SCIENTIFIC REPORTS

OPEN

Tree ring phototropism and implications for the rotation of the North China Block

Received: 20 November 2018
Accepted: 22 February 2019
Published online: 19 March 2019

Zikun Jiang[1,2], Benpei Liu[3], Yongdong Wang[2], Min Huang[1], Tom Kapitany[4], Ning Tian[5], Yong Cao[6], Yuanzheng Lu[7] & Shenghui Deng[7]

Trees grow towards the sunlight via a process of phototropism. The trunk phototropism processes are frequently observed in Northern Hemisphere from high latitude to at least the Tropic of Cancer region, and also occur in some *in situ* preserved vertical petrified woods in various geological ages. However, such evidence is still very limited and poorly known in fossil record; and the relationship between tree ring phototropism and rotation of tectonic blocks is unclear. Here we report the eccentricities of living and fossil trees as a proxy to determine geological block rotation at the same latitudes within the North China Block. The dominant eccentricity of living trees is southwest 219° ± 5°. By contrast, standing *in situ* fossil trunks in the Mid-Late Jurassic Tiaojishan Formation and the Late Jurassic Tuchengzi Formation had average eccentricities of 237° and 233.5°, respectively. These differences shed light on the palaeogeographical changes, indicating that the North China Block rotated clockwise from the Late Jurassic to the present day. This result is largely coincident with the palaeomagnetic results, indicating that the North China Block rotated clockwise by 26.5° ± 5.5° since the Middle to Late Jurassic transition.

Light is a key environmental factor that drives many aspects of plant growth and development[1]. Phototropism, the reorientation of growth towards light, is one of the most important adaptive processes[2]. Many results have been acquired for phototropism in a variety of aspects since Charles Darwin[3] published "The Power of Movement in Plants" e.g.[1,2,4–11]. Most growth ring studies focused on the dendrochronology as well as its utility for palaeoecologic and palaeoclimatic investigations in deep time e.g.[12–33]. However, little attention has been paid to the trunk phototropism represented by asymmetric growth of tree rings in response to a directed light source. In recent years, increased data have been accumulated for such eccentricity phototropism in both living and fossil tree ring observations, especially in some well-preserved individual fossil trunks[34,35]. However, such evidence is still very limited and poorly known in fossil record and the relationship between ring phototropism and rotation of block is undetermined. Here we report our recent systematic field surveys and investigation results on both living trees and *in situ* fossil wood from the North China Block, including 253 living trees from Beijing and Jilin Provinces, and 7 fossil *in situ* trunks from the Jurassic Tiaojishan and Tuchengzi formations in Liaoning and Beijing regions (Supplementary Information S1).

As eccentricity refers to the directional measurement of the longest distance from the pith to the outermost growth ring of an *in situ* tree trunk (southwest direction, when a tree with two largest growing directions), we thus use tree ring eccentricity as a proxy to determine the general block rotation. In addition, our palaeomagnatic data from the Tiaojishan Formation in Beipiao of Liaoning Province also provide support for the fossil data interpretation, indicating that the North China Block had rotated clockwise since the Middle to Late Jurassic transition (Supplementary Information S1).

[1]Chinese Academy of Geological Sciences, Beijing, 100037, China. [2]State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, and Center for Excellence in Life and Palaeoenvironment, Chinese Academy of Sciences, Nanjing, 210008, China. [3]China University of Geosciences, Beijing, 100083, China. [4]The National Dinosaur Museum, Canberra ACT, 2913, Australia. [5]College of Palaeontology, Shenyang Normal University, Shenyang, 110034, China. [6]Key Laboratory of Palaeomagnetism and Tectonic Reconstruction of Ministry of Land and Resources, Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing, 100081, China. [7]Research Institute of Petroleum Exploration & Development, PetroChina, Beijing, 100083, China. Correspondence and requests for materials should be addressed to Z.J. (email: jiangmaomao_925@sina.com) or Y.W. (email: ydwang@nigpas.ac.cn)

Content courtesy of Springer Nature, terms of use apply. Rights reserved

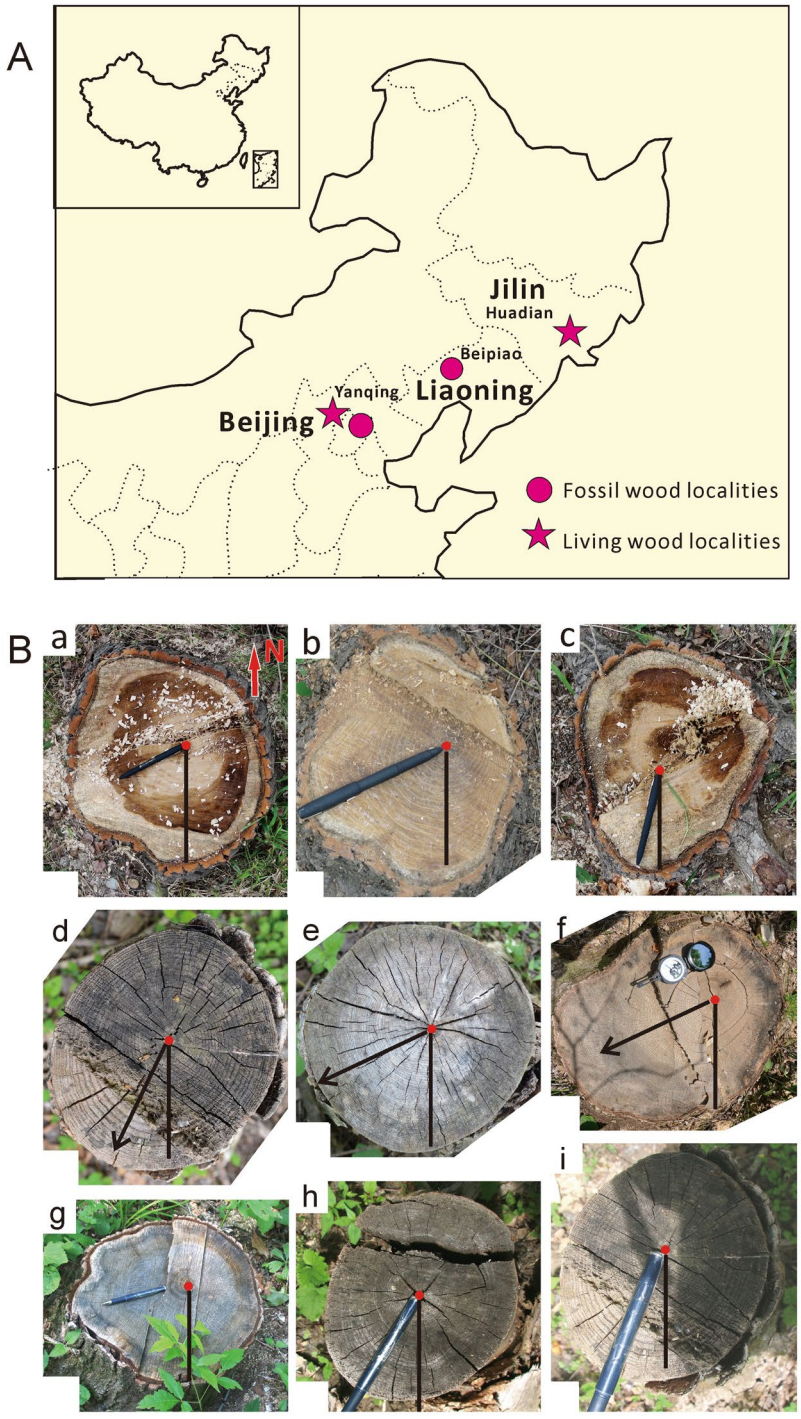

Figure 1. Representative living trees showing eccentricity in Xiangshan of Beijing and Huadian of Jilin Provinces (**A**), Living wood and fossil wood localities in North China region; (**B**) Living trees' phototropism directions. (a–c) From Xiangshan of Beijing with the eccentricity as 243°, 193°and 245° respectively. (d–i) From Huadian of Jilin Province with eccentricity directions as 210°, 240°, 240°, 202°, 212° and 255° respectively. Red arrow showing the geographical North direction. Black arrows and pens showing the largest growing part direction of wood.

Results

Phototropism in extant tree trunks. The shape, dominant eccentricities and other directions from the pith to the largest growing part (when a tree trunk with two largest growing parts) of living tree trunks were observed within the latitude ranges from 39°59.6′N to 43°15′N in northern China region. We measured 35 trunks at the Wofusi locality in Xiangshan of northern Beijing (39°59′36″N), and 218 tree trunks at the Hongshi Forestry locality of Huadian, Jilin Province (43°15′52.5″N) (Fig. 1) (Supplementary Information S2). In each site, the

Content courtesy of Springer Nature, terms of use apply. Rights reserved

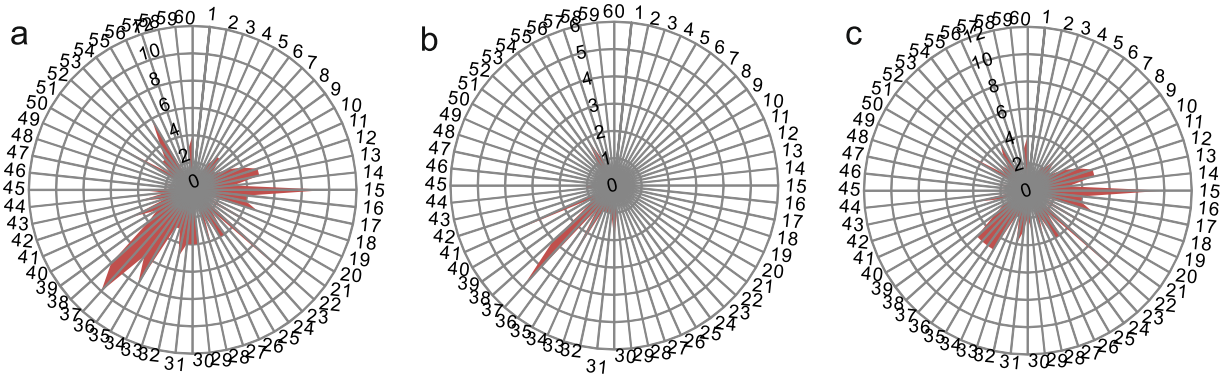

Figure 2. Radar map of living tree data. (**a**) Compilation of all data from localities of Xiangshan and Hongshi; (**b**,**c**) individual radar maps of data from Xiangshan (**b**), and Hongshi (**c**).

standing and recently fallen trunks were photographed and measured for their eccentricities. The eccentricity data of these living trees examined from Beijing and Jilin Provinces are shown in radar figures (Fig. 2).

The dominant direction of locality in Xiangshan is 222° (Fig. 2b, sector 37 on the circle), which indicates that the trees grow towards the light stimuli. The directions at 180° and 336° might result from two trees that shaded each other (Fig. 2b, sectors 30 and 57). In Honshi locality, the phototropism orientation ranges from 210° to 228° (Fig. 2c, sectors 35–37). The scatter of other orientations around the circle may indicate that the trees in Hongshi locality were influenced by factors other than light (such as gravity and shading). Both data from Xiangshan and Hongshi localities (Fig. 2a) show that the dominant growth direction of eccentricity is southwest, and their average value among the dominant sectors is 219° ± 5°, representing the profound phototropism in Beijing and Jilin Provinces. A secondary peak points directly eastward may result from the influence of other factors, such as gravity in mountain areas, water sources, or shading by other trees.

Phototropism of *in situ* petrified wood from the Tiaojishan Formation. Three *in situ* standing petrified fossil tree trunks with intact and distinct growth-rings are preserved in the fine-grained sandstone beds of the Middle to Late Jurassic Tiaojishan Formation in Heigou locality, Batuying Town of Beipiao City, Liaoning Province (41.5°N, 120.7°E) (Fig. 1A) (Supplementary Information S1).

The petrified wood trunk No. TJS 1 displays two outermost directions, with the principal eccentricity as 233° (towards the SW) (Fig. 3a), and the other direction as 305° (towards the NW) (Fig. 3b). A potential explanation for this later direction (305°) might be influenced by other disturbing factors, such as shading or other influencing factors (except gravity and water). Fossil wood trunks No. TJS 2 and No. TJS 3 shows an eccentricity of 247° (Fig. 3c,d) and 230° eccentricity (Fig. 3e,f), respectively (Table 1).

The average eccentricity of these *in situ* standing fossil trunks from the Tiaojishan Formation is 237°. Comparing with the extant phototropism direction and the *in situ* preserved fossil trunks (the difference between 219° ± 5° and 237°), the eccentricity of these petrified trunks shows ca. 13–23° more towards the southwest than that of the living trees.

Phototropism of *in situ* petrified wood from the Tuchengzi Formation. Four vertical *in situ* petrified tree trunks from the Tuchengzi Formation were examined from the Yanqing Global Geopark in northern Beijing. The Tuchengzi Formation conformably or disconformably overlies the Tiaojishan Formation, and is dated as Late Jurassic to Early Cretaceous in age (approximately 150 Ma)[36] (Supplementary Information S1).

The phototropism orientation of fossil wood trunk No. TCZ 1 is 230°(Fig. 4a). Trunk No. TCZ 2 indicates an orientation of 235° (Fig. 4b). Trunk No. TCZ 3 exhibits clear ring elongation in two directions, i.e. 236° (Fig. 4c) and 44° (Fig. 4d). Trunk No. 4 records a phototropism orientation of 233° (Fig. 4e) (Table 1).

The average phototropism direction of these fossil trunks is 233.5° in the Late Jurassic Tuchengzi Formation in the Yanqing of Beijing area, with the same latitude as in Xiangshan locality of living trees in Beijing. Compared with the average phototropism direction recorded in fossilized trees in the Tiaojishan Formation, there is a 3.5° difference in orientation (the difference between 233.5° and 237°). The eccentricity of the wood in the Tuchengzi Formation shows estimates of 9.5–19.5° difference (between 219° ± 5° and 233.5°) more towards the southwest than that of the extant trees. It is thus obvious that the different eccentricities of these two formations might reflect the continuous clockwise rotation of the North China Block.

Palaeomagnetic results from the Beipiao Basin in the North China Block. About 100 samples for palaeomagnetic analysis were collected from ten sites of the Tiaojishan Formation in Beipiao Basin, approximately 50 meters away from the *in situ* preserved petrified trunk occurrence. The Beipiao Basin is located along the northern margin of the North China Block. The combined mean palaeomagnetic direction of this study and the results from previous study[37] is Dg = 70.2°, Ig = 75.5°, kg = 12.6, α95 = 9.3° (in geographic coordinates) and Ds = 29.4°, Is = 67.2°, ks = 34.8, α95 = 5.5° (in stratigraphic coordinates). The corresponding paleopole lies at 67.1°N, 175.7°E with A95 = 8.0°. Compared with the present geomagnetic field (PGF) direction (D/I = 2.9°/57.0°), it is suggested that the North China Block has experienced clockwise rotation of 26.5° ± 5.5°

Content courtesy of Springer Nature, terms of use apply. Rights reserved

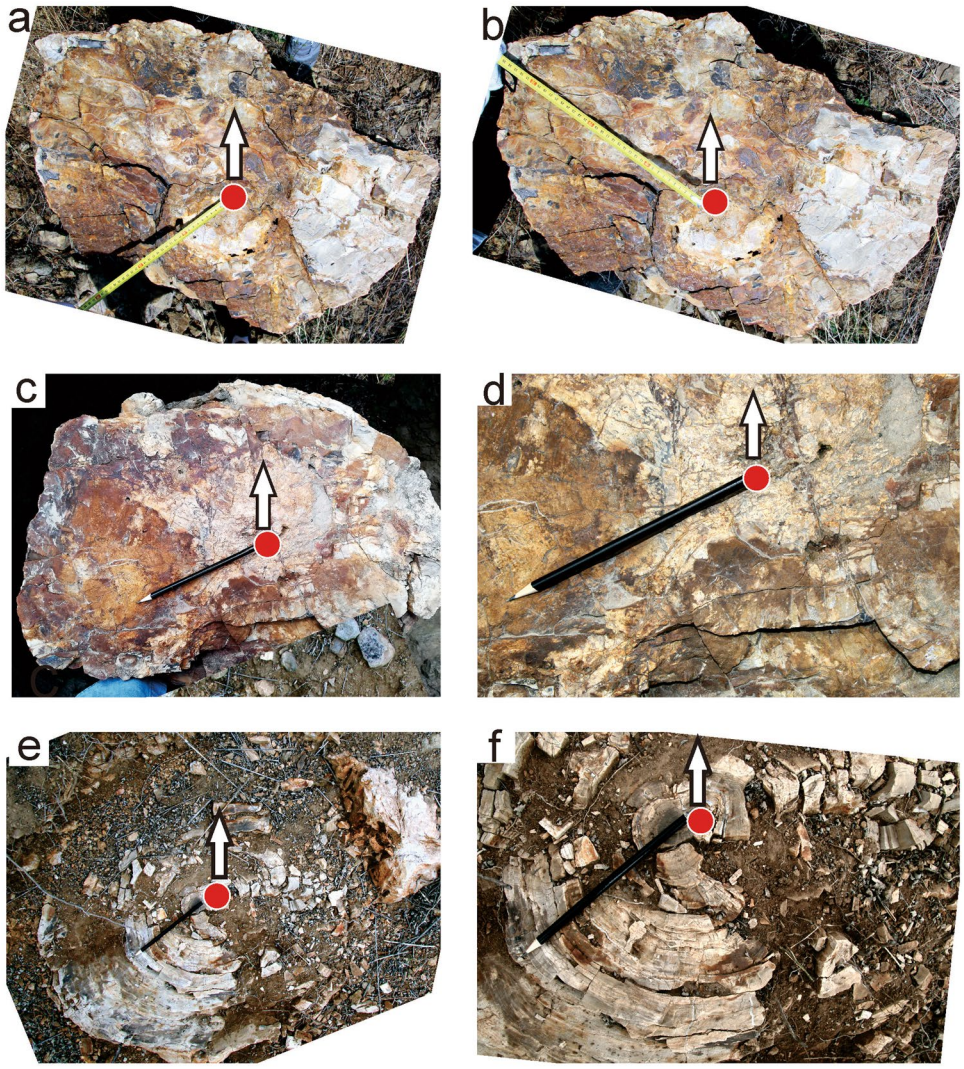

Figure 3. Phototropism in the *in situ* petrified tree trunks from the Tiaojishan Formation of the Late-Middle Jurassic transition in Beipiao of Liaoning Province (**a**,**b**), Petrified trunk No. TJS 1; (**c**,**d**) Fossil wood trunk No. TJS 2; (**e**,**f**) Fossil wood trunk No. TJS 3. Red points indicating piths, black arrows showing the north direction, rulers and pencils direction showing the largest growing part.

since the Late Jurassic (Fig. 5) (Supplementary Information S3). In addition to the previous studies[37], our palaeomagnetic result provides a more positive support to fossil wood evidence, as the palaeomagnetic sample locations are very close to the *in situ* petrified wood of Tiaojishan Formation in Beipiao, Liaoning Province, which reduced the effect of the local rotation.

Discussion

In the Northern Hemisphere, trunk phototropism is observed at high latitudes and extends south to at least the Tropic of Cancer (N23°26′)[34]. The magnitude of the phototropic response generally varies from stronger at the poles to weaker at the lower latitudes, finally disappearing near the tropics[34]. Observations of living trees indicate that the eccentricity of growth rings in the Northern Hemisphere trends more southwest than south, possibly due to the fact that trees might preferentially grow faster from after high noon, when the sun is in the southwest sky.

In addition to light, other factors such as gravity, water, shading, wind strength, and chemistry can influence the eccentric tropisms or movements of growth rings[38]. These conclusions are mostly based on observations of trees in mountainous regions, where the combination of phototropism and gravitropism affects the direction of plant growth[38]. To eliminate any potential influence from the above mentioned factors, particularly gravitropism, living trees in flat, unshaded areas were chosen to be the ideal condition to measure the eccentricity. Gravity is the most important influencing factor on tree morphology. In mountainous areas, regardless of whether a tree is located on the north or south slope of an inclined surface, the gravitropism impacts on growing stems. In our studies on living wood, all the tree trunks from Xiangshan of Beijing are located on flat ground without off-centre gravitational interference. Most of the tree trunks at the Hongshi of Jilin Province are on the flat ground, some limited tree trunks are on hills, and thus gravity may disturb some results of eccentricity. Other directions of the tree trunks at Hongshi of Jilin Province are influenced by trees shading by each other.

Content courtesy of Springer Nature, terms of use apply. Rights reserved

No.	Formation	GPS position	locality	Dominant Eccentricity	The other largest outermost directions
TJS 1	the Tiaojishan Formation	41°27′30″N, 120°47′13″E	Beipiao of western Liaoning province	233°	305°
TJS 2	the Tiaojishan Formation	41°27′30″N, 120°47′12″E	Beipiao of western Liaoning province	247°	No
TJS 3	the Tiaojishan Formation	41°21′30″N, 120°47′12″E	Beipiao of western Liaoning province	230°	No
TCZ 1	the Tuchengzi Formation	40°42′4.1″N, 116°25′15.399″E	Yanqing of Beijing	230°	No
TCZ 2 (modified from reference [34]—Jiang *et al.*, 2014)	the Tuchengzi Formation	40°42′5.301″N, 116°28′15.44″E	Yanqing of Beijing	235°	No
TCZ 3	the Tuchengzi Formation	40°42′5.362″N, 116°23′16.452″E	Yanqing of Beijing	236°	44°
TCZ 4	the Tuchengzi Formation	40°42′6.023″N, 116°23′17.07″E	Yanqing of Beijing	233°	No

Table 1. The eccentricity of *in situ* preserved petrified wood in the Tiaojishan and Tuchengzi Formations. Note: TJS = Tiaojishan TCZ = Tuchengzi.

A reasonable assumption can be made that the growth-ring asymmetry in vertical *in situ* fossil trunks was related almost entirely to sunlight. They were commonly preserved in open and flat environments[39]. The fossil wood in the Tuchengzi Formation in Yanqing of Beijing were generally deposited and buried in a lucastrine-flooding and volcanic ecosystem[40,41]. In the Tiaojishan Formation, *in situ* fossil trunks which were identified as conifer wood were preserved in upland under volcanic explosion which were far away from water sources[39]. The palaeoenvironment of the fossil trunks in the Tuchengzi Formation is also supposed to be forest far away from the lake deposit[39–41]. Obviously, information of geological significance could be thus obtained through an investigation into the shapes and rings of *in situ* fossil tree trunks[42]. Some trees may have two longest outermost growth rings of an *in situ* tree trunk. Therefore, it is crucial to distinguish the nature of these rings to be driven either by the light stimuli or by the other influencing factors.

However, as the mechanisms of phototropism are complex and thus other elements should also be considered for fossil wood trunk eccentricities. For example, petrified wood No. TJS 1 in Beipiao City of Liaoning Province (Fig. 3a,b) and No. TCZ 3 in Yanqing locality of northern Beijing (Fig. 4c,d) exhibits the two largest lengths. We interpret that 233° and 236° are the eccentricity directions (Figs 3a and 4c), and directions 305° and 44° may largely caused by shading or other influencing factors (except gravity and water) (Figs 3b and 4d). It is clear that light greatly contributes to the asymmetry of tree growth, although the degree of that contribution is still unknown. Though steps can be taken to minimize the likelihood that a growing tree was affected by factors other than light, a much larger dataset is required to complete the statistical analysis necessary to reduce signals caused by other influencing factors.

Compared with a large number of fossil fallen tree trunks, *in situ* preserved specimens are scarce. In this study, fieldwork was conducted across most localities of *in situ* fossil wood in China; however, because of weathering (Fig. 4f), transplanting and subsequent damage, a set of valid data were obtained in only three sites, e.g. three specimens were found in Beipiao of western Liaoning Province, and four samples were located in Yanqing of Northern Beijing. Compared with extant trees, a mass of statistical data on fossil wood is needed to determine the specific contribution of light, absent of other factors. Unfortunately, most vertical *in situ* petrified tree trunks have been damaged in the field, thus some of their eccentricities may be unclear.

The Baipiao Basin, from where we collected both fossil wood trunks and palaeomagnetic data, belongs to the North China Block. From the Jurassic to the present day, the Beipiao Basin may have undergone some tectonic movements caused by neighbouring small scale blocks within the North China Block[43–45]. However, such movements are too minor and can be ignored when compared with the block rotation degree of 26.5° ± 5.5°.

The geological age of the Tiaojishan and Tuchengzi formations correspond to the timing of the crustal rotation that occurred in the eastern part of the Yanshan Mountains in North China Plate[36]. The peak period of Yanshan tectonic evolution (165–136 Ma) is characterized by crust-mantle interactions[46], crustal rotation and subsequent destruction of the craton[47,48] and the formation of the so-called "Eastern China Plateau"[49]. Thus the rotation of the North China Block inferred by our fossil and living wood data analysis shed new light on the ecosystem response of this profound tectonic movement in East Asia. This is important for understanding the interaction between the various aspects of earth systems during the Mid-Late Jurassic to Early Cretaceous transition, particularly the relationships between tectonic movement and climate adjustments, and the subsequent impact on palaeogeography as well as on fauna migration and evolution.

Methods

Field collection and mapping of living wood. All the wood trunks in Xiangshan of Beijing, Huadian of Jilin Provinces were perpendicular to the horizon. Ruler was used to measure the outermost radius. Compass was applied to measure the eccentricity, e.g. the direction (southwest direction, when a tree has two largest growing parts) from the pith to the largest growing part. GPS was used to locate the precise positions. In order to exclude influencing factors other than light stimuli, tree trunks found in flat ground without any shadowing obstacles were selected as the ideal data. If the data were influenced by other factors, it was crucial to eliminate

Content courtesy of Springer Nature, terms of use apply. Rights reserved

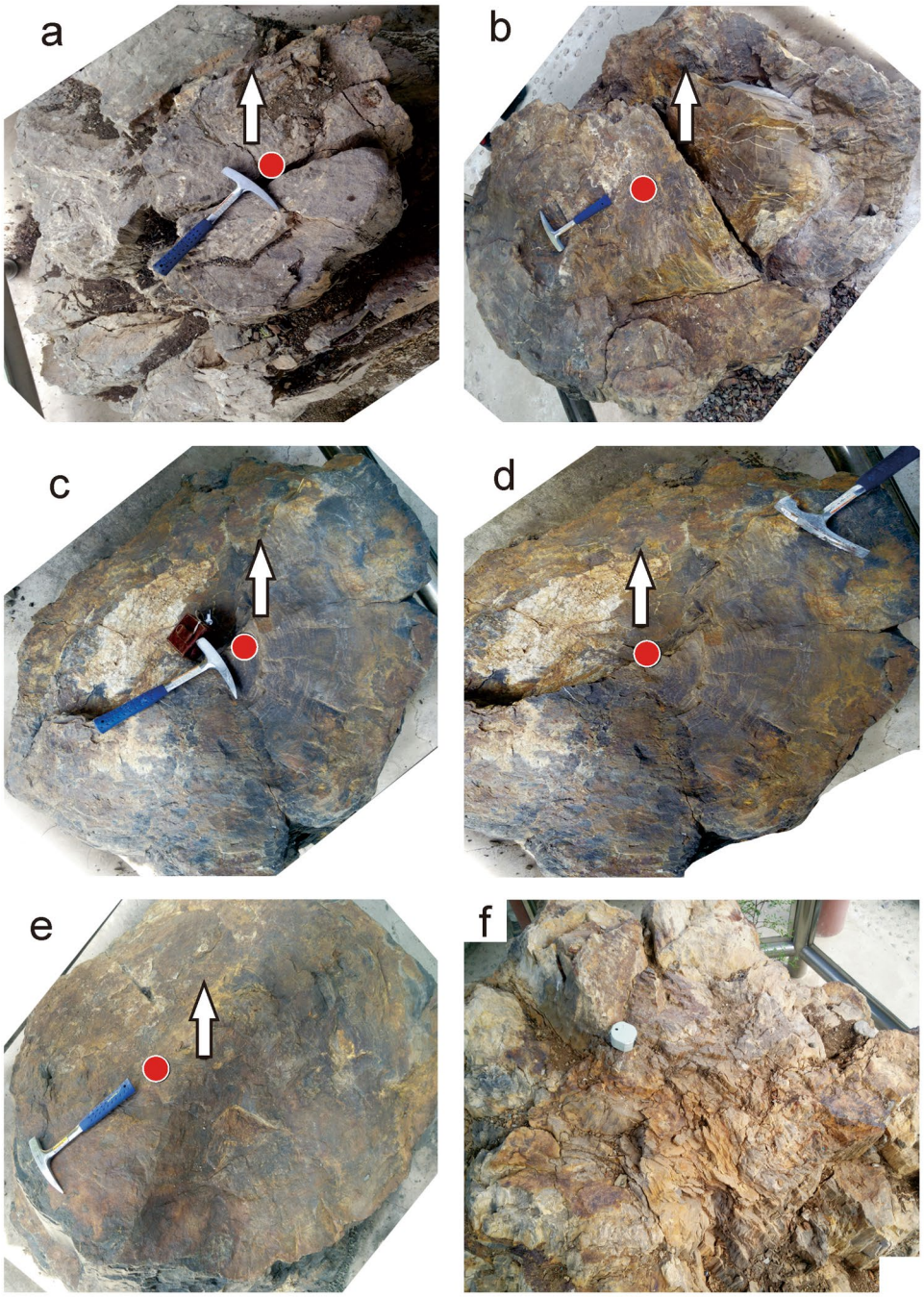

Figure 4. Phototropism in the *in situ* preserved petrified tree trunks from the Late Jurassic Tuchengzi Formation in Yanqing Geopark of Beijing. (**a**) Fossil wood trunk No. TCZ 1; (**b**) Fossil wood trunk No. TCZ 2 (modified from ref.[34]—Jiang *et al*. 2014); (**c**,**d**) Fossil wood trunk No. TCZ 3; (**e**) Fossil wood trunk No. TCZ 4; (**f**) a weathering trunk showing obscure ring features. Red points showing piths of the trunks. Black arrows indicating the North direction. Hammers pointing the largest growing outermost.

the interference factors in field study. In the common sense, the southwest direction is probably the phototropism direction; other directions are formed by the lateral factors.

We mapped the numbers of living tree data points (253 data) collected in each sector into a radar figure, in which the 360-degree circle was divided evenly into 60 sectors, each sector represents 6 degrees, and the data is arranged by angle in ascending order and sorted into the corresponding sectors.

Field collection of *in situ* petrified wood. *In situ* preserved petrified wood in two sites were discovered during the fieldwork. Two sites are located in Beipiao of Liaoning for the Tiaojishan Formation and in Beijing for the Tuchengzi Formation. In the Tiaojishan Formation, three stumps were found for measuring the eccentricity. In the Tuchengzi Formation, four stumps were chosen to indicate the phototropism. All the petrified wood trunks

Content courtesy of Springer Nature, terms of use apply. Rights reserved

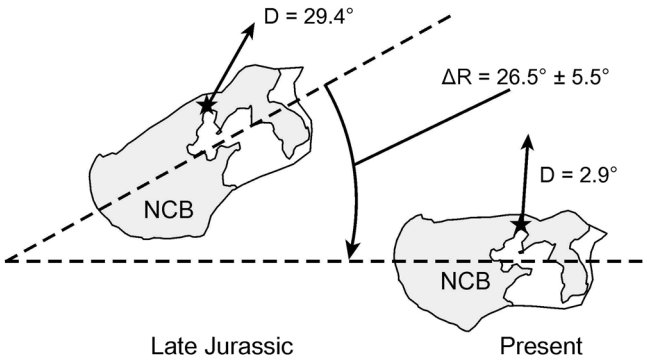

Figure 5. Schematic map illustrating the clockwise rotation of the North China Block from the Late Jurassic and the present day. NCB: North China Block, D: declination angle; ΔR: rotation angle, ★: study region.

are vertical to the bedding plane to ensure *in situ* status. Ruler, compass and GPS units were used when investigating fossil wood in the field. We measured the largest off-centre data of fossil wood, which is from the pith to the largest outermost of the trunk. In the field work, some fossil trunks have two largest growing directions, i.e. No. TJS 1 (233° and 305°) and No TCZ 3 (236° and 44°). The southwest directions (233° and 236°) are thus the direction of eccentricity, while the other directions (305° and 44°) may due to other influencing factors, i.e. shaded with other trees. For the *in situ* fossil trunks preserved in the open and flat environment and far away from the water sources[39–41], the influencing factor, i.e. gravity and near water sources are excluded.

During the field survey, we emphasized that both living and fossil trees may have a single, non-hollow trunk, and exhibit annual growth cycles. Structural changes caused by disease or damage by insects were not observed. Because the difference of tree species types does not affect heavily on the phototropism of living wood[50,51], therefore we followed this principle and did not distinguish their taxonomic position. In our study, all the fossil wood trunks are represented by gymnosperms. Living trees in Xiangshan of Beijing are angiosperms, whereas trees in Huadian of Jilin are 80% gymnosperms (conifers), and 20% are angiosperms.

All the growth rings in both living and fossil trees are larger than 30 circles, which means the trees are all older than 30 years. The average height of *in situ* preserved trees in the Tiaojishan Formation is about 25 m[52].

Palaeomagnetic data. We collected ten sites (approximately 100 samples) for palaeomagnetic analysis from the Tiaojishan Formation in Beipiao Basin, very close to the *in situ* preserved petrified wood samples. The occurrence of the stratum was measured on the intercalated sandstone layer in volcanic tuff (Supplementary Information S3). The strike and dip of the stratum is 42° and 14°, respectively. In total, material from ten sites were sampled using a gasoline-powered drill, and approximately ten oriented samples were collected from each site.

The samples were cut into cylinders 2.2 cm long for subsequent palaeomagnetic analysis. All samples underwent stepwise thermal demagnetization up to 680 °C that was performed with an ASC TD-48 thermal demagnetizer with an internal residual field of <10 nT. The demagnetization temperature intervals were generally large (40–50 °C) in the low-temperature part and smaller (20–30 °C) at higher temperatures. Remnant magnetizations were measured using a 2G-755R cryogenic magnetometer and a JR-6 spinner magnetometer. All measurements were carried out in a shielded room with residual fields of <300 nT at the Key Laboratory of Palaeomagnetism and Tectonic Reconstruction of the Ministry of Land and Resources, Institute of Geomechanics, Chinese Academy of Geological Science in Beijing. Magnetization directions were determined by principal component analysis[53] or remagnetisation circle analysis[54]. The average palaeomagnetic direction was counted with Fisher statistics[55] or the mixed mean of the unit vectors and remagnetisation great circles[56]. The computer program Kirsch developed by Enkin[57] and PaleoMac developed by Cogné[58] were used to analyse the palaeomagnetic data.

Data Availability

Additional data that support the findings of this study are available from the corresponding authors upon request.

References

1. Christie, J. M. & Murphy, A. S. Shoot phototropism in higher plants: New light through old concepts. *American Journal of Botany.* **100**, 35–46 (2013).
2. Holland, J. J., Roberts, D. & Liscum, E. Understanding phototropism: from Darwin to today. *J. Exp. Bot.* **60**, 1969–1978 (2009).
3. Darwin, C. The power of movement in plants. John Murray, London, UK (1880).
4. Overbeek, J. V. Phototropism. *Botanical Review.* **5**, 655–681 (1939).
5. Strong, D. R. & Ray, T. S. Host tree location behavior of a Tropical Vine (Monstera gigantea) by Skototropism. *Science.* **190**, 804–806 (1975).
6. Firn, D. R. Phototropism. Biological Journal of Linnean Society **34**, 219–228 (1986).
7. Iino, M. Phototropism: mechanisms and ecological implications. *Plant, Cell and Environment.* **13**, 633–650 (1990).
8. Lariguet, P. *et al.* Phytochrome Kinase Substrate 1 is a photoyropin 1 binding protein required for phototropism. Proc. of the Natl. Acad. of Sci. USA **103**, 10134-10139 (2006).
9. Boccalandro, H. E. *et al.* Phytochrome Kinase Substrate 1 regulates root phototropism and gravitropism. *Plant Physiology.* **146**, 108–115 (2008).
10. Christie, J. M. *et al.* Phot1 Inhibition of ABCA 19 Primes Lateral Auxin Fluxes in the shoot apex required for phototropism. *PLos Biology.* **9**, e1001076 (2011).

Content courtesy of Springer Nature, terms of use apply. Rights reserved

11. Hohm, T., Preuten, T. & Fankhauser, C. Phototropism: Translating light into direction growth. *American Journal of Botany.* **100**, 47–59 (2013).
12. Fritts, H. C. Tree rings and climate. (Academic Press, London), pp1-567 (1976).
13. Douglass, A. E. Climate and trees. *Nature Magazine* **12**, 51–53 (1928).
14. Jefferson, T. Fossil forest from the Lower Cretaceous of Alexander Island, Antarctica. *Palaeontology* **25**, 681–708 (1982).
15. Francis, J. E. The seasonal environment of the Purbeck (Upper Jurassic) fossil forests. *Palaeogeography, Palaeoclimatology, Palaeoecology* **48**, 285–307 (1984).
16. Francis, J. E. Growth rings in Cretaceous and Tertiary wood from Antarctica and their palaeoclimatic implications. *Palaeontology* **29**, 665–684 (1986).
17. Creber, G. T. & Chaloner, W. G. Influence of environmental factors on the wood structure of living and fossil trees. *The Botanical Review* **50**, 357–448 (1984a).
18. Creber, G. T. & Chaloner, W. G. Climate indication from growth rings in fossil wood. In: Brenchley, P. (ed), Fossil and Climate. John Wiley and Sons, *Chichester* 49–74 (1984b).
19. Creber, G. T. & Chaloner, W. G. Tree growth in the Mesozoic and Early Tertiary and the reconstruction of palaeoclimates. *Palaeogeography, Palaeoclimatology, Palaeoecology* **52**, 35–60 (1985).
20. Creber, G. T. & Chaloner, W. G. The contribution of growth ring studies to the reconstruction of past climates. In: Ward, R.G.W (ed) Application of Tree-Ring Studies. *British Archaeological Reports International Series* **333**, 37–67 (1987).
21. Philippe, M. & Thevenard, F. Distribution and palaeoecology of the Mesozoic wood genus Xenoxylon: palaeoclimatological implications for the Jurassic of Western Europe. *Review of Palaeobotany and Palynology* **91**, 353–370 (1996).
22. Keller, A. M. & Hendrix, M. S. Palaeoclimatologic analysis of a Late Jurassic Petrified Forest, Southeastern Mongolia. *Palaios* **12**, 282–291 (1997).
23. Ash, S. R. & Creber, G. T. Palaeoclimatic interpretation of the wood structures of the trees in the Chinle Formation (Upper Triassic), Petrified Forest National Park, Arizona, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology* **27**, 299–317 (1992).
24. Ash, S. R. & Creber, G. T. The Late Triassic *Araucarioxylon arizonucium* trees of the Petrified Forest National Park, Arizona, USA. *Palaeontology* **43**, 15–28 (2000).
25. Francis, J. E. & Poole, I. Cretaceous and Early Tertiary climates of Antarctica: evidence from fossil wood. *Palaeogeography, Palaeoclimatology, Palaeoecology* **182**, 47–64 (2002).
26. Harland, M., Francis, J. E., Beerling, D. J. & Brentnall, S. J. Cretaceous (Albian-Aptian) conifer wood from Northern Hemisphere high latitudes: forest composition and palaeoclimate. *Review of Palaeobotany and Palynology* **143**, 167–196 (2007).
27. Vozenin-Serra, C., Diez, J. B. & Ferrer, J. A new species of Protaxodioxylon (Cupressaceae s.l.) from the late Albian of the Aragonian branch of the Iberian Range (Spain) Palaeoclimatic implications. *Geodiversitas* **33**, 11–24 (2011).
28. Schweingruber, F. H. Tree Rings and Environment Dendroecology. (Swiss Federal Institute for Forest, Berne) pp1-609 (1996).
29. Falcon-Lang, H. J. & Cantrill, D. J. Leaf phenology of some mid-Cretaceous polar forests, Alexander Island, Antarctica. *Geological Magazine* **138**, 39–52 (2001).
30. Falcon-Lang, H. J. Growth interruptions in silicified conifer woods from the Upper Cretaceous (Late Campanian) Two Medicine Formation, Montana, USA: implications for palaeoclimate and dinosaur palaeoecology. *Palaeogeography, Palaeoclimatology, Palaeoecology* **199**, 299–314 (2003).
31. Barniak, J., Krapiec, M. & Jurys, L. Subfossil wood from the Rucianka raised bog (NE Poland) as an indicator of climatic changes in the first millennium BC. *Geochronometria* **41**, 104–110 (2014).
32. Falcon-Lang, H. J., Kurzawe, F. & Lucas, S. G. A late Pennsylvanian coniferopsid forest in growth position, near Socorro, New Mexico, USA: Tree systematic and palaeoclimate significance. *Review of Palaeobotany and Palynology* **2255**, 67–83 (2016).
33. Krapiec, M. *et al*. Late Holocene palaeoclimate variability: The significance of bog pine dendrochronology related to peat stratigraphy. The Puścizna Wielka raised bog case study (Orawa-Nowy Targ Basin, Polish Inner Carpathians). *Quaternary Science Reviews* **148**, 192–208 (2016).
34. Jiang, Z. K. *et al*. The Phototropism of Jurassic petrified wood in North China Plate. *Acta Geological Sinica* **88**, 1352–1355 (2014).
35. Jiang, Z. K. *et al*. The relationship between phototropism and plate motion. *Acta Geological Sinica* **91**, 345–346 (2017).
36. Xu, H., Liu, Y. Q., Liu, Y. X. & Kuang, H. W. Stratigraphy, sedimentology and tectonic background of basin evolution of the Late Jurassic- Early Cretaceous Tuchengzi Formation in Yinshan-Yanshan, North China. *Earth Science Frontiers* **18**, 088–106 (2011).
37. Ren, Q. *et al*. Further palaeomagnetic results from the ~155 Ma Tiaojishan Formation, Yanshan Belt, North China, and their implications for the tectonic evolution of the Mongol–Okhotsk suture. *Gondwana Res.* **35**, 180–191 (2016).
38. Liscum, E. P. Mechanisms and Outcomes. *Arabidopsis Book* **8**, 1–21 (2002).
39. Zheng, S. L. *et al*. Fossil Woods of China, Beijing: China Forestry Publishing House 1–356 (2008).
40. Zhang, Y. F., Wei, X. J., Xu, J. & Wang, H. Continental sequence stratigraphy analysis of "Fossil wood" Geological Park section in Yanqing Country, Beijing. *Earth Science Frontiers* **19**, 68–77 (2012).
41. Jiao, R. C., Wang, R. R. & Zhang, S. Y. Occurrence strata and formation age of petrified wood in Qianjiadian Area of Yanqing County. *Urban Geology* **11**, 56–59 (2016).
42. Liu, B. P. Problem of Tectonics Research on the integrate multi-discipline and mutual verification. 5*th National Synposium on Structural Geology & Geodynamics*, *Abstracts*. China University of Geosciences (Wuhan), 26–27 (2012).
43. Cheng, R. H., Cao, S. L., Wang, D. P. & Liao, X. M. The basement structure and tectonic patterns of the Mesozoic Basins in west Liaoning Province and its northern adjacent area. *Journal of Changchun University of Science and Technology* **29**, 29–32 (1999).
44. Du, X. D., Xue, L. F. & Wu, G. H. Distribution of Mesozoic Basin and discussion geodynamics of continent interior in the Eastern China. *Journal of Changchun University of Science and Technology* **29**, 138–143 (1999).
45. Yan, Y., Li, K. & Li, Z. A. Characteristics of the Jurassic filling sequence and the indication of tectonic evolution of Beipiao Basin, western Liaoning. *Journal of Stratigraphy* **26**, 151–155 (2002).
46. Shao, J. A., Zhang, L. Q. & Mou, B. L. Transformation of the tectonic regime is a lithospheric-scale activity. *Geol Bull of China* **23**, 973–979 (2004).
47. Wan, T. F. Rotation of the Jurassic crust and transformation of the lithosphere in eastern China. *Geol Bull of China* **23**, 966–972 (2004).
48. Zhu, R. X. *et al*. Timing, scale and mechanism of the destruction of the North China Craton. *Sci. China Earth Sci.* **54**, 989–747 (2011).
49. Zhang, Q. *et al*. Discussion of north boundary of the East China Plateau during late Mesozoic Era. *Acta Petrologica Sinica* **23**, 689–700 (2007).
50. Esau, k Anatomy of Seed Plants. *Bulletin of the Torrey Botanical Club* **90**, 362–364A (1960).
51. Gartner, B. Personal communication, Oregon State University, Dept. of Forest Products (1995).
52. Jiang, Z. K., Wang, Y. D., Tian, N., Zhang, W. & Zheng, S. L. Paleoclimate and paleoenvironment implications of the Middle-Late Jurassic Tiaojishan Formation, western Liaoning Province: Evidence from fossil wood data. *Acta Geologica Sinica* **90**, 1669–1678 (2016).
53. Kirschvink, J. L. The least-squares line and plane and the analysis of palaeomagnetic data. *Geophys J Roy Astron Soci* **62**, 699–718 (1980).
54. Halls, H. C. The use of converging remagnetization circles in paleomagnetism. *Phys. Earth Planet In.* **16**, 1–11 (1978).
55. Fisher, R. Dispersion on a sphere. *P Roy Soc London A* **217**, 295–305 (1953).

Content courtesy of Springer Nature, terms of use apply. Rights reserved

56. McFadden, P. L. & McElhinny, M. W. The combined analysis of remagnetisation circles and direct observations in palaeomagnetism. *Earth Planet Sci. Lett.* **87**, 161–172 (1988).
57. Enkin, R. J. Formation et déformation de l'Asiedepuis la fin de l'èreprimaire: les apports de l'étudepaléomagnétique des formations secondaires de Chine du Sud. Ph D thesis, (University of de Paris, Paris) pp 333 (1990).
58. Cogné, J. P. PaleoMac: A Macintosh™ application for treating palaeomagnetic data and making plate reconstructions. *Geochem. Geophys. Geosys.* **4**, 1007 (2003).

Acknowledgements

We acknowledge grants from the National Natural Sciences Foundation of China (Grant Nos 41772023, 41709545, 41688103, 41402004 and 41302004), the Strategic Priority Program (B) of CAS (XDB 18000000 and 2600000), the State Key Program for Basic Research & Development of Ministry of Science & Technology of China (2016YSC0600406) and the State Key Laboratory of Palaeobiology and Stratigraphy (Nanjing Institute of Geology and Palaeontology, CAS) (Grant No. 173113).

Author Contributions

Study concept and design: Z.K.J., B.P.L. and Y.D.W.; Acquisition of data: Z.K.J., B.P.L., M.H., N.T., Y.C., Y.Z.L. and S.H.D.; Redaction of the manuscript: Z.K.J., T.K. and Y.D.W.

Additional Information

Supplementary information accompanies this paper at https://doi.org/10.1038/s41598-019-41339-2.

Competing Interests: The authors declare no competing interests.

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2019

Content courtesy of Springer Nature, terms of use apply. Rights reserved

Terms and Conditions

Springer Nature journal content, brought to you courtesy of Springer Nature Customer Service Center GmbH (“Springer Nature”).
Springer Nature supports a reasonable amount of sharing of research papers by authors, subscribers and authorised users (“Users”), for small-scale personal, non-commercial use provided that all copyright, trade and service marks and other proprietary notices are maintained. By accessing, sharing, receiving or otherwise using the Springer Nature journal content you agree to these terms of use (“Terms”). For these purposes, Springer Nature considers academic use (by researchers and students) to be non-commercial.
These Terms are supplementary and will apply in addition to any applicable website terms and conditions, a relevant site licence or a personal subscription. These Terms will prevail over any conflict or ambiguity with regards to the relevant terms, a site licence or a personal subscription (to the extent of the conflict or ambiguity only). For Creative Commons-licensed articles, the terms of the Creative Commons license used will apply.
We collect and use personal data to provide access to the Springer Nature journal content. We may also use these personal data internally within ResearchGate and Springer Nature and as agreed share it, in an anonymised way, for purposes of tracking, analysis and reporting. We will not otherwise disclose your personal data outside the ResearchGate or the Springer Nature group of companies unless we have your permission as detailed in the Privacy Policy.
While Users may use the Springer Nature journal content for small scale, personal non-commercial use, it is important to note that Users may not:

1. use such content for the purpose of providing other users with access on a regular or large scale basis or as a means to circumvent access control;
2. use such content where to do so would be considered a criminal or statutory offence in any jurisdiction, or gives rise to civil liability, or is otherwise unlawful;
3. falsely or misleadingly imply or suggest endorsement, approval , sponsorship, or association unless explicitly agreed to by Springer Nature in writing;
4. use bots or other automated methods to access the content or redirect messages
5. override any security feature or exclusionary protocol; or
6. share the content in order to create substitute for Springer Nature products or services or a systematic database of Springer Nature journal content.

In line with the restriction against commercial use, Springer Nature does not permit the creation of a product or service that creates revenue, royalties, rent or income from our content or its inclusion as part of a paid for service or for other commercial gain. Springer Nature journal content cannot be used for inter-library loans and librarians may not upload Springer Nature journal content on a large scale into their, or any other, institutional repository.
These terms of use are reviewed regularly and may be amended at any time. Springer Nature is not obligated to publish any information or content on this website and may remove it or features or functionality at our sole discretion, at any time with or without notice. Springer Nature may revoke this licence to you at any time and remove access to any copies of the Springer Nature journal content which have been saved.
To the fullest extent permitted by law, Springer Nature makes no warranties, representations or guarantees to Users, either express or implied with respect to the Springer nature journal content and all parties disclaim and waive any implied warranties or warranties imposed by law, including merchantability or fitness for any particular purpose.
Please note that these rights do not automatically extend to content, data or other material published by Springer Nature that may be licensed from third parties.
If you would like to use or distribute our Springer Nature journal content to a wider audience or on a regular basis or in any other manner not expressly permitted by these Terms, please contact Springer Nature at

onlineservice@springernature.com