Numerical simulation of the surface flux of an alpine grassland in the source region of the Yellow River by the land surface model

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Abstract
The simulation performance of the land surface model Community Land Model 5.0 (CLM5.0) is tested by using the eddy correlation system and micrometeorological tower observational data at the Maqu observation field in 2016. The results show that the CLM5.0 model has a good simulation effect on the soil temperature and can well reflect the seasonal variation characteristics of soil temperature. In addition, the model can well simulate the seasonal variation in shallow soil moisture (5 cm and 10 cm). However, the deviations between the simulated and observed values are large. CLM5.0 cannot simulate the water holding capacity of shallow soil well, resulting in its underestimation. The simulation performance of the upward longwave radiation and net radiation is substantially better than that of the upward shortwave radiation due to the change in surface albedo caused by precipitation from March to July. CLM5.0 can also well reproduce the variation trend of the latent heat flux and 5 cm soil heat flux (heat exchange of soil at 5 cm). When the leaf area index (LAI) and Medlyn slope values are changed to 10%, 20%, and 50% of the default values, the simulation effects of soil moisture at depths of 5 cm and 10 cm are significantly improved, and the best simulation effects are achieved at 0.5 times the default values. This result indicates that lower LAI and Medlyn slope values are more suitable for simulating shallow soil moisture.

Keywords Land surface · Grassland · Yellow River

Introduction

Land surface processes are an important part of Earth science (Dickison 1995; Henderdon-Sellers 1993), and they determine the material and energy exchange between the land surface and atmosphere and further profoundly affect global atmospheric circulation and regional weather and climate (Heusinkveld et al. 2004; Sun 2005). In recent years, land surface processes and their interactions with climate have attracted widespread attention and gradually become an important field of scientific research (Cai et al. 2019; Lawrence et al. 2016; Rosenzweig et al. 2014). The source region of the Yellow River is located in the northeastern part of the Qinghai-Tibet Plateau, which is an important water conservation area in China and an essential part of the Sanjiangyuan national natural reserve (Gu et al. 2015; Yao et al. 2011). This region is a typical representative of the complex underlying surface of lake-alpine grassland (Li et al. 2016). The land–atmosphere interaction of the complex underlying surface in the source region not only directly affects the climate and environmental changes on the Qinghai-Tibet Plateau but also has a great impact on the climate and environment of East Asia and even the world (Li et al. 2016). At present, increasing attention has been given to studying the energy and material exchange between the land and atmosphere, as well as the hydrothermal transport process in the source region of the Yellow River. Chen et al. (2016) used soil moisture observation data from the Maqu Soil Moisture Observation Network in the source region of the Yellow River to estimate the required minimum number of soil moisture observation sites under certain accuracy requirements, and furthermore, they studied site representativeness.
Li et al. (2013) compared the characteristics of surface heat sources on different underlying surfaces of water and land and analyzed the influence of meteorological factors on the surface energy distribution by using eddy correlation data in the source region of the Yellow River.

Historically, this region has experienced serious ecological degradation due to climate change and human activities (Yin et al. 2014; Zhou et al. 2005). Since the rapid decrease in the discharge of the Yellow River in the 1990s, a series of ecological restoration and protection projects have been carried out in the Sanjiangyuan area that have improved grassland coverage and water supply capacity (Jiang and Zhang 2016; Shao et al. 2017). Process-based land surface models (LSMs) are a useful tool for quantifying the effect of land cover change on the surface energy and water cycle. A large number of studies on the land surface processes on the Tibetan Plateau have been carried out by using LSMs. Yang et al. (2009) implemented an advanced soil water flow scheme and considered the excessive resistance of the heat flux in Simple Biosphere version 2 (SiB2), which improves the simulation of soil water and energy fluxes. Luo et al. (2017) introduced gravel and organic matter into the Community Land Model 4.5 (CLM4.5) soil parameterization and improved the simulation of freeze–thaw processes. Yuan et al. (2018) developed the combined surface-subterranean process version 2 (CSSPv2), which greatly improved the simulation of water flow. Most LSMs are calibrated based on areas with abundant observation data, but calibration is not as effective for areas with limited observation data (such as the Tibetan Plateau). In recent years, with the increase in observations of the eddy flux, the parameter sensitivity and uncertainty of different LSMs for the Tibetan Plateau have been explored in several studies, such as the Noah-Multiparameterization Land Surface Model (Noah-MP, Arsenault et al. 2018) and the Common Land Model (CoLM, Gao et al. 2015; Peng and Sun 2019; Peng et al. 2020; Su et al. 2010).

The CLM is one of the most mature and widely applicable models (Oleson et al., 2013; Felfelani et al. 2018). CLM5.0 is the latest version and was developed on the basis of CLM4.5, improving the soil and vegetation hydrology, snow density, river model, carbon and nitrogen cycling and coupling, and crop model. In addition to a more comprehensive and explicit representation of the change in land use and land cover, the CLM mainly improves the dynamics of key processes. Currently, simulation studies using the CLM5.0 model in the source region of the Yellow River are still insufficient. Moreover, many parameters in the LSMs need to be calibrated according to the limited field observations. However, the process of accounting for regional representativeness among these observation sites needs to be determined and verified through LSM simulation studies.

In this study, CLM5.0 was used to conduct a numerical simulation experiment at the Maqu site. The applicability of the model to the underlying surface of an alpine grassland was studied by comparing it with the observation data at the Maqu site in 2016. Finally, the model simulation effect was improved by changing the values of key parameters, such as the leaf area index (LAI). We hope this study will provide a basis for improving and developing a model parameterization scheme and an evaluation and estimation of regional climate and environmental changes, which is of great significance to the development of the local social economy. The remainder of this paper is organized as follows: Sect. 2 introduces the observation data and numerical experimental design. The simulation results are analyzed in detail in Sect. 3. In Sect. 4, the improvements to the parameterization schemes are discussed. Section 5 provides a summary and conclusions.

### Observational data and numerical experimental design

#### Observation area and data

The average altitude of the Tibetan Plateau is more than 4000 m, accounting for approximately one-third of the height of the troposphere. In summer, the surface of the Tibetan Plateau is a heat source, and the South Asian high is dominant at the upper levels. At that time, the surface is controlled by the thermal low pressure, resulting in low-level convergence and upward movement. In winter, the surface is a cold source controlled by the strong cold high, so the air diverges at the low levels and sinks in the vertical direction. Climate change on the Tibetan Plateau has an important impact on East Asian atmospheric circulation as well as on the weather and climate. The data used in this study were obtained from the main alpine-grassland observation field in Maqu that is part of the Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences (Fig. 1). The Maqu area is an important part of the source region of the Yellow River and is located in the northeastern part of the Tibetan Plateau. The observation field is located on the natural grassland of Maqu County, Gannan Tibetan Autonomous Prefecture, Gansu Province (102°08′E, 33°53′N), at an altitude of 3423 m. Given the specific topography and climatic characteristics of the Tibetan Plateau, it is difficult to distinguish four seasons in Maqu; thus, there are only cold and warm seasons. The warm season is humid, and the cold season is dry. The annual average temperature is 1.2 °C, the number of frost days is approximately 270 days, and the annual average precipitation is 595 mm, mainly concentrated from May to September. The annual evaporation is approximately 1353.4 mm, the annual sunshine duration is 2583.9 h, and the annual average wind speed is 2.5 m·s⁻¹. The terrain around the observation field is flat with the underlying
surface of the alpine grassland. The vegetation types mainly include *Artemisia humilis*, *Potentilla anserine*, and *Kobresia humilis*, with a coverage of 92%. The grass height is approximately 15 cm in summer and approximately 5 cm in winter. The main soil type is subalpine grassland soil. The proportions of sandy soil (particle size is less than 0.02 mm), silt (particle size in 0.02–0.05 mm), and clay (particle size in 0.05–2 mm) in the shallow layer within 20 cm are 3.4%, 80.1%, and 16.5%, respectively.

In this study, in 2016, the eddy correlation system and micrometeorological gradient tower data were obtained from the Maqu observation field with the data collectors CR3000 and CR23XTD (Campbell Scientific Incorporated Company, Utah, United States of America), respectively. The air temperature and relative humidity obtained from the Vaisala HUMICAP45C sensor (HMP45C, United States of America, with a precision of ±0.2 °C), the four components of radiation obtained from the net radiation sensor NR01 (United States of America, with a precision of ±10%), sensible and latent heat flux data, relative humidity and saturation water vapor pressure data were used in this study. In addition, the observed precipitation data were obtained from rain gauges. The soil temperature was collected by a 107L temperature sensor (United States of America, with a precision of ±0.2 °C). The soil moisture was collected by the Campbell Scientific 616 (CS616) soil moisture sensor (United States of America, with a precision of ±2.5%). The data time interval was 30 min. The soil heat flux was obtained by the HPF01 SC-L heat flux plate (United States of America, with a precision of ±3%).

In order to improve the accuracy of data, the research has conducted quality control over the eddy observation data (Xu et al. 2008), including abnormal data deletion, ultrasonic temperature correction of sensible heat flux, and WPL correction of water vapor and carbon dioxide flux. This research has eliminated the data that was obviously abnormal (mainly due to data anomalies and missing data caused by rain and snow), and the missing data was supplemented by interpolation.

**Model description and numerical experiment**

The Community Land Model (CLM) is a comprehensive land surface model that simulates biophysical (e.g., radiation transfer, energy fluxes, and hydrology) and biogeochemical processes (e.g., carbon and nitrogen dynamics). CLM5.0 is the latest version of the CLM that was released in February 2018. Compared to the prior version CLM4.5 (released
in July 2013), CLM5.0 largely modified vegetation-related processes and replaced the Ball-Berry stomatal conductance model (Collatz et al. 1991) with the Medlyn stomatal conductance model (Medlyn et al. 2011). In addition, this version of the model abandoned the previously used simple plant water stress calculations that were based on only soil water potential and adopted a plant hydraulic scheme that accounts for different water potentials at the leaf, stem, and root and soil. CLM5.0 also added a soil dry layer that largely reduced soil evaporation that was usually overestimated in earlier versions of the CLM (Swenson and Lawrence 2014).

The atmospheric forcing data for the site simulations were the CLM default global forcing data (CRUNCEP). The air temperature retrieved from the global product well matched the site observations in 2016 for Maqu at the monthly scale, with an $R^2$ higher than 0.95. The other forcing variables had $R^2$ values within 0.78–0.94, except for the wind speed. The main land cover types at the Maqu site are alpine grassland and meadow, with a vegetation coverage rate of more than 92%.

In our simulation, we set the Maqu site to consist of 100% vegetation. The soil textures were 17% clay, 80% silt, and 3% sand. We cycled the 2016 CRUNCEP forcing to run a spin-up for 300 years at each site to ensure that the surface variables entered steady states (Yang et al. 1995).

Results

Soil temperature and moisture

Soil temperature is an important part of soil properties and is related to the energy exchange and water cycle between the ground and the atmosphere, which directly affects changes in sensible heat, latent heat, and soil heat flux. Soil moisture can affect climate change by changing the albedo, soil thermal conductivity, and sensible and latent heat that are transmitted to the atmosphere. In addition, the phase change process of soil moisture will release and absorb heat, which will have a significant impact on heat transmission in the soil.

Figure 2 shows the comparison between the observed and simulated values of the soil temperature in each soil layer at the Maqu site in 2016. The simulation results of CLM5.0 and CLM4.5 are generally the same. They simulate soil temperature at each depth well and reflect the variation characteristics of soil temperature with the seasons. The correlation coefficients between the simulations by the CLM5.0 and the observations are all above 0.95, and the simulation effect of the 160 cm soil temperature is better than that of the other soil layers, with a correlation coefficient of 0.99 and a root mean square error of 3.7 °C. The simulation effects in spring and autumn are better than those in winter and summer. The simulated soil temperature at each depth in winter (from November to the following February) and summer (from June to August) is lower than the soil temperature observations. The observed soil temperature begins to drop to 0 °C near November, while the model is slightly ahead. The shallow soil is obviously affected by the temperature with a relatively severe fluctuation. The model better captures the variation trend of the soil temperature. With increasing depth, the influence of temperature on soil temperature decreases, and the daily variation curve is smoother. The soil temperatures at depths of 80 cm and 160 cm in winter are above 0 °C; namely, the deep soil is not frozen, but the simulated value is negative.

From the simulation and observation of the soil moisture in each depth in Fig. 3, it is indicated that the simulation effects of CLM5.0 and CLM4.5 on soil moisture at the Maqu site are less effective, and the performance of CLM5.0 is significantly better than that of CLM4.5. Except for the simulation of the 20 cm soil moisture that is close to the observed value, the simulated values of soil moisture are significantly lower than the soil moisture observations in the shallow layers (5 cm and 10 cm) but higher in the deep layers (20 cm, 40 cm, 80 cm, and 160 cm), especially in summer. From November to mid-February of the following year, the soil in the alpine grassland is frozen, and the soil moisture in the shallow layers is close to 0. Although the soil temperature is still below 0 °C in mid-February, the soil moisture begins to increase due to day-thawing and night-freezing. With the increase in precipitation, the shallow soil moisture increases rapidly and fluctuates strongly, and the model better reflects its change trend. The correlation coefficients of soil moisture at depths of 5 cm and 10 cm are 0.85 and 0.89, respectively, which surpass the 99% confidence level. However, the simulated values have large deviations from the observed values, with root mean square errors of 0.08 and 0.1, respectively. This result means that the CLM5.0 does not simulate the water holding capacity of the shallow soil well (5 cm and 10 cm), resulting in an underestimation of soil moisture. Of the simulations, that of the 20 cm soil moisture is best, with a correlation coefficient of 0.89 and a root mean square error of 0.06. The soil moisture in the deep layers of 80 cm and 160 cm is less affected by precipitation, the values are relatively stable, and the change curve is relatively smooth. With the soil freezing close to November, the soil moisture begins to decline significantly in November, and the simulated soil moisture by the CLM is approximately 10 days ahead of the observed values, which is similar to the simulated results of soil temperature. In general, the simulation effect of soil temperature was better than that of soil moisture, which is mainly due to the large deviations in the soil hydrothermal properties that are caused by the physical differences in the thermal conductivity, heat capacity, and water conductivity between the water and ice.
Radiation flux

Surface energy exchange processes include the surface heat balance and radiation balance, which are the main processes of Earth-atmosphere interactions and the key link for the Earth system to convert solar energy and to carry out heat and water cycles. The influence of solar activity, plant growth, and human activity on climate change is mainly based on the change in surface heat and radiation balances, and their responses to climate change are also transmitted through surface energy exchange processes. Therefore, the change characteristics of surface heat are of extreme concern in the study of global change and climate anomalies. Whether simulations of surface heat and the radiation flux are accurate is often the main indicator used to evaluate the simulation performance of a land surface model.

Fig. 2 Comparison of the observed and simulated values of soil temperature at each depth at the Maqu site in 2016
Figure 4 shows the comparison of the upward shortwave radiation (FSR), upward longwave radiation (FIRE), and net radiation (RN) between the observations and simulations. Overall, the simulation results of CLM5.0 were similar to those of CLM4.5, and the performance of CLM5.0 was slightly better than that of CLM4.5. The simulation of shortwave radiation by CLM5.0 is not perfect. The curve of the simulated values is relatively smooth, and the annual fluctuation is small. The annual average short-wave radiation simulated by the CLM5.0 is 35.6 W·m⁻², but the observation is 43.5 W·m⁻². From March to July, the surface albedo changes due to more precipitation.
in this period, leading to an intense fluctuation of the upward shortwave radiation, which is not well reflected in CLM5.0, with a correlation coefficient of only 0.46. The simulated values of the upward shortwave radiation from January to August are lower than the observed values, which mainly occurs because of the low selected LAI value and surface albedo. The simulation effect of CLM5.0 on the upward longwave radiation is more ideal, with a correlation coefficient of 0.93 and a root mean square error of 37 W·m⁻². The model well reflects the variation trend of the upward longwave radiation, as well as the corresponding peaks and valleys. The upward longwave radiation reaches a peak from July to August in summer, with an average of 382 W·m⁻², while the simulated value is lower, with an average of 366 W·m⁻², which may be due to the underestimation of the surface temperature.

Net radiation has obvious seasonal variation characteristics and is mainly determined by the total radiation and surface albedo. In winter, the total radiation is relatively small, the surface albedo is large, and the net radiation is the smallest in winter. The daily average net radiation increases rapidly in March and reaches its peak in July, which is directly related to the decrease in surface albedo caused by the increase in soil humidity. CLM5.0 well reflects the change trend of net radiation, and the correlation coefficient is 0.78. Generally, the simulated value is lower than the observed value, which is also related to the low simulation of upward shortwave radiation.

**Heat flux**

Figure 5 shows the observed and simulated values of the sensible heat flux (H), latent heat (LE) flux, and 5 cm soil heat flux (G-5 cm). The sensible heat flux simulation performances of CLM5.0 and CLM4.5 are relatively poor, with a correlation coefficient of only 0.32. The simulated values are lower in winter and higher in summer. The sensible heat flux increases significantly in early February, while CLM5.0 fails to simulate its variation trend; in addition, the simulated values are negatively correlated with the observed values. The seasonal variation in the latent heat flux is obvious, and the variation trend is opposite that of the sensible heat flux. The latent heat flux is small in winter and significantly increases in summer. The model has a better simulation effect on the latent heat flux, except in late July, when the simulated values are significantly lower than the observations. The simulation results of CLM5.0 are better than those of CLM4.5, with the correlation coefficient reaching 0.87. The latent heat flux reaches its peak in summer. The average values of the observed and CML5.0 simulated latent heat flux values in May to July are 80.8 W·m⁻² and 77.2 W·m⁻², respectively. The simulation value is very close to the observed value. For the whole year, the surface flux is dominated by the latent heat flux in the study area.

The daily average soil heat flux at 5 cm is positive from mid-March to late August, indicating that the soil heat flux transfers from the surface to the deep layers. During other periods, the daily average soil heat flux is negative, which means that the soil heat flux transfers from the deep layer to the surface. CLM5.0 well reflects its variation trend, and the CLM5.0 simulation effect is significantly better than that of CLM4.5, with a correlation coefficient of 0.70, surpassing the 99% confidence level. At the beginning of March, the average daily soil heat flux is abnormally large, which is related to the melting of frozen soil. Because ice needs to absorb a part of the heat to melt into water, the soil temperature gradient increases, and the heat flux from the soil surface to the deep layers further increases, which is also well captured by CLM5.0.
Parameterization schemes

In general, the simulation effect of CLM5.0 at the Maqu site is significantly better than that of CLM4.5 due to its great improvement in the parameterization schemes of some physical processes. These new parameterization schemes can be better applied to the underlying surface of the alpine grassland in the source region of the Yellow River. However, the simulation results for soil moisture, sensible heat flux, and upward shortwave radiation in the shallow layers show that there is still a deviation between the simulations and the observations. Changing the values of some key parameters is expected to improve the simulation effect of CLM5.0. Due to the high vegetation coverage at the Maqu site and the strong sensitivity of the vegetation parameters (such as the LAI) to the simulation, the vegetation-related parameters are those that should be improved.

The LAI is a sensitive parameter in CLM5.0, and its change has a significant impact on the simulation. In this study, the LAI is changed to 10%, 20%, and 50%, which are 2, 5, and 10 times the default value. From Figs. 6 and 7, it can be seen that when the LAI value is set to 10%, 20%, and 50% of the default value, the simulation performances of the 5 cm and 10 cm soil moisture levels are significantly improved. Although the simulation results show no significant change in winter, in comparison to previous simulations, the simulation is significantly improved from March to September. The simulation performance is the best when the LAI is set at 50% of the default value. The correlation coefficient and root mean square error of the 5 cm soil moisture are 0.89 and 0.07, respectively, and the correlation coefficient and root mean square error of the 10 cm soil moisture are 0.91 and 0.09, respectively. These results are all better than the simulation results with the default LAI value. However, when the LAI value is changed to 2 times, 5 times, and 10 times the default value, the simulation effects of the soil moisture at 5 cm and 10 cm worsen, indicating that the lower LAI value is, the more suitable it is for simulating shallow soil moisture.

CLM5.0 calculates stomatal conductance using the Medlyn stomatal conductance model (Medlyn et al. 2011). Previous versions of the CLM calculated leaf stomatal resistance using the Ball-Berry conductance model as described by Collatz et al. (1991) and implemented in global climate models (Sellers et al. 1996). The Medlyn model calculates stomatal conductance (i.e., the inverse of resistance) based on net leaf photosynthesis, the vapor pressure deficit, and the CO$_2$ concentration at the leaf surface.

It can be seen from Figs. 8 and 9 that after making the same change to the value of the Medlyn slope as that of the LAI, the simulation results of the 5 cm and 10 cm soil humidity are similar to those after the change in the LAI. When the value of the Medlyn slope becomes 10%, 20%, and 50% of the default value, the simulation results of the 5 cm and 10 cm soil humidity are similar to the LAI. The simulation results also have no significant change in winter, but they are significantly improved from March to September. The simulation performance is the best when the Medlyn slope is set as 50% of the default value. When the Medlyn slope value becomes 50% of the default value, the root mean square errors of the 5 cm and 10 cm soil moisture are 0.07 and 0.08, respectively, and the simulation effect of CLM5.0 has also significantly improved. When the Medlyn slope value becomes 2, 5, and 10 times the default value, the performance of the 5 cm and 10 cm soil moisture simulations worsen.
Conclusions

(1) CLM5.0 simulated soil temperature at each depth well and can reflect the variation characteristics of soil temperature with the seasons. The simulation effects in spring and autumn are better than those in winter and summer. The shallow soil is obviously affected by the temperature with a relatively severe fluctuation. In comparison to earlier versions, CLM5.0 better capture the variation trend of the soil temperature. The simulation effects of the CLM5.0 model on soil moisture at the Maqu site are less effective. Except for the simulation of the 20 cm soil moisture that is close to the

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Fig. 6 Comparison between the observed and simulated values of the 5 cm soil moisture after changing the LAI values

Fig. 7 Comparison between the observed and simulated values of the 10 cm soil moisture after changing the LAI values
observed, the simulated soil moisture values are significantly lower than the observed soil moisture values in the shallow layers but higher in the deep layers; however, the model better reflects the change trend of the shallow layers. This result indicates that CLM5.0 cannot simulate the water holding capacity of shallow soil well, resulting in an underestimation of shallow soil moisture.

(2) The shortwave radiation simulation performance of CLM5.0 is not exact. The curve of the simulated values is relatively smooth, and the annual fluctuation is small. From March to July, the surface albedo changes due to
more precipitation occurring in this period, leading to an intense fluctuation of the upward shortwave radiation, which is not well reflected in CLM5.0. The simulated values of the upward shortwave radiation from January to August are lower than their observed values, which mainly occurs because of the low selected LAI value and surface albedo. The upward longwave radiation simulation effect of CLM5.0 is more ideal. The model well reflects the variation trend of the upward longwave radiation, as well as the corresponding peaks and valleys. The net radiation has obvious seasonal variation characteristics. Generally, the simulated value is lower than the observed value, which is also related to the poor simulation of the upward shortwave radiation.

(3) The sensible heat flux simulation performance of CLM5.0 is relatively poor. The simulated values are lower in winter and higher in summer. The model has a better latent heat flux simulation effect. The simulation value is very close to the observed value. CLM5.0 can well reflect the variation trend of the soil heat flux at 5 cm, and the simulation effect is significantly better than that of CLM4.5. At the beginning of March, the average daily soil heat flux is abnormally large, which is related to the melting of frozen soil. Because the ice needs to absorb a part of the heat to melt into water, the soil temperature gradient increases, and the heat flux from the soil surface to the deep layers further increases, which is also well captured by CLM5.0.

(4) When the LAI and Medlyn slope values are set to 10%, 20%, and 50% of the default value, the simulation performances of the 5 cm and 10 cm soil moisture levels are significantly improved. The simulation performance is the best when the LAI and Medlyn slope are set at 50% of the default value. The results are all better than the simulation with the default LAI and Medlyn slope values. However, when the LAI and Medlyn slope values are changed to 2 times, 5 times, and 10 times the default value, the simulation effects on the soil moisture at 5 cm and 10 cm worsen, indicating that the lower LAI and Medlyn slope values are more suitable for simulating shallow soil moisture.

In general, the simulation effect of CLM5.0 on the underlying surface of alpine grass at the Maqu site is good. However, there are still certain deviations in the simulations of soil moisture and sensible heat flux. The soil hydrothermal parameterization scheme of the model needs to be further improved. At the same time, this study only evaluates the model at a single point at the Maqu site and needs to be verified at more observation sites.

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**Declarations**

**Conflict of interest** The authors declare that they have no competing interests.

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