Traffic area	0.04
Traffic area	0.05	Educational area	0.02
Industrial area	0.02	Ecological area	0.02
Ecological area	0.07	Industrial area	0.01
Other functional areas	0	Other functional areas	0

2.61 GHz q = 0.28). The stepwise regression results showed a linear correlation between 2G 960 MHz, 2G 1.83 GHz, 4G 2.61 GHz radiant power and educational areas, with R^2 values of 0.546, 0.582, and 0.605, respectively.

4. Discussion

4.1. Analysis of the current structure and mechanism of the EME

The EMR in the urban area mainly comes from televisions, radio towers, mobile communication base stations, high-voltage transmission lines, transportation systems, and medical research and other high-frequency medical equipment. The operation of high-frequency equipment in the industrial area and the density of the mobile base station in the commercial area both elevated the electromagnetic strength. The seaside scenic area has a flat land and the EMR generated by mobile base stations is slowly attenuated, thereby resulting in a relatively higher field strength.

In this study, it was found that the tourism areas with a large number of playground facilities, communication equipment, and mobile users (sites 18 and 44), the densely populated commercial residential areas (sites 15 and 16), and the busy traffic ports (sites 1, 41, and 42) are all of higher electric field intensity, while the highly industrialized industrial areas (site 39), airport areas (site 20), and tourism areas (sites 18 and 44) have higher magnetic flux density. Overall, the EMR strength in Xiamen Island is uniform. The integrated electric field intensity in Xiamen Island ranged from 0.32 V/m to 1.70 V/m, while the integrated magnetic flux density ranged from 0.11 μT to 0.50 μT. The electric field intensity and magnetic flux density in Xiamen are far below reference levels for general public exposure (Table 1).

In terms of mobile communication band, the 2G and 3G communication signals cover a wide area, and the radiant power of 2G is higher than that of 3G and 4G. The coverage of the 3G signal was more uniform than the others. The unevenly distributed radiation power indicated that the 4G communication signal's coverage is still developing. The 2G base stations were located far away from one another, thereby resulting in a high radiant power. By contrast, the 3G and 4G base stations were layout intensive, thereby resulting in low radiant power.

4.2. Correlation between EME and urban functional areas

The different dominating functions of urban areas determine the type, layout, and number of buildings in these areas, and the number and types of EMR sources differ across these areas. Thus, it may cause the amount of EMR differs across these areas.

In this paper, the analysis of Xiamen Island EME and urban functional areas revealed no correlation between functional areas and electric field intensity, and a positive correlation between residential areas and magnetic flux density. The intensive distribution of household electronic equipment in residential areas resulted in a relatively high magnetic flux density.

The relationship between mobile phone RF radiant power and functional areas was further analyzed. 2G and 4G radiation power are positively related to the educational (Edu) function area. Given many universities located in educational function areas, and the high population density, high concentration of mobile phone users, the communication signal in these areas is stronger than that in other areas. A relationship between 2G radiation power and residential area was also observed, indicating that many people at residential areas, especially in the old urban district, are using 2G mobile phones.

5. Conclusion

Large-scale field observations and monitoring of EME were performed in Xiamen Island over the past six years. We found that the integrated electric field intensity in Xiamen Island ranged from 0.32 V/m to 1.70 V/m, while the integrated magnetic flux density ranged from 0.11 μT to 0.50 μT; the radiation power of 2G is higher than that of 3G and 4G. Analysis a relationship between EME characteristic and urban functions based on Geographical detector. Results showed that electric field intensity had no correlation with functional areas, magnetic flux density had a positive correlation with residential area; 2G and 4G radiation power are positively related to the educational function area, and there was a positive relationship between 2G (1.8 GHz) radiation power and residential area. We concluded that there is a strong link between the Xiamen Island's EME and the distribution of EMR sources; the denser and wider distributed EMR sources lead to a more complicated urban EME. The urban functional areas should be divided in scientific and rational to make sure the coordination relationship between EMR level and urban functional areas.

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Table 3
The relationship between functional areas and mobile phone RF radiant power.

Functional areas	960 MHz q statistic	Functional areas	1.8 GHz q statistic	Functional areas	2.13 GHz q statistic	Functional areas	2.61 GHz q statistic
Educational area	0.22	Educational area	0.47	Residential area	0.12	Educational area	0.28
Residential area	0.15	Residential area	0.20	Educational area	0.12	Ecological area	0.10
Ecological area	0.11	Commercial area	0.07	Traffic area	0.08	Residential area	0.08
Traffic area	0.09	Industrial area	0.01	Commercial area	0.03	Industrial area	0.07
Industrial area	0.05	Ecological area	0.01	Ecological area	0.02	Traffic area	0.05
Commercial area	0.04	Traffic area	0.01	Industrial area	0.01	Commercial area	0.02
Other functional areas	0.00	Other functional areas	0.00	Other functional areas	0.00	Other functional areas	0.01

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Conceived and designed the experiments: P. Cai, C. Tang and C. Yang.

Performed the monitoring experiments: C. Tang, C. Yang, R. S. Cai, Z. Zhang, L. Duan, Z. Shi, K. Lin, X. Huang and H. Zhang.

Wrote the paper: C. Tang, C. Yang, R. S. Cai, P. Cai, H. Ye and J. Yang.

Analyzed data and drew pictures: C. Yang, H. Ye and J. Song.

All authors reviewed the manuscript.

Conflict of interest

The authors have no conflicts of interest in this paper.

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