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# Climatic factors affecting water quality under natural conditions: a field survey of a local reservoir

*Authors' contributions*

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## ABSTRACT

The global water cycle is closely related to climate change, and fresh water is a precious resource. Therefore, the effects of climate change on fresh water quality are of major importance. Worldwide, shallow lakes and ponds are the most abundant reservoir types. However, there have been few studies about ponds despite their large number. It is commonly accepted that wind-driven currents and thermal stratification mainly affect water circulation and oxygen diffusion in lakes. The presented research aims to verify whether this accepted view would be observed in a pond (· 1 m depth and · 5,600 m<sup>2</sup> area) under natural conditions accompanying changes in temperature and wind. A field survey performed over 7 months in Japan has demonstrated that (i) the temperature variations in the air and the pond water were negatively correlated with the dissolved oxygen concentration; and (ii) the wind variation shows weak negative correlation with the dissolved oxygen level in the bottom layer. A simple concept of the link between temperature and dissolved oxygen is established through these findings – the oxygen solubility dependent on temperature is important rather than thermal stratification and wind in terms of discussing the climate change effects on pond water quality.

*Keywords: Climate Change effects, Pond, Reservoir Types, Water Quality*

## 1. INTRODUCTION

Global climate change is often thought of as something that will happen in the future, but it is an ongoing process [1]. Changes in Earth's climate, driven by increased greenhouse gases, are already having widespread effects on the environment such as droughts, wildfires, and torrential downpours [2]. The global water cycle is closely related to climate change, land use and the environment through complex interactions [3] — water is fundamental to all life on Earth; for example, water makes up about 70% of the human body by weight, so a loss of only 4% of water from the body leads to dehydration and a loss of 15% results in death [4 & 5].

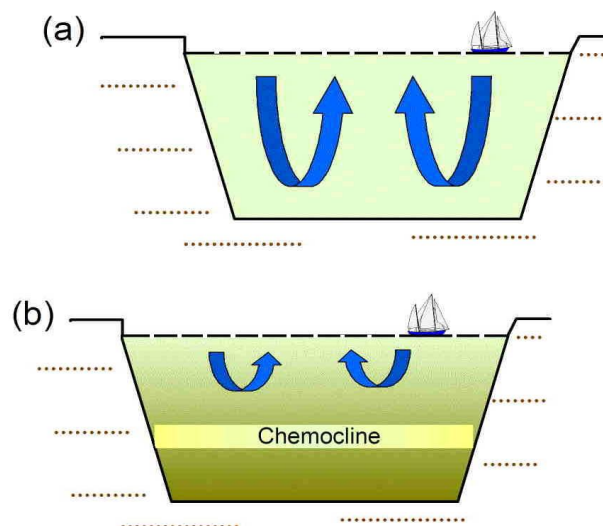
Regarding the sources of water indispensable to life, the main ones include fresh surface water, which accounts for just 1/10,000 of the total water available on the planet [6], and on a global scale the amount of fresh surface water is almost constant over time, being replenished by water precipitation previously evaporated from the ocean (~350,000 km<sup>3</sup>) and land areas (~70,000 km<sup>3</sup>). Most precipitation falls back into the ocean, and only ~110,000 km<sup>3</sup> falls on the land; that means, fresh water is a scarce resource. About 4 billion people currently experience water shortages for at least one month of the year [7], and these water

35 crises place third in a list of impact risks [8]. Modification in the distribution of groundwater  
36 recharge and river flows over space and time are determined by changes in temperature,  
37 evaporation and, mainly, precipitation [9]. Therefore, the effects of climate change on fresh  
38 water quality seem to be an urgent issue that confronts not only human beings but also  
39 many other species. This paper attempts to elucidate the interaction between climate  
40 change and water quality on the basis of a field survey of a local reservoir, to assess  
41 dissolved oxygen differences in ponds.

42 Multidisciplinary knowledge may be required to understand the relation between climate  
43 change and water quality in reservoirs such as lakes and ponds. The overall aim of this  
44 paper is to present a comprehensive case study on the relation of water quality with climate  
45 change; therefore, basic information about key factors is briefly reviewed first, followed by a  
46 description of the main discussion.

### 47 1.1 Holomictic and meromictic

48  
49 A lake can be basically classified as holomictic or meromictic in terms of mixing [10].  
50 Holomictic lakes follow a seasonal cycle of stratification and complete mixing (Fig. 1a), but  
51 meromixis is a condition in which a lake does not mix completely [11] (Fig. 1b).



52 **Fig. 1. Conceptual pattern of water circulation in lakes (redrawn from [12 & 13]):** (a)  
53 *holomictic lake — physical circulation (i.e. mixing) occurs between the surface and the deep waters;*  
54 *and (b) meromictic lake — circulation is possible only within a layer, so turnovers from top to bottom do*  
55 *not occur. A chemocline (i.e. transition zone) is commonly formed and separates the upper and lower*  
56 *layers.*

57

58 In holomictic lakes, the water body circulates at least once a year due to homothermal  
59 conditions, and mixing is complete or partial. The circulation homogenizes oxygen and  
60 nutrient concentrations throughout the water mass [14].

61 In meromictic lakes, the lack of circulation between layers creates radically different  
62 environments for organisms to live in: among the consequences of this stratification, or  
63 stable layering, of lake waters is that the bottom layer receives little oxygen from the  
64 atmosphere, hence becoming depleted of oxygen. While the surface layer may have 10 mg/l

65 or more dissolved oxygen in summer, the depths of a meromictic lake can have less than 1  
66 mg/l [15].  
67 Most lakes on Earth are holomictic, whereas meromictic lakes are rare [14]. However, in the  
68 case of Lake Biwa (the largest lake in Japan, see also Fig. 2) having about 670 km<sup>2</sup> of  
69 surface area and 41 m of mean depth, for the first time in recorded history, full circulation  
70 was not observed in 2018, and this phenomenon continued in 2019 [12]. A warmer than  
71 usual temperature continued at that time [12]. Hence it can be considered that the lake  
72 turnover did not occur completely because the water density did not change due to the  
73 insufficient function of temperature. As Lake Biwa is a main source of drinking water for 14  
74 million people in the Kansai region of Japan [16], the quality degradation of the lake water  
75 became a potential threat to the neighboring population, agricultural irrigation and regional  
76 ecosystems [17, 18 & 19].  
77

## 78 1.2. Shallow lakes and ponds

79  
80 Worldwide, shallow lakes and ponds are the most abundant water reservoirs on land, and  
81 these reservoirs supply lots of ecosystem services, goods and materials [20]. Many shallow  
82 lakes and ponds have been created by humans after millennia of landscape modification,  
83 such as stream and river impoundment. It is considered that the historical undercounting of  
84 small lakes and/or ponds has led to a significant underestimation of the world's lake and  
85 pond area [20].  
86 As stated above, there are many shallow lakes and ponds throughout the world. They are  
87 usually wind-exposed [11]. After thermal stratification develops during the daytime, full  
88 circulation takes place at night due to wind-induced mixing and convection from surface  
89 cooling [21]. Regarding the diurnal mixed layer in a shallow lake, the relative buoyancy ( $\epsilon \cdot g$ )  
90 caused by solar radiation can be expressed as follows (cf. [21 & 22]):  
91

$$92 \quad \epsilon \cdot g = (\Delta\rho/\rho_0) \cdot g = \epsilon_0 \cdot g \cdot \exp(-z/H) \text{ — (Eq. 1)}$$

93  
94 where  $\rho_0$  is the reference density of water,  $\Delta\rho$  is the density variation caused by solar  
95 radiation,  $g$  is the gravitational acceleration,  $\epsilon_0$  is the value  $\epsilon$  in the water surface,  $z$  is the  
96 water depth, and  $H$  is the center of buoyancy.  
97 Assuming that the wind blows at the point where the relative buoyancy is formed, the  
98 integrated value of buoyancy  $B$  within the interval  $z=0$  to  $z=h$  is denoted as follows:  
99

$$100 \quad B = \int \epsilon_0 \cdot g \cdot \exp(-z/H) dz = \epsilon_0 \cdot g \cdot H \cdot [1 - \exp(-h/H)] \text{ — (Eq. 2)}$$

101  
102 The value  $H$  is  $h/2$  where the cline (e.g. a layer in which the water property varies) exists in  
103  $z=h$ , and the increment of potential energy  $P$  (cf. turbulent kinetic energy) represented by the  
104 value  $B$  is expressed by the following equation:  
105

$$106 \quad P = B \cdot (h/2 - z_0) = \epsilon_0 \cdot g \cdot H \cdot h \cdot [\frac{1}{2} \cdot \{1 + \exp(-h/H)\}] - H/h \{1 - \exp(-h/H)\} \text{ — (Eq. 3)}$$

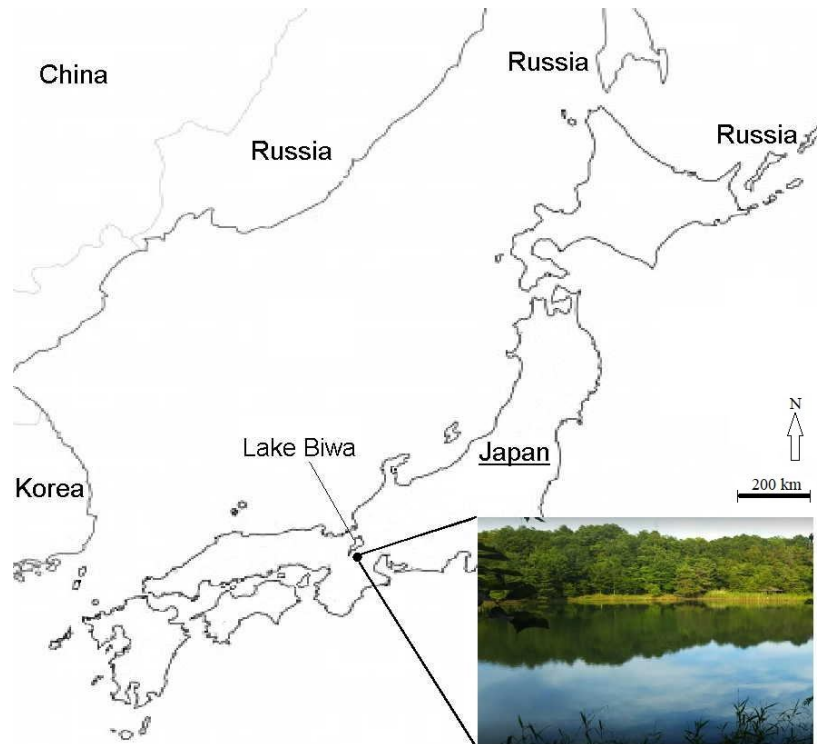
## 107 2. MATERIALS AND METHODS

108  
109 As stated in section 1.2, it is commonly accepted that wind-driven currents and temperature  
110 variations (e.g. thermal stratification) mainly affect water circulation and oxygen diffusion in  
111 lakes. This research aims to verify whether this accepted view is actually observed under  
112 natural conditions accompanying changes in temperature and wind in ponds. The research  
113 was carried out in Japan from June to December of 2021.  
114

### 115 2.1. Survey area

116

117 There are about 160 thousand artificial ponds (i.e. water reservoirs) in Japan, and about  
118 70% of them were built before the 17th century (the Edo period) in order to supply water for  
119 agricultural activities [23]. Japanese ponds are generally characterized by an area lower  
120 than 7,000 m<sup>2</sup>, a depth below 1.0 m and a storage capacity below 7,000 m<sup>3</sup> [24]. In  
121 comparison with lakes and rivers, most ponds are not located in public water areas, but their  
122 management has to follow the general environmental quality standards [24]; therefore, there  
123 have been few reports about the study of ponds despite their large number.  
124



125 **Fig. 2. Location of the study area (34°97'N and 135°93'E).** *The picture shows a view of*  
126 *Nagao Pond.*  
127

128 A typical pond was selected as the research target. The study focuses on Nagao Pond (Fig.  
129 2), a kind of artificial water reservoir located on the north side (34°97'N and 135°93'E) of  
130 Lake Biwa (section 1.1) in western Japan. The area encompasses about 5,600 m<sup>2</sup> and the  
131 mean depth is about 1.0 m. The survey region belongs to a temperate zone with four distinct  
132 seasons.

133 According to meteorological data in the research region [25 & 26], the snow period lasts for  
134 1.5 months from January to mid-February, and the month with the most snow is February  
135 with an average snowfall of 30 mm/month; the period of the summer season is about 3  
136 months from mid-June to mid-September, and the maximum temperature is 26°C and the  
137 average diurnal difference between the maximum and the minimum temperatures is 10°C;  
138 the period of the winter season lasts for about 3.5 months from December to mid-March,  
139 with average monthly maximum and minimum temperatures of 12°C and 0°C, respectively.  
140 Wind speed and the predominant wind direction vary throughout the year – winds often blow  
141 from the north at an average speed of 1.8 m/s during February-June and September-  
142 November, from the south at an average speed of 1.6 m/s during July-August, and from the  
143 west at an average speed of 2.2 m/s during December-January.

144 The spot information on wind speed and direction was gathered through a local climate  
145 database by JMA [25], and the procedures used in this survey are summarized below.

146

## 147 **2.2. Water sampling**

148

149 Five points were chosen for water sampling, including the center section: the northeast  
150 section, the northwest section, the southeast section, the southwest section, and the center  
151 of Nagao Pond. Using a Heyroth sampler, 250 ml of water were collected from the surface  
152 layer and the bottom layer of each point, respectively. The sampling was carried out in the  
153 early afternoon once every 2 weeks, and two samples per point were collected.

154

## 155 **2.3. Measurements and analysis**

156

157 The following parameters were measured in the field: (i) the water depth was measured  
158 using an ultrasonic echo sounder (Hondex PS7); (ii) the surface water temperature and the  
159 deep water temperature were measured using a digital multimeter (Hanna HI98129N); and  
160 (iii) the concentration of dissolved oxygen was determined using a digital oxygen meter with  
161 polarographic probe (Lutro PDO-520). In addition, a portion of each sample was promptly  
162 transported to a laboratory for the quantification of (iv) total phosphorus (TP) through  
163 molybdate colorimetry at 880 nm wavelength (cf. Japan Industrial Standard K0102 46.1.1);  
164 and (v) ammonia nitrogen ( $\text{NH}_4\text{-N}$ ) by indophenol blue colorimetry at 630 nm wavelength (cf.  
165 Japan Industrial Standard K0102 42.6).

166

## 167 **2.4. Data processing**

168

169 Using numerical analysis with R software, the correlation coefficient was applied to evaluate  
170 the relation between the temperature and the other parameters. The correlation coefficients  
171 interpreted in this paper are as follows:  $0 \leq |r| < 0.2$  indicates little or no association;  $0.2 \leq |r| < 0.4$   
172 indicates weak association;  $0.4 \leq |r| < 0.7$  indicates moderate association; and  $0.7 \leq |r| \leq 1.0$   
173 indicates strong association

174

## 175 **3. RESULTS AND DISCUSSION**

176 The data taken in this survey are summarized in Table 1. All data are shown as average  
177 values, which are considered to be representative. Variations in parentheses represent the  
178 minimum and maximum values measured.

179

### 180 **3.1. Water depth**

181

182 There is a clear difference between the least (0.4 m) and greatest values (1.0 m) of water  
183 depth, but the average depth varied slightly from 0.7 m to 0.8 m (Table 1). Viewing the  
184 detailed data for each survey point, the variations in water depth were similar ( $0.78 \pm 0.05$  m)  
185 at all sampling points except the northeast point; on the other hand, the water depth varied  
186 from 0.4 m to 0.5 m at the northeast point; generally, the water depth at the northeast point  
187 is about one half of that at the other points.

188 When considering all five sampling sites, the dissolved oxygen level does not vary  
189 statistically from the surface layer to the bottom layer ( $p > 0.05$ ). Considering that dissolved  
190 oxygen enters water through the air or as a plant byproduct (review in [27]), the following  
191 hypothesis is proposed to interpret this specific phenomenon: oxygen originating in the air  
192 can diffuse across the water's surface and be naturally mixed in a shallow pond, that is, the  
193 diffused oxygen easily reaches equilibrium to some extent throughout the whole pond; and  
194 even if a large portion of photosynthesis (e.g. phytoplankton) takes place underwater,

195 sunlight can penetrate shallow water and reach the bottom, meaning that the phytoplankton  
 196 is not likely to suppress the photosynthesis linked with oxygen supply.  
 197 Although Nagao Pond is man-made, it has an uneven bottom contour – i.e. deep and  
 198 shallow parts. It is reported that there are about 160 thousand artificial ponds and these  
 199 ponds are generally characterized by a depth of below 1.0 m (cf. section 2.1). Doubt remains  
 200 as to whether most of the other ponds have uneven bottom contours similar to Nagao Pond.

201 **Table 1. Average values of parameters measured at five sampling points in Nagao**  
 202 **Pond over the study period**

	Date	Water depth (m)	Wind (m/s)	Temperature (□)			Dissolved oxygen (mg/l)		TP (mg/l) Bottom	NH <sub>4</sub> -N (mg/l) Bottom
				Air	Surface	Bottom	Surface	Bottom		
June	2nd week	0.7 (0.5 - 0.9)	1.5 NW	24.2	29.4	28.5	4.8 (4.4 - 5.1)	4.8 (4.1 - 5.4)	NA	NA
	4th week	0.8 (0.5 - 1.0)	1.8 ESE	23.7	29.9	28.1	5.4 (4.8 - 5.9)	5.1 (4.9 - 5.1)	NA	NA
July	2nd week	NA	1.4 WNW	25.7	NA	NA	NA	NA	NA	NA
	4th week	0.8 (0.5 - 1.0)	1.6 NW	28.4	32.5	31.2	5.4 (5.1 - 5.8)	5.9 (5.1 - 6.2)	NA	NA
Aug.	2nd week	0.8 (0.4 - 0.9)	1.3 WNW	24.0	34.6	33.7	5.0 (3.7 - 6.0)	5.0 (4.3 - 5.4)	NA	NA
	4th week	0.7 (0.4 - 0.8)	1.4 ENE	28.0	30.3	29.9	5.8 (5.5 - 6.7)	5.9 (4.7 - 7.2)	NA	NA
Sept.	2nd week	0.7 (0.5 - 0.9)	1.0 NW	22.5	26.9	26.8	5.4 (5.5 - 6.1)	5.5 (5.2 - 6.3)	NA	NA
	4th week	0.7 (0.4 - 0.9)	1.8 ESE	23.8	25.1	24.8	5.8 (5.7 - 6.0)	5.9 (5.7 - 6.4)	NA	NA
Oct.	2nd week	0.7 (0.4 - 0.9)	1.5 NE	20.0	26.0	26.0	5.6 (5.2 - 6.1)	5.9 (5.2 - 6.5)	0.022	NA
	4th week	0.7 (0.4 - 1.0)	1.2 WNW	15.0	18.2	18.0	7.0 (6.7 - 7.3)	7.2 (6.8 - 7.5)	0.014	0.015
Nov.	2nd week	0.7 (0.4 - 0.9)	1.1 W	12.1	17.7	17.6	7.2 (6.8 - 7.7)	7.3 (6.9 - 7.8)	0.015	0.290
	4th week	0.7 (0.4 - 1.0)	1.4 E	9.6	16.7	16.3	7.6 (7.3 - 8.2)	7.6 (7.3 - 8.0)	0.016	0.180
Dec.	2nd week	0.7 (0.4 - 0.9)	1.3 W	7.7	13.4	13.4	8.0 (7.4 - 8.6)	8.1 (7.5 - 8.6)	0.009	0.425

TP - total phosphorus; NA- not available

203  
 204 **3.2. Eutrophication**  
 205

206 Eutrophication is the nutrient enrichment of waters that stimulates an array of symptomatic  
 207 changes, including increased phytoplankton and rooted aquatic plant production, fisheries  
 208 and water quality deterioration, and other undesirable changes that interfere with water uses  
 209 [28]. Two primary nutrient cycles, phosphorus (P) and nitrogen (N), are generally focused on  
 210 anthropogenic perturbations and their cumulative effects [29]. Some threshold values for  
 211 eutrophication management range from 0.01 to 0.09 mg/l TP and 0.15 to 1.30 mg/l NH<sub>4</sub>-N  
 212 [29]. As seen in Table 1, the measured values are comparatively lower than the threshold  
 213 ones. On the other hand, Lake Kasumigaura, the largest shallow lake (about 4 m depth) in  
 214 Japan, continues to show typical signs of eutrophication [30]. This is due to the increased  
 215 nutrient loadings from urbanization, agricultural development and fishing culture [31].  
 216 Although the Environmental Quality Standard of TP is set to 0.03 mg/l, the TP value  
 217 increased from 0.04 mg/l to 0.10 mg/l in Lake Kasumigaura over the past 30 years;  
 218 meanwhile, the total nitrogen concentration also increased from 0.8 mg/l to 1.3 mg/l [32].  
 219 Continuous measurements of water quality parameters should be performed in Nagao Pond  
 220 to infer the actual/potential occurrence of eutrophication.  
 221

222 **3.3. Climatic effect on dissolved oxygen**

223

224 As stated in sections 1.2 and 2, mainly wind-driven currents and temperature variations  
225 affect water circulation in shallow lakes and ponds. It is therefore assessed whether such  
226 climatic conditions are linked with the dissolved oxygen (DO) level near the bottom layer. As  
227 seen in Table 2, the temperature variations in both air and water are negatively correlated  
228 with the variation in bottom dissolved oxygen ( $r \approx -0.9$ ), and the temperature difference  
229 between the surface layer and the bottom layer also shows moderate negative correlation ( $r$   
230  $\approx -0.6$ ); by contrast, the wind variation shows weak negative correlation ( $r \approx -0.4$ ).

231 It can therefore be concluded that both the air temperature and the water surface  
232 temperature dominantly affect the dissolved oxygen level in the bottom layer of a shallow  
233 pond under natural conditions accompanying changes in temperature and wind.

234  
235

**Table 2. Correlation coefficients (r) of parameters measured in Nagao Pond (p < 0.05).**

	Air temperature	Water surface temperature	Temperature difference between pond surface and bottom	Wind
- Dissolved oxygen in the pond bottom	-0.870	-0.922	-0.581	-0.369
- Correlation strength	Strong	Strong	Moderate	Weak

236

237 As stated in section 1.2, pond stratification leads to the bottom layer receiving little oxygen  
238 from the atmosphere, which may become depleted of oxygen. However, it is possible to  
239 consider that stratification associated with temperature variation hardly occurs in a shallow  
240 pond because there is no statistic evidence ( $p = 0.84$ ) showing a temperature difference  
241 between the surface layer and the bottom layer. This may have resulted in a weak  
242 correlation of the surface-bottom temperature difference with the dissolved oxygen level.  
243 Other studies developed in a 1.8 m-deep pond also show no clear gradient of temperature to  
244 a depth of 1.2 m [33]. Thus, it can be considered that a shallow pond is not thermally  
245 stratified.

246

247

**4. CONCLUSIONS**

248 The global water cycle is related closely to climate change. Fresh surface water accounts for  
249 just 1/10,000 of the total water available on the planet (section 1), and shallow lakes and  
250 ponds are worldwide the most abundant in lake types (section 1.2). It is accepted that wind-  
251 driven currents and thermal stratification mainly affect oxygen diffusion and its dissolved  
252 concentration in lakes (section 2). The present research aimed to verify whether this  
253 accepted view would be really observed. Our field survey in a 1 m-deep pond has  
254 demonstrated that (i) the temperature variations in the air and the pond water were  
255 negatively correlated with the dissolved oxygen level in the bottom layer (section 3.3); (ii)  
256 there was no statistic evidence showing a temperature difference between the surface layer  
257 and the bottom layer (section 3.3.); (iii) there was no statistic evidence for differences in  
258 dissolved oxygen concentration between the surface and bottom layers (section 3.1).

259 As to shallow reservoirs like ponds, a simple concept of the link between temperature and  
260 dissolved oxygen is established through these findings – the oxygen solubility in water  
261 decreases as the temperature increases [34].

262 As stated above, fresh water is a precious resource worldwide, and shallow lakes and ponds  
263 are abundant worldwide. However, there have been few reports about ponds despite their  
264 large number (section 2.1). As the presented research was often restricted by the global  
265 pandemic, long-term observation is necessary to collect reliable data for underpinning the  
266 proper management of water reservoirs.

267

268

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269

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274

## 275 **COMPETING INTERESTS**

276

277 Authors have declared that no competing interests exists.

278

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