Response to reviewers

We received two referees' reports. Referees 1 recommended minor revisions, and Referee 2 provided major comments. We address each point made by the referees below. Our responses are in red, and the new text added to the manuscript is indented and italicized.

Anonymous Referee #1

The manuscript by Ge et al. 2019 (HESSD) presents a very important study on exploring the impacts of revegetation of on regional water balance over the Loess Plateau, China. The GFGP was initiated in late 1990s and has tremendous influences on the Loess Plateau. The impacts of revegetation on the region's hydrological balance should be carefully investigated using both observation and model simulations. The current study has tried to answer this question using WRF model, and provide knowledge and information for policy makers. In general, I think it is a very interesting and important study, and I would recommend it for publication after minor revision.

Thank you!

Please find my detailed comments below.

1. In introduction section, please add some introduction or examples about published studies that used WRF for hydrological balance analysis. The related references will add confidence of using WRF in the current study and demonstrate the solidness of the current results.

We have added some further literature using WRF for hydrological balance analysis in the revised manuscript:

> Line 102: *WRF has been shown to perform well in dynamic downscaling of regional climate over China (e.g., He et al., 2017; Sato and Xue, 2013; Yu et al., 2015). Additionally, WRF has been used to study the impact of land use and land cover change on the hydrological balance at regional scales (Deng et al., 2015; Zhang et al., 2018). While WRF is therefore potentially suitable for evaluating the impact of revegetation on the hydrology of the Loess Plateau we undertake an evaluation of WRF in simulating surface air temperature and rainfall for this region (See Section 3.1).*

2. In regard to the findings of the current study, it would be better to add some discussions on similarity/difference with existing studies. It will add extra values if published study has found similar trend in evapotranspiration based on satellite products/groundbased measurements, or model simulations.

We have added some discussions on similarity/difference with existing studies in the revised manuscript. For example:

> Line 383: *Our results on changes of evapotranspiration, soil moisture and runoff are broadly consistent with both field (Jia et al., 2017; Jian et al., 2015; Jin et al., 2011) and satellite (Feng et al., 2017; Li et al., 2016; Xiao, 2014) observations. For example, the spatial pattern of our simulated soil moisture decline in the growing season is*

similar to observations from the Advanced Microwave Scanning Radiometer on the Earth Observing System by the Japanese Aerospace Exploration Agency (Feng et al., 2017). Although the increased evapotranspiration due to revegetation of the Loess Plateau has been examined before (e.g., Cao et al., 2017, 2019; Li et al., 2018; Lv et al., 2019), the reduction in runoff and soil moisture in response to revegetation of the Loess Plateau, which is consistent with observations, has been rarely reported in modeling results previously. Moreover, our simulated weak response of rainfall to revegetation of the Loess Plateau, which is hard to determine from observations, is useful in assessing the hydrometeorology of this region.

Line 408: *WRF shows little response of rainfall to revegetation since the launch of the GFGP, which contradicts earlier results (Cao et al., 2017, 2019; Li et al., 2018; Lv et al., 2019).*

Line 443: *These factors account for the discrepancy between our result and another model based study (Li et al., 2018). Li et al (2018) found a positive rainfall feedbacks to greening and consequently small changes in runoff and soil moisture over north China using a Global Climate Model. In contrast, we demonstrate the rainfall change is too small to compensate for the strongly enhanced evapotranspiration, causing a reduction of runoff and soil moisture in response to revegetation over the Loess Plateau.*

Anonymous Referee #2

Review comments for the manuscript “Impact of revegetation of the Loess Plateau of China on the regional growing season water balance” by Jun Ge, Andrew J. Pitman, Weidong Guo, Beilei Zan, Congbin Fu.

General

The paper investigated the impact of revegetation on the hydrology of the Loess Plateau. The introduction needs to be further clarified. For example, the authors stated that “the response of rainfall to large-scale revegetation is rarely investigated”. As far as I known, there are studies (e.g., Ma et al., 2013; Chen et al., 2016; Yosef et al., 2018) that have investigated it.

We stated “the response of rainfall to large-scale revegetation is rarely investigated” following the “The impact of revegetation on evapotranspiration, soil moisture and runoff over the Loess Plateau has been studied” in the original manuscript. Our statement therefore relates to the Loess Plateau. However, we recognize this could have been confusing and therefore we have clarified the introduction:

> Line 54: *Despite the increasing observational evidence demonstrating that revegetation tends to impair the hydrological balance of the Loess Plateau, the response of rainfall to revegetation over this region has commonly been overlooked. This is mainly due to the difficulty in detecting the impact of revegetation on rainfall from observations.*

> Line 65*: In contrast with observations, modeling can help disentangle the impact of revegetation on rainfall from the impact of other drivers. Cao et al. (2017) and Li et al.*

> *(2018) performed numerical experiments over the whole China and demonstrated that the revegetation over the Loess Plateau can enhance the rainfall locally. Very recently, Lv et al. (2019b) and Cao et al. (2019) performed simulations focused on the Loess Plateau to examine the impact of revegetation or afforestation on rainfall. Lv et al. (2019) reported a significant increase in rainfall while Cao et al. (2019) found spatially divergent changes of rainfall. We also note some earlier studies investigating the response of rainfall to land cover change across China (e.g., Chen et al., 2017; Ma et al., 2013; Wang et al., 2014). Unfortunately, these studies either focused less on the Loess Plateau (Ma et al., 2013) or applied land cover changes unable to reflect the revegetation of the Loess Plateau (Chen et al., 2017; Wang et al., 2014). Therefore, large uncertainties remain in the response of rainfall to revegetation of the Loess Plateau owing to inconsistent conclusions derived from limited studies.*

Furthermore, the authors mentioned in the discussion section that “Our results are broadly consistent with both field (Jia et al., 2017; Jian et al., 2015; Jin et al., 2011) and satellite (Feng et al., 2017; Li et al., 2016; Xiao, 2014) observations”. Therefore, the new findings in this work need to be further highlighted.

We have further clarified the new findings of this work in the revised manuscript. There are basically three findings of this work. First, we used WRF to demonstrate the reduction in soil moisture and runoff due to revegetation over the Loess Plateau, which has been rarely reported in previous modeling studies and thereby further confirm the observations. We make this clear in the revised manuscript:

> Line 383: *Our results on changes of evapotranspiration, soil moisture and runoff are broadly consistent with both field (Jia et al., 2017; Jian et al., 2015; Jin et al., 2011) and satellite (Feng et al., 2017; Li et al., 2016; Xiao, 2014) observations. For example, the spatial pattern of our simulated soil moisture decline in the growing season is similar to observations from the Advanced Microwave Scanning Radiometer on the Earth Observing System by the Japanese Aerospace Exploration Agency (Feng et al., 2017). Although the increased evapotranspiration due to revegetation of the Loess Plateau has been examined before (e.g., Cao et al., 2017, 2019; Li et al., 2018; Lv et al., 2019), the reduction in runoff and soil moisture in response to revegetation of the Loess Plateau, which is consistent with observations, has been rarely reported in modeling results previously. Moreover, our simulated weak response of rainfall to revegetation of the Loess Plateau, which is hard to determine from observations, is useful in assessing the hydrometeorology of this region.*

Second, we used WRF to demonstrate the marginal response of rainfall to revegetation over the Loess Plateau, which contradicts previous modeling results that used older experimental methods. We also demonstrate that the impact of revegetation on rainfall is very likely overestimated in previous studies due to limited members in simulations. As we stated in the revised manuscript:

Line 407: *We focused on the response of rainfall to revegetation over the Loess Plateau, which is probably the most uncertain of the hydrological components. WRF shows little response of rainfall to revegetation since the launch of the GFGP, which contradicts earlier results (Cao et al., 2017, 2019; Li et al., 2018; Lv et al., 2019). Moreover, the rainfall is weakly affected by further revegetation despite large increase in evapotranspiration. We also demonstrate that the rainfall change is strongly affected by internal variability and a large number of realisations are required before any impact of revegetation on rainfall might be robustly identified. We suggest that some previous studies (Cao et al., 2017, 2019; Lv et al., 2019) based on model simulations may have exaggerated the impact of revegetation on rainfall over the Loess Plateau due to the lack of sufficient realisations. For example, Cao et al. (2017, 2019) and Lv et al. (2019) used the same WRF to perform only three or five member simulations, and concluded a significant change in rainfall caused by revegetation over the Loess Plateau. More interestingly, Cao et al. (2017) and Cao et al. (2019) obtained different conclusions on the rainfall change over the Loess Plateau with same WRF model. They used a broadly similar experimental design but different spatial resolution (30 km and 10 km respectively) and simulations from 2001-2002 with three ensembles and consecutive simulation from 2000-2004 respectively. We could also demonstrate large changes in rainfall over the plateau if we chose 3-5 members but we could demonstrate either large increases or large decreases in 3-5 member averages. Returning to Fig. 6, ET shows a highly consistent increase in response to revegetation among the 20 years, suggesting*

> *that ET change is robustly linked with revegetation. Although changes in runoff and soil moisture also show large variability among the 20 years, the distribution of the runoff and soil moisture changes are negative biased. More importantly, the distribution of the runoff and soil moisture changes systematically shift towards negative values. This suggest runoff and soil moisture changes are very likely linked with revegetation. The large variability in runoff or soil moisture changes is induced by the large variability of rainfall. Given the tight linkage between rainfall and runoff or soil moisture, the changes in runoff or soil moisture tends to be mistakenly represented if the rainfall change is not robustly examined, and this requires internal model variability to be thoroughly addressed.*

Third, we investigated the potential future impact on the hydrology of the Loess Plateau if revegetation was continued, which has never been assessed before. As we stated in the revised manuscript:

> Line 394: *We also investigated the potential future impact on the hydrology of the Loess Plateau if revegetation was continued, which has not been assessed before but is important for both scientific communities and policymakers.*

The applied land cover change in 2015 relative to 2001 was not consistent with the expected fact. Explanations were missing in several places in the manuscript which kind of focused more on the phenomenon.

We obtain the land cover change from the latest version (version 6) of MODIS land cover product, which should be one of the most reliable datasets. We have added some explanations in the revised manuscript accounting for this comment raised by the reviewer:

> Line 188: *In addition to the gain of forests (including evergreen needleleaf, evergreen broadleaf, deciduous needleleaf, deciduous broadleaf and mixed forests) and savannas (including woody savannas and savannas), other changes in land cover type include the expansion of croplands (including croplands and cropland/natural vegetation mosaics) at the expense of grasslands and savannas (Fig. 2g). These increased croplands revealed by the MODIS land cover product, which seem unlikely, have been reported previously (Fan et al., 2015; Lv et al., 2019), and are likely associated with expanded irrigation activities along the Yellow River (Fan et al., 2015; Zhai et al., 2015).*

Detailed comments are given below.

Specific Concerns/Comments

1) Line 55: The authors stated that “the response of rainfall to large-scale revegetation is rarely investigated”. As far as I known, there are studies that have investigated it.

Ma, D., M. Notaro, Z. Liu, G. Chen, and Y. Liu. Simulated impacts of afforestation in East China monsoon region as modulated by ocean variability, Climate Dynamics, 41(9-10), 2439-2450, 2013, doi: 10.1007/s00382-012-1592-9

Chen, L., Z. Ma, R. Mahmood, T. Zhao, Z. Li, and Y. Li. Recent land cover changes and sensitivity of the model simulations to various land cover datasets for China, Meteorology and Atmospheric Physics, 129(4), 395-408, 2016, doi:10.1007/s00703-016-0478-5

Yosef, G., R. Walko, R. Avisar, F. Tatarinov, E. Rotenberg, and D. Yakir. Large-scale semi-arid afforestation can enhance precipitation and carbon sequestration potential. Scientific Reports, 8(1), 996, 2018. doi:10.1038/s41598-018-19265-6

Wang, Y. L, Feng, J. M, Gao, H. Numerical simulation of the impact of land cover change on regional climate in China. Theoretical & Applied Climatology, 2014, 115(1-2):141-152

Chen, H. S et al. Numerical Simulation of the Impact of Land Use/Land Cover Change over China on Regional Climates during the Last 20 Years. Chinese Journal of Atmospheric Sciences, 2015

Xu, L., G. Yang, Y. Feng, Y. Du, and X. Han. A study on microclimate impacts of artificial vegetation on the Loess Plateau, Research of Soil and Water Conservation, 17(4), 170-179, 2010

Ma, Y. Climatic and agricultural effect of converting farmland into forest or grass land in ShanGanNing region in China, Chinese Academy of Meteorological Sciences and Nanjing University of Information Science & Technology, 2011

We thank the reviewer for providing some literature that we should have cited. We think some literature are helpful and related with this work, such as Ma et al. (2013), Chen et al. (2017), Wang et al. (2014) and Yosef et al. (2018), so we have cited this four literature in the revised manuscript. For example:

> Line 70: *We also note some earlier studies investigating the response of rainfall to land cover change across China (e.g., Chen et al., 2017; Ma et al., 2013; Wang et al., 2014). Unfortunately, these studies either focused less on the Loess Plateau (Ma et al., 2013) or applied land cover changes unable to reflect the revegetation of the Loess Plateau (Chen et al., 2017; Wang et al., 2014).*

> Line 456: *It is very likely this would be the consequences in some regions such as Amazonia (Lawrence and Vandecar, 2015; Perugini et al., 2017; Spracklen et al., 2018) and Sahel (Kemena et al., 2018; Xue and Shukla, 1996; Yosef et al., 2018).*

We also note the reviewer provided some literature in Chinese, such as Chen et al. (2015), Xu et al. (2010) and Ma et al. (2011). Given that these literature are not accessible to the readership of *Hydrology and Earth System Sciences*, we think it is unsuitable to cite these literature in the revised manuscript.

2) Lines 69–70: “Thus, the impact of revegetation on the hydrology of the Loess Plateau remains unclear due to the uncertainty in the rainfall response.” The conclusion is kind of arbitrary because there are multiple factors, for example, whether the applied land use change

data can reflect the reality, and whether a continuous change in the vegetation boundary condition is considered in the modeling. To my knowledge, the existing modeling studies are mainly about sensitivity experiments which cannot exactly reveal what happened in the real world. This manuscript was also a sensitivity experiment. On the other hand, the change in soil moisture under the GFGP was associated with the investigated soil layer depths. The soil moisture above 1 m on the Loess Plateau was mainly controlled by precipitation.

We agree and we have rewritten this sentence in the revised manuscript:

> Line 79: *Here, we note it might be unfair to directly compare the observational and modeling results because observational results commonly incorporate multiple factors and modeling results are subject to uncertainties in both land cover change and biophysical parametrization schemes implemented in models (de Noblet-Ducoudre et al. 2012; Pitman et al. 2009). These intrinsic differences between observational and modeling cannot fully account for the disagreement on the runoff and soil moisture change due to revegetation over the Loess Plateau.*

3) As shown in Fig. 2g, the croplands mainly increased from 2015 to 2001, which is contrary to the expected fact. The applied land cover change data cannot reflect the reality well. Consequently, readers may wonder how much the simulation can represent the fact.

As we mentioned above, we obtained the land cover change from MODIS land cover product, which is an authoritative dataset worldwide and should be reliable. We have explained why croplands increased from 2001 to 2015 over the Loess Plateau in the revised manuscript:

> Line 192: *These increased croplands revealed by the MODIS land cover product, which seem unlikely, have been reported previously (Fan et al., 2015; Lv et al., 2019), and are likely associated with expanded irrigation activities along the Yellow River (Fan et al., 2015; Zhai et al., 2015).*

We have also added some warnings in the revised manuscript. For example:

> Line 184: *We note that the difference between LC2001 and LC2015 should not be regarded as equivalent to the impact of GFGP for two reasons.*

> Line 449: *Last, we investigated the impact of revegetation or greening, rather than GFGP, on the hydrology of the Loess Plateau. Directly linking our results to the impact of GFGP on the hydrology of the Loess Plateau should be avoided.*

4) Lines 70–71: "Moreover, as far as we know, there has been no study investigating how the regional hydrology would be affected if further revegetation was undertaken." The current effects of land use/cover change still need to be further identified. Readers may want to know to what extent can we trust the conclusion of the study with further revegetation?

We have clarified why we study the impact of further revegetation on the hydrology of the Loess Plateau in the revised manuscript:

> Line 89: *As far as we know, there has been no study investigating how the regional hydrology would be affected by further revegetation over the Loess Plateau, something important for informing policymakers on the mitigation and adaptation of climate change for this region. Additionally, the vegetation over the Loess Plateau is fragile and highly dependent on the water availability (Fu et al. 2017). How the hydrology would be impacted by further revegetation determines the water availability, and in turn how much more revegetation can be sustained over the Loess Plateau. Neglecting this process risks errors in assessing the upper threshold of vegetation of the Loess Plateau (Feng et al., 2016; Zhang et al., 2018). Given the importance of revegetation over the Loess Plateau now and in the future we examine the impact of further revegetation on the hydrology of the Loess Plateau and pay particular attention to the response of rainfall to revegetation.*

5) Lines 107–109: “The MCD12Q1 data were reprojected to Geographic Grid data with a resolution of 30 second (approximately 0.9 km) by the MODIS Reprojection Tool to make them suitable for WRF.” Why didn’t you resample the MCD12Q1 data into 10km that is exactly the same to the domain 2?

We have further clarified this comment in the revised paper:

> Line 134: *We changed the land cover type within the Loess Plateau while retaining the default land cover type for other regions in our experiments (see details in Section 2.3). Therefore, the MCD12Q1 data were reprojected to Geographic Grid data with a*

> *resolution of 30 second (approximately 0.9 km) by the MODIS Reprojection Tool to make them consistent with the default land cover map in WRF.*

6) Lines 155–156: “We note land cover change here, rather than revegetation or afforestation, for two reasons. First, actual land cover changes since the launch of the GFGP are highly spatially heterogeneous.” However, the authors mentioned “revegetation” throughout the manuscript including the title and abstract. If the applied land cover change cannot represent the fact, the simulated conclusions cannot provide too much guidance for the implement of GFGP.

We have rewritten this sentence:

> Line 184: *We note that the difference between LC2001 and LC2015 should not be regarded as equivalent to the impact of GFGP for two reasons.*

We have also added a caveat in discussions of the revised manuscript:

> Line 449: *Last, we investigated the impact of revegetation or greening, rather than GFGP, on the hydrology of the Loess Plateau. Directly linking our results to the impact of GFGP on the hydrology of the Loess Plateau should be avoided.*

We think “revegetation” is a suitable word to basically describe the land cover change of the Loess Plateau due to a significant greening trend in the past decades. It has been also widely used in previous literature.

7) The significant changes (grey) in rainfall were not located in the main area of vegetation changing under the “Grain for Green Program” in Fig. 11l. What is the reason?

We have demonstrated these rainfall changes (e.g., increased rainfall of the northeast Loess Plateau) is associated with model internal variability. Please see section 3.6 for details.

8) Lines 161–168: The used VEGFRA, LAI and changes also incorporated other factors including improved agricultural management, climate variability, rising atmospheric CO2 concentration and nitrogen deposition. This may interfere the isolation of vegetation change effect. Please clarify.

We have clarified this comment in the revised manuscript:

> Line 449: *Last, we investigated the impact of revegetation or greening, rather than GFGP, on the hydrology of the Loess Plateau. Directly linking our results to the impact of GFGP on the hydrology of the Loess Plateau should be avoided.*

9) As shown in Fig. 5c, the latent heat flux (ET) increased significantly almost across the Loess Plateau. However, the LAI and land cover almost didn’t change in the region except the ELP and SLP (i.e., the region near the internally draining area). Moreover, the extent of changes in the green vegetation fraction was much larger than that of LAI (LC2015-LC2001). Please clarify the reasons. Additionally, what induced the changes in albedo in the region near the internally draining area? Furthermore, the LAI changed in the ELP and SLP regions,

but there was almost no change in albedo. What is the reason? The Lines 248-250 need to be further explained.

We actually masked the small changes in LAI in the original manuscript. We have changed the colorbar scheme of Fig. 3 to avoid readers misunderstanding the biophysical changes. It is visible that LAI indeed change outside ELP and SLP.

The difference between green vegetation fraction change and LAI change is not surprising because green vegetation fraction and LAI are different measures.

To clarify the albedo change, we have added some text in the revised manuscript:

> Line 198: *For example, the α decrease mostly occurs over grasslands in northwest (Fig. 3e), where land cover type is rarely changed (Fig 2c). This decreased α is attributed to increased precipitation as well as the restoration of grasslands benefiting from the Returning Rangeland to Grassland Program launched in 2003 over this region (Zhai et al., 2015). In contrast, the α change is negligible in the SLP and ELP, owing to the combined effects of increased forests (Fig. 2a) and croplands (Fig. 2d).*

10) The rainfall change mainly occurred in the region above the ELP (Fig. 7a), which was not consistent with the mainly occurring area of GFGP. What is the reason? Moreover, the convective rainfall increased and non-convective rainfall decreased for LC2015-LC2001 in Fig. 7. Please clarify the reason.

Similar to comment #7, we have demonstrated the increased rainfall of the northeast Loess Plateau is associated with model internal variability. Please see section 3.6 for details.

The reviewer thinks the convective rainfall increased and non-convective rainfall decreased for LC2015-LC2001 in Fig. 7, while these changes are negligible small. Basically the RAIN change is divided almost evenly between RAINC and RAINNC (Fig. 7c and 7e). This demonstrates the weak linkage between RAIN, RAINC and RAINNC changes and revegetation, and these rainfall changes appears randomness which is more likely induced by model internal variability.

11) Lines 260–262: “Moreover, the increased rainfall in northeast Loess Plateau occurring in LC2015-LC2001 dissipate when further revegetation is implemented suggesting that this change is largely associated with internal model variability.” However, the initial conditions were the same between LC2015-LC2001 and LCfutr-LC2001 with the only differences in land cover and the biogeophysical parameters.

To clarify this comment, we have rewritten this sentence in the revised manuscript:

> Line 297: *Moreover, the increased RAIN in northeast Loess Plateau occurring in LC2015-LC2001 dissipate when further revegetation is implemented while the changes in both land cover type and biophysical parameters are relatively small over this regions. This increased RAIN should be maintained in LCfutr-LC2001 if the change in*

> *RAIN is robust for LC2015-LC2001. We will analyse the increased RAIN of the northeast Loess Plateau in LC2015-LC2001in Section 3.6.*

12) Suggest the authors to add one more figure of spatial P-ET changes which is highly correlated with runoff and soul moisture above 1 m.

We have added the figure of spatial P-ET changes in the revised manuscript. Please see Fig. 8e and 8f.

13) The rainfall responses were obviously different in different years in Figure 10 under the same vegetation change. Please give some explanation. The Figure 12 was used to demonstrate the impact of model internal variability, but one important factor for the phenomenon may be the large variability in rainfall.

We have explained why rainfall responses are different in different years:

> Line 308: *This large variability in RAIN changes among the twenty members can be attributed to either different boundary conditions (background climate), which causes the impact of land cover change to diverge (Pitman et al., 2011), or model internal variability.*

We further chose 2001 as a case to examine the whether the increased rainfall in 2001 can be robustly linked with revegetation. We demonstrated that the rainfall changes in 2001 are not robust as we can modified the rainfall changes only by changing the initial conditions. As we said:

> Line 357: *We therefore show the RAIN change in each realisation for LCENS2015-LCENS2001 in Fig. 11. These eleven ensemble members share the same boundary conditions with small differences in initial conditions. In contrast with the increased RAIN obtained from setting initial date on 1st May (Fig. 10f), the RAIN changes are modified by an advance of 1 to 10 days in initial conditions. For example, WRF cannot simulate the increased RAIN over northeast Loess Plateau when using an initial date of 22nd, 25th, 27th and 30th April, highlighting that the RAIN change is very sensitive to the initial conditions. Thus, the RAIN increase in 2001 with an initial date of 1st May is likely associated with internal variability rather than revegetation. In another words, the RAIN change due to revegetation is negligible relative to the RAIN change induced by internal variability. We therefore conclude that the multiyear averaged RAIN increase over northeast Loess Plateau for LC2015-LC2001 (Fig. 7a) cannot be robustly linked with revegetation.*

Fig. 12 is to demonstrate that running more members and averaging them can effectively reduce the noise induced by model internal variability. Running multiple years or running a year but with multiple realisations are both effective. As a the reviewer said “one important factor for the phenomenon may be the large variability in rainfall”, so it is necessary to examine the rainfall change in a single year with multiple realisations, in which case the large variability in rainfall is absent due to the same boundary condition (background climate).

14) Lines 365–371: Generally, if a continuous simulation is conducted, much time will be taken. This may be why the simulation periods were usually not too long in a certain number of studies. If long time spans are considered, continuous simulations usually cannot be realized like this study (only including the growing season). On the other hand, the effects of land cover change are likely associated with the backgrounds of circulation, which suggests that the effects could be different for different research time periods. Tobella et al. (2014) reported that tree planting had both negative and positive effects on water resources in drylands and the net effect was the result of a balance between them. Similarly, this manuscript found that there existed both positive and negative effects of vegetation change on rainfall, and the effects were not small as stated in Line 267 and Fig. 6b. The authors concluded that the results show no impact on rainfall in most places of this manuscript. It seems that the expression is inappropriate because the negative and positive effects likely canceled each other out from 1996 to 2015.

We agree that the time scale should be considered when the impact of revegetation is evaluated. As we stated in the revised manuscript:

> Line 430: *First, observations of soil moisture declines associated with revegetation can be alleviated once trees mature (Jia et al., 2017; Jin et al., 2011). Our simulations only capture an initial decline in runoff and soil moisture linked with the higher*

> *evapotranspiration and we note that the impact of revegetation on the long-time trend (25 - 50 years) would be valuable. Second, we used current boundary conditions (1996-2015) for WRF to predict the impact of further revegetation on the hydrology, which means the boundary conditions do not change in the future in response to climate change. This suggests that we might underestimate the impact of further revegetation in the future if future climate of the Loess Plateau suffers from large changes in response to global warming.*

We have added some discussions on the work of Tobella et al. (2014):

> Line 459: *Additionally, Tobella et al. (2014) reported a positive impact of trees on soil hydraulic properties influencing groundwater recharging when termite mound is taken into account in Africa. While the termite mound is rare over the Loess Plateau suggesting this positive impact of trees is unlikely to occur.*

The reviewer think “It seems that the expression is inappropriate because the negative and positive effects likely canceled each other out from 1996 to 2015”. This statement is true if the rainfall change in individual year can be robustly linked with revegetation. While we demonstrate that the rainfall change in individual year (we take 2001 for instance) cannot be linked with revegetation. In another word, the rainfall change in individual year, which is induced by model internal variability, cancelled each other from 1996 to 2015. It is therefore legitimate to conclude revegetation has no impact on the rainfall of the Loess Plateau.

15) Lines 307–316: It was first stated that “the RAIN increase in 2001 with an initial date of 1st May is likely associated with internal variability rather than land cover change.” Then, it was concluded “the multiyear averaged RAIN change over northeast Loess Plateau for LC2015-LC2001 (Fig. 7a) cannot be robustly linked with land cover change.” If the rainfall response was not associated with the land cover change, does it mean all the results in the manuscript were not linked with the vegetation change?

We have added a text to clarify this comment:

> Line 421: *Returning to Fig. 6, ET shows a highly consistent increase in response to revegetation among the 20 years, suggesting that ET change is robustly linked with revegetation. Although changes in runoff and soil moisture also show large variability among the 20 years, the distribution of the runoff and soil moisture changes are negative biased. More importantly, the distribution of the runoff and soil moisture changes systematically shift towards negative values. This suggest runoff and soil moisture changes are very likely linked with revegetation. The large variability in runoff or soil moisture changes is induced by the large variability of rainfall. Given the tight linkage between rainfall and runoff or soil moisture, the changes in runoff or soil moisture tends to be mistakenly represented if the rainfall change is not robustly examined, and this requires internal model variability to be thoroughly addressed.*

16) The authors mentioned that their simulations were at high resolution of 10 km many times in the manuscript. However, I don’t think a 10 km resolution is high nowadays.

We have replaced “high resolution” with “relatively high resolution” throughout the revised manuscript.

17) Suggest the authors to give the study periods (1996-2015 or just 2001) in the figure captions.

We have added the study periods in the figure captions.

18) Typo mistakes:

Line 20: Results suggests that...

This has been revised.

Line 122: “As we only focus the growing season” should be “focus on the growing season”.

This has been revised.

Line 308: “cf. Fig. 7a and 10f”

This has been revised.

Impact of revegetation of the Loess Plateau of China on the regional growing season water balance

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Abstract. To resolve a series of ecological and environmental problems over the Loess Plateau, the "Grain for Green Program (GFGP)" was initiated at the end of 1990s. Following the conversion of croplands and bare land on hillslopes to forests, the Loess Plateau has displayed a significant greening trend with soil erosion being reduced. However, the GFGP has also affected the hydrology of the Loess Plateau which has raised questions whether the GFGP should be continued in the future. We investigated the impact of revegetation on the hydrology of the Loess Plateau using relatively high resolution simulations and multiple realisations with the Weather Research and Forecasting (WRF) model. Results suggest~~s~~ that ~~land cover change~~~~the~~ revegetation since the launch of the GFGP has reduced runoff and soil moisture due to enhanced evapotranspiration. Further revegetation associated with the GFGP policy is likely to increase evapotranspiration further, and thereby reduce runoff and soil moisture. The increase in evapotranspiration is associated with biophysical changes, including deeper roots that deplete deep soil moisture stores. However, despite the increase in evapotranspiration our results show no impact on rainfall. Our study cautions against further revegetation over the Loess Plateau given the reduction in water available for agriculture and human settlements, without any significant compensation from rainfall.

■ 1 Introduction

The Loess Plateau is a highland region of north central China, covering about 640,000 km^2. The loess soils are well suited for agriculture so natural forests have been progressively converted to farmland to support the growing population over the last 7000 years (Fu et al., 2017). However, the loess is also prone to wind and water erosion, and the long history of deforestation is associated with soil erosion, resulting in land degradation, low agricultural productivity and significant local poverty in some farming communities (Bryan et al., 2018; Chen et al., 2015; Fu et al., 2017). The soil erosion aggravates the flux of sediment into the Yellow River (Fu et al., 2017; Miao et al., 2010; Peng et al., 2010) increasing the risk of catastrophic flooding in some densely populated regions downstream (Bryan et al., 2018; Chen et al., 2015; Fu et al., 2017).

To minimise soil erosion, mitigate flood risk, store carbon and improve livelihoods over the Loess Plateau, the "Grain for Green Program (GFGP)" was initiated by reforesting hillslopes in the late 1990s (Bryan et al., 2018; Fu et al., 2017; Liu et al., 2008). Consequently, the Loess Plateau has displayed a significant "greening" trend (Chen et al. 2015; Fu et al., 2017; Li et al., 2017). The large scale vegetation restoration program has also reduced soil erosion over the Loess Plateau and alleviated sediment transport into the Yellow River (Fu et al., 2017; Liang et al., 2015; Miao et al., 2010; Peng et al., 2010; Wang et al., 2016).

As a consequence of the beneficial outcomes of the GFGP, further investment is planned with a commitment of around $US33.9 billion by China through to 2050 (Feng et al., 2016). However, further revegetation over the Loess Plateau is controversial (Cao et al., 2011; Chen et al., 2015; Fu et al., 2017) with evidence from field (Jia et al., 2017; Jin et al., 2011; Wang et al., 2012) and satellite (Feng et al., 2017; Lv et al., 2019a; Xiao, 2014) observations that revegetation has affected the hydrological balance of the region. Compared with croplands or barren surfaces, the planted forests enable higher evapotranspiration associated with a larger leaf area, higher aerodynamic roughness and deeper roots (Anderson et al., 2011; Bonan, 2008; Bright et al., 2015). Consequently, revegetation tends to decrease soil moisture and runoff with the associated risk of limiting water availability for agriculture, human consumption and industry (Cao et al., 2011; Chen et al., 2015; Fu et al., 2017). Indeed, the present vegetation over the Loess Plateau, which to some extent reflects decades of reafforestation, may already exceed the limit that the local water supply can support, and hence further revegetation may not be sustainable (Feng et al., 2016; Zhang et al., 2018).

Despite the increasing observational evidence demonstrating ~~the~~that revegetation tends to impair the hydrological balance of the Loess Plateau, the response of rainfall to revegetation over this region has ~~always~~commonly been overlooked. This is mainly due to the difficulty in detecting the impact of revegetation on rainfall from observations.~~The impact of revegetation on evapotranspiration, soil moisture and runoff over the Loess Plateau has been studied; however the response of rainfall to large-scale revegetation is rarely investigated~~. As an important component of hydrological cycle of the Loess Plateau, rainfall not only controls the terrestrial water budget, but also influences soil erosion and the discharge of sediment into the Yellow River (Liang et al., 2015; Miao et al., 2010; Peng et al., 2010; Wang et al., 2016). Therefore, how rainfall responds to revegetation is critical to a comprehensive assessment of the impact of revegetation on the hydrology of the region. Indeed, if rainfall responds to revegetation, this may influence national policies on whether to continue large scale vegetation restoration programs. Afforestation or deforestation does have the potential to affect rainfall via changes in biogeophysical processes, but any impact of afforestation or deforestation~~reforestation~~ on rainfall tends to be highly regionally specific (~~Chen and Dirmeyer, 2017; Quesada et al., 2017~~Findell et al., 2006; Lorenz et al., 2016; Winckler et al., 2017).

~~Superior~~In contrast with ~~to~~ observations, modeling can help ~~to effectively~~ disentangle the impact of revegetation on rainfall from the impact of other drivers. Cao et al. (2017) and Li et al. (2018) ~~carried out~~performed numerical experiments over the whole China and demonstrated that the revegetation over the Loess Plateau can enhance the rainfall locally. Very recently, Lv et al. (2019b) and Cao et al. (2019) ~~carried out~~performed simulations ~~numerical experiments~~ focussed on ~~targeting~~ the Loess Plateau to examine the impact of revegetation or afforestation on rainfall. Lv et al. (2019) reported a significant increase in rainfall while Cao et al. (2019) found spatially divergent changes of rainfall. We also note some earlier studies investigating the response of rainfall to land cover change across China (e.g., Chen et al., 2017; Ma et al., 2013; Wang et al., 2014). Unfortunately, these studies either focused less on the Loess Plateau (Ma et al., 2013) or applied land cover changes unable to reflect the revegetation of the Loess Plateau (Chen et al., 2017; Wang et al., 2014). Therefore, ~~there remains~~ large uncertainties remain in the response of rainfall to revegetation of the Loess Plateau owing to inconsistent conclusions derived from limited studies. ~~Several studies have used coupled models to assess the hydrological impact of revegetation across China (Cao et al., 2017; Li et al., 2018). Lv et al. (2019b) examined revegetation over the Loess Plateau and found an increase in the simulated rainfall.~~

~~Furthermore~~We note~~,~~ Li et al. (2018) ~~also~~ reported that ~~a positive feedback of~~the increased rainfall due to revegetation over North China (covering but not limited to the Loess Plateau)~~, which~~ was large enough to compensate for the increase in evapotranspiration and resulted in little impact on soil moisture. This simulated negligible soil moisture change associated with revegetation is contradicted by extensive studies based on observations (e.g., Feng et al., 2017; Jia et al., 2017; Wang et al., 2012). Here, we note it might be unfair to directly compare the observational and modeling results because observational results commonly incorporate multiple factors and modeling results are subject to uncertainties in both land cover change and biophysical parametrization schemes implemented in models (de Noblet-Ducoudre et al. 2012; Pitman et al. 2009). ~~Despite these~~These intrinsic differences between observational and modeling ~~results, they can't~~cannot fully ~~totally~~ account for the disagreement on the runoff and soil moisture change due to revegetation over the Loess Plateau. Thus, the impact of revegetation on the hydrology of the Loess Plateau remains unclear and needs careful re-evaluations.~~ due to the uncertainty in the rainfall response~~.

~~Moreover, as far as we know, there has been no study investigating how the regional hydrology would be affected if further revegetation was undertaken over the Loess Plateau. This is highly relevant with the policymakers' decision on the mitigation and adaptation of climate change for this region. Additionally, the vegetation over the Loess Plateau is fragile and highly dependent on the water availability (Fu et al. 2017). How the hydrology would be impacted by further revegetation determines the water availability, and in turn how much more revegetation can be sustained over the Loess Plateau. Neglecting this process risks to overestimate or underestimate the upper threshold of vegetation of the Loess Plateau (Feng et al., 2016; Zhang et al., 2018). Thus, the impact of further revegetation on the hydrology of the Loess Plateau should be explicitly investigated.~~

In this study, we examine the impact of revegetation following the launch of the GFGP on the hydrology of the Loess Plateau using relatively high resolution simulations with the Weather Research and Forecasting model. We also examine the impact of further revegetation on the hydrology of the Loess Plateau with the goal of providing helpful information to policy~~-~~makers. As far as we know, there has been no study investigating how the regional hydrology would be affected by further revegetation over the Loess Plateau, something important for informing policymakers on the mitigation and adaptation of climate change for this region. Additionally, the vegetation over the Loess Plateau is fragile and highly dependent on the water availability (Fu et al. 2017). How the hydrology would be impacted by further revegetation determines the water availability, and in turn how much more revegetation can be sustained over the Loess Plateau. Neglecting this process risks errors in assessing the upper threshold of vegetation of the Loess Plateau (Feng et al., 2016; Zhang et al., 2018). Given the importance of revegetation over the Loess Plateau now and in the future we examine the impact of further revegetation on the hydrology of the Loess Plateau and~~We~~ pay particular attention to the response of rainfall to revegetation~~, which is rarely available from observations~~.

2 Methods

2.1 Model configuration

The Weather Research and Forecasting (WRF, version 3.9.1.1, Skamarock et al., 2008), a fully coupled land-atmosphere regional weather and climate model, was used in our study. WRF has been ~~extensively demonstrated~~shown to perform well in dynamic downscaling of regional climate over China (e.g., He et al., 2017; Sato and Xue, 2013; Yu et al., 2015). Additionally, WRF has been used to study the impact of land use and land cover change on the hydrological balance at regional scales (Deng et al., 2015; Zhang et al., 2018). While WRF is therefore potentially suitable ~~to~~for evaluating~~e~~ the impact of revegetation on the hydrology of the Loess Plateau we undertake an evaluation of ~~. While the performance of~~ WRF in simulating surface air temperature and rainfall ~~of the Loess Plateau was validated in this study~~for this region –(See Section 3.1). ~~Therefore, WRF is potentially suitable to evaluate the impact of revegetation on the hydrology of the Loess Plateau. While the performance of WRF in simulating surface air temperature and rainfall of the Loess Plateau was validated in this study (See Section 3.1).~~ To perform simulations at high spatial resolution over the Loess Plateau region, we applied two-way nested runs, with two domains at different grid resolutions running simultaneously. The ERA-Interim reanalysis data (Dee et al., 2001, Table 1) provided the boundary conditions for the larger and coarser resolution (30 km) domain, and the larger domain provided boundary conditions for the smaller and higher resolution (10 km) domain. The ERA-Interim reanalysis data also provided the initial conditions for both domains. Using a lambert projection, the larger domain was centred at 100^{o}E, 37^{o}N, with 180 grid points in west-east direction and 155 grid points in south-north direction, covering most of China and some surrounding regions (Fig.

1a). The inner domain covers the entire Loess Plateau with 166 grid points in west-east direction and 151 grid points in south-north direction (Fig. 1a and 1b). Both domains had 28 sigma levels in vertical direction with the top level set at 70 hPa. ~~Figure~~ Fig. 1b shows the region analysed in this paper.

The main physical parameterization schemes used in our study included the WRF Single-Moment 6-class scheme (Hong and Lin, 2006) for microphysics, the Dudhia scheme (Dudhia, 1989) for shortwave radiation, the Rapid Radiative Transfer Model (RRTM, Mlawer et al., 1997) for longwave radiation, a revised MM5 scheme (Jimenez et al., 2012) for the surface layer, the Noah Land Surface Model (Ek, 2003), the Yonsei University scheme (Hong et al., 2006) for the planetary boundary layer, and the Kain-Fritsch scheme (Kain, 2004) for cumulus convection. The Noah Land Surface Model used the Unified NCEP/NCAR/AFWA scheme with soil temperature and moisture in four layers (1st layer: 0-10 cm, 2nd layer: 10-40 cm, 3rd layer: 40-100 cm, 4th layer: 100-200 cm), fractional snow cover and frozen soil physics. A sub-tiling option considering three land cover types within each grid cell was applied to help improve the simulations of the land surface fluxes and temperature (Li et al., 2013).

2.2 Data

2.2.1 Satellite data

We used satellite observed land cover type ~~data~~ obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type product (MCD12Q1, Version 6, Friedl and Sulla-Menashe, 2019, Table1). This provides land cover types based on International Geosphere-Biosphere Program (IGBP) classification scheme (Table 2) globally at a spatial resolution of 500 m, and at yearly intervals from 2001 to 2017. The MCD12Q1 Version 6 is improved over previous versions via substantial improvements to algorithms, classification schemes and spatial resolution (Sulla-Menashe et al., 2019). We changed the land cover type within the Loess Plateau while retaining~~ed~~ the default land cover type for other regions in our experiments (see details in Section 2.3). Therefore, t~~T~~he MCD12Q1 data were reprojected to Geographic Grid data with a resolution of 30 second (approximately 0.9 km) by the MODIS Reprojection Tool to make them ~~suitable for WRF~~consistent with the default land cover map in WRF.

Key land surface biogeophysical parameters include the green vegetation fraction (*VEGFRA*), snow free albedo (α), leaf area index (*LAI*), and the background roughness length (Z_0). The fraction of Photosynthetically Active Radiation (*FPAR*) can be used as a proxy of *VEGFRA* (Kumar et al., 2014; Liu et al., 2006) enabling both *VEGFRA* and *LAI* data to be obtained from the MODIS Terra+Aqua LAI/FPAR product (MCD15A2H, Version 6, Myneni et al., 2015a, Table 1). This provides 8-day composite *LAI* and *FPAR* globally at a spatial resolution of 500 m since 4th July, 2002. The MODIS Terra LAI/FPAR product (MOD15A2H, Version 6, Myneni et al., 2015b, Table 1) was also used to provide observations prior to 2002 as it started on 8th February, 2000. Although MOD15A2H has a longer span time, MCD15A2H is generally preferred. This is because only observations from the MODIS sensor on NASA's Terra satellite is used to generate MOD15A2H, but observations from sensors on both Terra and Aqua satellites are used for MCD15A2H. The MCD15A2H and MOD15A2H Sinusoidal Tile Grid data were reprojected before use. The 8-day *LAI* and *FPAR* data were composited to monthly data to make them suitable for WRF.

As we only focus on the growing season (see Section 2.3.1), α can be assumed to be equivalent to satellite observed snow-free albedo. The α data was derived from the blue sky albedo for shortwave provided by the Global Land Surface Satellite (GLASS) product (Liang and Liu, 2012, Table 1). This provides an 8-day composite albedo globally at a spatial resolution of 0.05° from 1981 to present. Compared with the MODIS albedo product, the GLASS albedo product has a higher temporal resolution and captures the surface albedo variations better (Liu et al. 2013). The 8-day α data were composited to monthly data.

The background roughness length (Z_0) was calculated following Eq. (1):

$$Z_0 = Z_{min} + \frac{VEGFRA - VEGFRA_{min}}{VEGFRA_{max} - VEGFRA_{min}} \times (Z_{max} - Z_{min}) \qquad (1)$$

where Z_{max} and Z_{min} were land cover dependent maximum and minimum background roughness length respectively, provided by lookup tables. $VEGFRA$, $VEGFRA_{\max}$ and $VEGFRA_{\min}$ are the instantaneous, maximum and minimum green vegetation fraction, which were calculated from satellite observed *VEGFRA* (equal to *FPAR*) which would be implemented in WRF (see Section 2.3).

■ 2.2.2 Observation data

To evaluate the WRF model performance in simulating the surface air temperature and rainfall over the Loess Plateau, we used a gridded observation dataset developed by the National Meteorological Information Centre of the China Meteorological Administration (Zhao et al., 2014, Table 1). The dataset provides monthly surface air temperature and rainfall at a spatial resolution of 0.5° from 1961 to present and was produced by merging more than 2400 station observations across China using Thin Plate Spline interpolation. The dataset has been widely used to analyse the surface air temperature and rainfall over the Loess Plateau (Sun et al., 2015; Tang et al., 2018). To facilitate the comparison between simulations and observations, the observation data were bilinearly interpolated to the WRF inner domain grid.

2.3 Experiment design

2.3.1 The impact of ~~land cover change~~revegetation since the launch of the GFGP

To examine the impact of ~~land cover change~~revegetation on the hydrology of the Loess Plateau since the launch of the GFGP we conducted a control experiment (LC$_{2001}$) and a sensitivity experiment (LC$_{2015}$). For the LC$_{2001}$, satellite observed land cover type, *VEGFRA*, *LAI* and α in 2001 were used to approximate land cover type and land surface biogeophysical parameters before the launch of the GFGP. There is a one-year gap between the launch of the GFGP (end of 1999) and 2001, but any bias introduced by this gap is small compared with the changes in land cover type and land surface biogeophysical parameters between 1999 and present. Satellite observed land cover type, *VEGFRA*, *LAI* and α in 2015, representing the current land cover type and land surface biogeophysical status, were used for the LC$_{2015}$. Model configurations were identical for the LC$_{2001}$ and LC$_{2015}$ except for land cover type and land surface biogeophysical parameters. Comparing the LC$_{2001}$ and LC$_{2015}$ therefore isolates the impact of ~~land cover change~~revegetation since the launch of the GFGP.

~~Here it should be noted~~We note that the difference between LC$_{2001}$ and LC$_{2015}$ should not be regarded as equivalent to the impact of GFGP ~~We note land cover change here, rather than revegetation or afforestation, ~~for two reasons. First, actual changes in land cover type ~~changes ~~since the launch of the GFGP are highly spatially heterogeneous due to various anthropogenic activities including GFGP, irrigation and urbanization. MCD12Q1 suggests that most changes in land cover type ~~changes ~~have occurred in the south Loess Plateau (SLP, 105-111°E, 35-37°N) and east Loess Plateau (ELP, 111-114°E, 35-39°N) (Fig. 2a, 2c, 2e and 2g). In addition to the gain of forests (including evergreen needleleaf, evergreen broadleaf, deciduous needleleaf, deciduous broadleaf and mixed forests) and savannas (including woody savannas and savannas), other changes in land cover ~~changes ~~type include the expansion of croplands (including croplands and cropland/natural vegetation mosaics) at the expense of grasslands and savannas (Fig. 2g). These increased croplands revealed by the MODIS land cover product, which seem ~~contrary to the reality~~unlikely, have ~~also~~ been reported previously (Fan et al., 2015; Lv et al., 2019), and are likely associated with expanded irrigation activities along the Yellow River (Fan et al., 2015; Zhai et al., 2015). Second, the observed *VEGFRA*, *LAI* and α changes also incorporate other factors including improved agricultural management, climate variability, rising atmospheric CO$_2$ concentration and nitrogen deposition (Li et al., 2017; Fan et al., 2015; Piao et al., 2015). As shown in Fig. 3a, 3c, 3e, and 3g, the biogeophysical changes are not strictly limited to the regions undergoing changes in land cover type~~change~~. For example, the α ~~change~~ decrease mostly occurs over grasslands in northwest (Fig. 3e), where land cover type ~~changes are less intense~~is rarely changed (Fig 2c). This decreased α is attributed to increased precipitation as well as the restoration of grasslands benefiting from the Returning Rangeland to Grassland Program launched in 2003 over this region (Zhai et al., 2015). In contrast, the α change is negligible ~~small~~ in the SLP and ELP, ~~which is likely~~ owing to the combined effects of increased forests (Fig. 2a) and croplands (Fig. 2d). Overall however, the MCD12Q1 demonstrates a significant greening trend (increased *VEGFRA*, *LAI* and Z_0 and decreased α) over the Loess Plateau since the launch of the GFGP (~~Figure~~ Fig. 3), which are spatially consistent with previous studies (e.g., Cao et al., 2019; Xiao, 2014; Zhai et al., 2015).

Both LC$_{2001}$ and LC$_{2015}$ were run from 1st May to 30th September for years from 1996 to 2015 resulting in twenty realisation members for each of LC$_{2001}$ and LC$_{2015}$. We only run for the growing season; any impact of ~~reforestation~~ revegetation should be most apparent during the growing season given that over 70% of the annual rainfall occurs over the Loess Plateau in this season (Sun et al., 2015; Tang et al., 2018).

■ 2.3.2 The impact of further revegetation on the Loess Plateau

If the GFGP is continued in the future, further revegetation could impact the hydrology of the Loess Plateau. We therefore conducted a third experiment (LC$_{futr}$) in which the coverage of forests was assumed to be maximum over the Loess Plateau following the policy of the GFGP. To maximise forests we first assumed all croplands and barren on hillslopes were converted to forests. Second, we assumed savannas or forests with low coverage (e.g., low *VEGFRA*) became dense forests. The land cover and land surface biogeophysical parameters for the LC$_{futr}$ were then constructed following two steps.

First, all croplands, barren and savannas pixels on hillslopes (>15°) were replaced by forests pixels over the Loess Plateau based on the land cover map of 2015. The slope is derived from the Shuttle Radar Topography Mission

(SRTM version 2.0, Table 1) Digital Elevation Model at a spatial resolution of 3 second (about 90 m). The pixel resolution of the land cover type is 30 second, so every land cover type pixel covered 100 (10×10) slope values. To maximise the revegetation, land cover type pixels with maximum slope values over 15° were regarded as hillslopes. For a pixel to be changed, the forest class was determined by the class of neighbouring forests pixels, considering the adaptation of planted trees to local climate. Using this strategy, forests pixels increased by 164% and croplands pixels decreased by nearly a half in the constructed land cover map compared with the land cover type in 2001, with most conversions occurring in SLP (Fig. 2b and 2h).

Second, we constructed the *VEGFRA*, *LAI* and α map in line with the land cover type ~~map~~ constructed in the first step. For each forests class, we screened out the "dense forests" pixels with *VEGFRA* over the 95th percentile among the pixels labelled as the same forests class over the Loess Plateau. The monthly values of *VEGFRA*, *LAI* and α of the "dense forest" pixels were calculated for each forests class. We then adjusted the monthly *VEGFRA*, *LAI* and α of other "non-dense forests" pixels to the values of the "dense forests" pixels. Using this strategy, all forests pixels over the Loess Plateau were changed to more dense forest. Consequently, the Loess Plateau shows an amplified greening trend in LC_{futr}, especially in SLP (Fig. 3b, 3d, 3f and 3h).

The LC_{futr} was run from 1st May to 30th September for years from 1996 to 2015. Therefore comparing LC_{2001} and LC_{futr} isolates the impact of further revegetation on the hydrology of the Loess Plateau.

■ 2.3.3 Identification of the impact of revegetation

Model internal variability is defined as the difference between realisation members where the only differences are the initial conditions. These differences result from nonlinearities in the model physics and dynamics (Giorgi and Bi, 2000; Christensen et al., 2001). This means some differences between LC_{2001} and LC_{2015} (or LC_{futr}) will be caused by internal variability in addition to ~~land cover changes~~revegetation (Lorenz et al., 2016; Ge et al., 2019). To minimise the impact of internal model variability we performed multiple simulations for the year 2001 by changing initial conditions. Specifically, we carried out a pair of experiments named $LCENS_{2001}$ and $LCENS_{2015}$, which were the same as LC_{2001} and LC_{2015} except that $LCENS_{2001}$ and $LCENS_{2015}$ were only run for the year 2001 but initialized for each day between 21st to 30th April, and ending on 30th September. This led to a total of eleven members (including the members with initial dates of 1st May in LC_{2001} and LC_{2015}) for $LCENS_{2001}$ and $LCENS_{2015}$

respectively. Comparing LCENS$_{2001}$ and LCENS$_{2015}$, simulated changes were likely robust if the impact from revegetation was large and consistent relative to the differences caused by the change in the initial condition.

Results before 1st June was discarded as spin-up time in each simulation. Our analysis focusses on June, July, August and September (JJAS) averages.

■ 2.5 Local significance test

To test the statistical significance of the local impact of ~~land cover change~~revegetation on the hydrology we calculate a grid-point by grid-point Student's *t*-test. This tests the null hypothesis that the two groups of data are from independent random samples from normal distributions with equal means and equal but unknown variances. The local difference is regarded as statistically significant when the *p*-value of the two-tailed *t*-test passes the significance level of 95%.

■ 3 Results

■ 3.1 Evaluation of WRF's skill in simulating temperature and rainfall

We first evaluate WRF's simulation of surface 2m air temperature (*T2*) and rainfall (*RAIN*), the quantities with the most credible observations available over the Loess Plateau, ~~using~~by comparing the averaged value of the eleven members in LCENS$_{2001}$ with the observed values in 2001. After topographic correction (Zhao et al., 2008), WRF simulates *T2* over the Loess Plateau mostly within 2°C of the observations (Fig. 4a, 4c, 4e) although there are small areas where WRF simulates warmer temperatures than the observations by 4°C. The model also performs well in simulating *RAIN* (Fig. 4b, 4d, 4f) including a region of higher observed rainfall from the southwest to the central Loess Plateau. The *RAIN* bias between the WRF simulations and the observations is below 0.5 mm/day for almost the entire Loess Plateau (Fig. 4f). Larger *RAIN* biases mostly occur around the eastern and southern borders of the Loess Plateau, most likely due to extremely complex topography in these locations. Since we focus on the impact of land cover change on the hydrology of the region, the reasonable simulation of *RAIN* gives us confidence in the results from WRF, particularly in SLP.

■ 3.2 Impacts on surface fluxes

We first examine the change in the land surface radiation budget, energy and water fluxes as these are directly impacted by changes in land cover type and the surface biogeophysical ~~changes~~parameters. Comparing LC$_{2001}$

and LC_{2015} (LC_{2015}-LC_{2001}), land surface net radiation (R_{net}), latent heat flux (Q_E) and sensible heat flux (Q_H) changes mainly occur where land cover type and land surface biogeophysical parameters are changed, suggesting a strong local effect on R_{net}, Q_E and Q_H. R_{net} increases by around 5-20 W·m^{-2} (Fig. 5a), over most of the region due to a reduction in α (Fig. 3e). While Q_E increases by 10-30 W·m^{-2} (Fig. 5c) and Q_H reduces by around 10 W·m^{-2} (Fig. 5e), mostly in SLP and ELP as a result of increased *VEGFRA*, *LAI* and Z_0 (Fig. 3a, 3c and 3g). Changes in R_{net} and Q_E are statistically significant at a 95% confidence level over most of the region, but statistically significant changes in Q_H are mostly limited to SLP and ELP (see the embedded subplots in each panel, Fig. 5a, 5c and 5e). As a consequence of further revegetation (LC_{futr}-LC_{2001}), R_{net}, Q_E and Q_H changes are intensified (Fig. 5b, 5d and 5f), especially in SLP where large areas of croplands are converted to forest leading to large changes in land surface biogeophysical parameters in LC_{futr} (Fig. 2 and 3).

Focusing on SLP, the increase in evapotranspiration (*ET*) is 0.49 mm·day^{-1} between LC_{2001} and LC_{2015} (Fig. 6a). WRF simulates further water loss (0.85 mm·day^{-1}) through *ET* if the revegetation is continued in the future (Fig. 6c). For ELP, where relative fewer croplands or barren can be further converted to forests in LC_{futr}, the future *ET* increase is still considerable (0.72 mm·day^{-1}, Fig. 6b and 6d). The values of regional mean *ET* change among the twenty members of LC_{2015}-LC_{2001} and LC_{futr}-LC_{2001} remain consistently positive over SLP and ELP. This indicates that the simulated higher *ET* is a consistent result from WRF as a consequence of the ~~land cover changes~~ revegetation since the launch of the GFGP, and is likely to be further strengthened by continued revegetation over the Loess Plateau.

■ 3.3 Impacts on rainfall

Increased *ET* can contribute to the formation of clouds and rainfall, and we therefore examine whether this is the case for the Loess Plateau. The *RAIN* is composed of convective rainfall (*RAINC*) calculated by the cumulus convection scheme, and non-convective rainfall (*RAINNC*) calculated by microphysics scheme in WRF. Thus we separate *RAINC* and *RAINNC* changes in addition to the *RAIN* change in Fig.7. As for LC_{2015}-LC_{2001}, the change in *RAIN* is spatially heterogeneous, with an increase of up to 1.2 mm·day^{-1} in small parts of the northeast and a decrease around -1.0 mm·day^{-1} along the southeast border of the Loess Plateau (Fig. 7a). The *RAIN* change is divided almost evenly between *RAINC* and *RAINNC* (Fig. 7c and 7e). However, most of the *RAIN*, *RAINC* and *RAINNC* changes are not statistically significant. In terms of LC_{futr}-LC_{2001}, *RAIN*, *RAINC* and *RAINNC* are not significantly changed by further revegetation (Fig. 7b, 7d and 7f). Moreover, the increased ~~rainfall~~ *RAIN* in northeast Loess Plateau occurring in LC$_{2015}$-LC$_{2001}$ dissipate when further revegetation is implemented while the changes in both land cover type and biophysical parameters are relatively small over this regions. ~~In another word,~~T ~~t~~his increased *RAIN* should be maintained in LC$_{futr}$-LC$_{2001}$ if ~~this~~the change in *RAIN* ~~change~~ is robust for LC$_{2015}$-LC$_{2001}$. We will ~~in detail~~ analyze the increased *RAIN* of the northeast Loess Plateau in LC$_{2015}$-LC$_{2001}$ ~~suggesting that this change is largely associated with internal model variability.~~in Section 3.6.

For both LC$_{2015}$-LC$_{2001}$ and LC$_{futr}$-LC$_{2001}$ cases, most *RAIN* changes seem~~s~~ to be randomly scattered around the Loess Plateau instead of being located coincident with SLP or ELP where land cover type, land surface biogeophysical parameters and land surface fluxes are most strongly modified (Fig. 7a and 7b). In contrast, t~~T~~he *RAIN* change is negligible over SLP and ELP for both LC$_{2015}$-LC$_{2001}$ and LC$_{futr}$-LC$_{2001}$ cases (Fig. 6 and 7). However, the *RAIN* change in individual realisation~~s~~ is not small, e.g., the *RAIN* change varies from -2.11 to 2.21 mm·day^{-1} over the ELP for LC$_{2015}$-LC$_{2001}$ (Fig. 6b). So averaging the divergent *RAIN* changes among the twenty members causes a negligible *RAIN* change overall. This large variability in *RAIN* changes among the twenty members can be attributed to either different boundary conditions (background climate), which causes the impact of land cover change to diverge (Pitman et al., 2011), or model internal variability. This will be further analysed in Section 3.6.

■ 3.4 Impacts on runoff

As a consequence of the significant *ET* increase and negligible and statistically insignificant *RAIN* change, underground runoff (*UDROFF*) is reduced by up to 1.5 mm·day^{-1} locally for LC$_{2015}$-LC$_{2001}$ (Fig 8c). Averaged over the SLP and ELP, the *UDROFF* decreases by 0.16 mm·day^{-1} (-23%) and 0.34 mm·day^{-1} (-23%) for SLP and ELP respectively (Fig. 6a and 6b). These *UDROFF* changes are not statistically significant and vary strongly among the twenty members, suggesting a large uncertainty in the *UDROFF* change. WRF simulated a larger *UDROFF* decrease due to further revegetation (Fig. 8d), especially over SLP and ELP where the regional mean *UDROFF* decreases by 0.38 mm·day^{-1} (-54%) and 0.63 (-42%) respectively (Fig. 6c and 6d). These *UDROFF* decreases are statistically significant at a 95% confidence level for both SLP and ELP. Moreover, the upper quartile of *UDROFF* changes among the twenty members systematically shift below the 0 mm·day^{-1} value for both the SLP and ELP. These results indicate a larger chance of the *UDROFF* decrease if the revegetation is continued over the SLP and ELP. Moreover, the spatial change in *UDROFF* is ~~highly~~ consistent with that of the net budget of *RAIN* and *ET* (*RAIN-ET*) for both LC$_{2015}$-LC$_{2001}$ and LC$_{futr}$-LC$_{2001}$ (Fig. 8e and 8f), suggesting that the *UDROFF* change can be mostly explained by the change of *RAIN-ET*. We also note some *UDROFF* changes in adjacent regions of the Loess Plateau (Fig. 8c and 8d) associated with *RAIN* changes (Fig. 7a and 7b).

Compared with the *UDROFF* change, the surface runoff (*SUROFF*) change are mostly small for both LC$_{2015}$-LC$_{2001}$ and LC$_{futr}$-LC$_{2001}$ (Fig. 8a and 8b). However, the relative change of *SUROFF* is considerable, especially for the LC$_{futr}$-LC$_{2001}$ case in which *SUROFF* decreased by 21% for the SLP and 14% for the ELP respectively (Fig. 6c and 6d). We also find the upper quartile of the *SUROFF* change systematically shifts below the 0 mm·day^{-1} value although the *SUROFF* change are not statistically significant for the LC$_{futr}$-LC$_{2001}$.

■ 3.5 Impacts on soil moisture

In addition to the decline in runoff, the soil moisture (*SMOIS*) of each layer is significantly reduced over the Loess Plateau for LC$_{2015}$-LC$_{2001}$ (Fig. 9a, 9c, 9e and 9g) with larger decreases in the middle two layers. The regional mean *SMOIS* for the SLP decreases by 0.02 m·m^{-3} (-8%) and 0.03 m·m^{-3} (-12%) for the second and third layers (Fig. 6a). WRF simulated further falls in soil moisture following further revegetation, with a larger impact on deeper soil layer moisture (Fig. 9b, 9d, 9f and 9h). For example, the decrease in regional mean soil moisture of the bottom layer for the SLP varies from -0.01 (or -5%) in LC$_{2015}$-LC$_{2001}$ (Fig. 6a) to -0.04 (or -17%) in LC$_{futr}$-LC$_{2001}$ (Fig. 6c). Similar to the *UDROFF* change, the spatial change in *SMOIS* ~~of~~for each layer is ~~also~~ consistent with that of *RAIN-ET* for both LC$_{2015}$-LC$_{2001}$ and LC$_{futr}$-LC$_{2001}$ (Fig.8e and 8f).

■ 3.6 Robust identification of rainfall change

We found a large variability in changes in *RAIN* among the twenty members over the SLP and ELP for both LC$_{2015}$-LC$_{2001}$ and LC$_{futr}$-LC$_{2001}$. We next examine whether these can be attributed to ~~land cover change~~revegetation. We first show the *RAIN* change in individual members for LC$_{2015}$-LC$_{2001}$ (Fig. 10). The large variability of *RAIN* changes among the twenty members occur throughout the study region. Even the increase in *RAIN* over the northeast Loess Plateau (Fig. 7a), which is available by comparing multiyear mean *RAIN* between LC$_{2001}$ and LC$_{2015}$, is not consistent for every year. As for the northeast Loess Plateau, the *RAIN* shows an increase in 8 years (1997, 2001, 2003, 2004, 2007, 2010, 2012 and 2015), decrease in 5 years (1996, 1999, 2006, 2009 and 2014) and negligible changes in other 7 years. This results in a net increase in *RAIN* over the twenty years, but a different selection of years could show an overall decrease (the result is similar for LC$_{futr}$-LC$_{2001}$, not shown). Similarly, other statistically significant *RAIN* changes ~~scatted~~occur in the study region (e.g., decreased *RAIN* to the southwest Loess Plateau shown in Fig. 7a) but these are not consistent ~~among~~across the twenty years~~ either~~. As mentioned ~~before~~earlier, this large variability in *RAIN* changes among the twenty members is possibly attributed to different boundary conditions (background climate), and we next examine whether this ~~case~~ is true over the Loess Plateau.

We note that the pattern of *RAIN* change in 2001 is very similar to the multiyear averaged one, but with a larger magnitude (~~cf.~~ Fig. 7a and 10f). The *RAIN* increase of the northeast Loess Plateau in just 2001 explains about 30% of the multiyear mean *RAIN* increase in the same region. We therefore show the *RAIN* change in each realisation for LCENS$_{2015}$-LCENS$_{2001}$ in Fig. 11. ~~It should be noted that~~T~~t~~hese ~~to highlight that the changes are not consistent among the~~ eleven ensemble members ~~despite their~~ shar~~e~~ing the same boundary conditions~~ (background climate),~~ with ~~tiny~~small differences in initial conditions. In contrast ~~of~~with the increased *RAIN* obtained from setting initial date on 1st May (Fig. 10f), the *RAIN* changes are ~~mostly~~ modified ~~due to~~by an advance of 1 to 10 days in initial conditions. For example, WRF cannot simulate the increased *RAIN* over northeast Loess Plateau when using an initial date of 22nd, 25th, 27th and 30th April, highlighting that the *RAIN* change is very sensitive to the initial conditions. Thus, the *RAIN* increase in 2001 with an initial date of 1st May is likely associated with internal variability rather than ~~land cover change~~revegetation. In another words, the *RAIN* change due to revegetation is negligible ~~small~~ relative to the *RAIN* change induced by internal variability~~ of model~~. We therefore conclude that the multiyear averaged *RAIN* ~~change~~ increase over northeast Loess Plateau for LC$_{2015}$-LC$_{2001}$ (Fig. 7a) cannot be robustly linked with ~~land cover change~~revegetation.

3.7 How many members do we need to get a robust signal?

Model internal variability is inevitable when we use models to investigate the impact of land cover change on climate. The model internal variability can be minimised as the number of individual realisations is increased to form a larger sample to calculate any average. We therefore examine the relationship between the *RAIN* change and the number of realisation members (Fig. 12). Focusing on the SLP and ELP, the range of *RAIN* change decreases as the number of realisations increase. For example, the *RAIN* change over the ELP varies from -0.97

to 1.07 mm·day^{-1} when only three members are included. The range of *RAIN* is narrowed to between -0.25 and 0.24 mm·day^{-1} when fifteen members are simulated. It is similar for LCENS$_{2015}$-LCENS$_{2001}$; the range in the change in *RAIN* decreases as the number of simulation members increases. The change in *RAIN* suggests an increase of 0.48 and 0.40 mm·day^{-1} for the SLP and ELP respectively when the simulation members are increased to eleven.

■ 4 Discussion

Following the launch of the GFGP by China in the late 1990s, the Loess Plateau has shown a significant greening trend, but with simultaneous concerns about water security for agriculture and other human activities. We investigated the impact of ~~land cover change~~revegetation since the launch of the GFGP on the hydrology of the Loess Plateau using WRF. Simulations show that the revegetation of the plateau is associated with a decrease in runoff and soil moisture as a consequence of higher evapotranspiration and little feedback from rainfall.

Our results on changes of evapotranspiration, soil moisture and runoff are broadly consistent with both field (Jia et al., 2017; Jian et al., 2015; Jin et al., 2011) and satellite (Feng et al., 2017; Li et al., 2016; Xiao, 2014) observations. For example, the spatial pattern of our simulated soil moisture decline in the growing season is similar to observations from the Advanced Microwave Scanning Radiometer on the Earth Observing System by the Japanese Aerospace Exploration Agency (Feng et al., 2017). Although the increased evapotranspiration due to revegetation of the Loess Plateau has been ~~extensively simulated~~examined before (e.g., Cao et al., 2017, 2019; Li et al., 2018; Lv et al., 2019), the reduction in runoff and soil moisture in response to revegetation of the Loess Plateau, which is consistent with observations, has been rarely reported in modeling results previously. Moreover, our simulated ~~little~~weak response of rainfall to revegetation of the Loess Plateau, which ~~is rarely obtained from~~is hard to determine from observations, is useful in assessing the hydrometeorology of this region.~~also fill in the gap of our knowledge .~~ ~~Observations of soil moisture declines associated with revegetation are not always permanent and may be alleviated once trees exceed 25 years (Jia et al., 2017; Jin et al., 2011). Our simulations only capture the initial decline in runoff and soil moisture linked with the higher evapotranspiration and we note that the impact of revegetation on the long-time trend (25 - 50 years) would be valuable.~~

We also investigated the potential future impact on the hydrology of the Loess Plateau if revegetation was continued~~.~~, which has ~~never~~not been assessed before but is important for both scientific communities and policymakers. WRF suggests that further revegetation would exacerbate soil moisture and runoff declines with particularly large effects on the underground runoff and soil moisture in deeper layers. Our simulations suggested that the potential revegetation that could still be achieved would have larger consequences than those simulated since the launch of the GFGP. ~~However, we note some limitations in our experiment design. First we use current boundary conditions (1996-2015) to drive WRF, which means the background climate does not change in the future in response to climate change. Second, uncertainties exist in the current land surface model used to represent the response of vegetation to climate change in future. While using satellite observations to construct the land surface biogeophysical parameters helps overcome some land surface parameter limitations, this approach is obviously limited looking forward in terms of the status of future vegetation. Despite these limitations, our~~ Our results provide useful advances in our understanding of the impact of further revegetation on the Loess Plateau. For example, both Feng et al. (2016) and Zhang et al. (2018) estimated the current vegetation over the Loess Plateau is approaching or may have exceeded the threshold of ecological equilibrium. They omitted the potential response of rainfall to further revegetation over the Loess Plateau when predicting future thresholds (Feng et al., 2016; Zhang et al., 2018). Our result demonstrate that there is almost no feedback of rainfall associated with further revegetation, supporting the approach of Feng et al. (2016) and Zhang et al. (2018) in this specific region. That said, our approach does not attempt to incorporate changes in climate over the Loess Plateau and so the viability of large-scale reforestation in this region is not something we attempted to assess.

We focused on the response of rainfall to revegetation over the Loess Plateau, which is probably the most uncertain of the hydrological components. WRF shows little response of rainfall to ~~the land cover change~~revegetation since the launch of the GFGP, which contradicts ~~another modeling~~ earlier results (Cao et al., 2017, 2019; Li et al., 2018; Lv et al., 2019). Moreover, the rainfall is weakly affected by further revegetation despite large increase in evapotranspiration. We also demonstrate that the rainfall change is strongly affected by internal variability and a large number of realisations are required before any impact of ~~land cover change~~revegetation on rainfall might be robustly identified. We suggest that some previous studies (Cao et al., 2017, 2019; Lv et al., 2019) based on model simulations may have exaggerated the impact of ~~land cover change~~revegetation on rainfall over the Loess Plateau due to the lack of sufficient realisations. For example, Cao et al. (2017, 2019) and Lv et al. (2019) used the same WRF to perform only three ~~and~~ or five member simulations, and concluded a significant ~~increase~~ change in rainfall caused by ~~land cover change~~revegetation over the Loess Plateau. More interestingly, Cao et al. (2017) and Cao et al. (2019) obtained different conclusions on the rainfall change over the Loess Plateau with same WRF model. They used a broadly ~~,~~similar experimental design but ~~same physical parameters schemes and same changes in land cover type and biophysical parameters despite some differences in~~ different spatial resolution (30 km and 10 km respectively) and ~~simulation strategy (~~simulations from 2001-2002 with three ensembles and consecutive simulation from 2000-2004 respectively~~)~~. We could also demonstrate large changes in rainfall over the plateau if we chose 3-5 members but we could demonstrate either large increases or large decreases in 3-5 member averages. Returning to Fig. 6, ET shows a highly consistent increase ~~trend~~ in response to revegetation among the 20 years, suggesting that ET change is robustly linked with revegetation. Although changes in runoff and soil moisture also show large variability among the 20 years, the distribution of the runoff and soil moisture changes are negative biased. More importantly, the distribution of the runoff and soil moisture changes systematically shift towards negative values. This suggest runoff and soil moisture changes are very likely linked with revegetation. T~~Actually, the~~he ~~–~~large variability in runoff or soil moisture changes is induced by the large variability of rainfall. Given the tight linkage between rainfall and runoff or soil moisture, the changes in runoff or soil moisture tends to be mistakenly represented if the rainfall change is not robustly examined~~.~~, and this ~~–Clearly, a robust result~~ requires internal model variability to be thoroughly addressed.

Our studies are also subject to some caveats. First, observations of soil moisture declines associated with revegetation ~~are not always permanent and may~~can be alleviated once trees ~~exceed 25 years~~mature (Jia et al., 2017; Jin et al., 2011). ~~Therefore~~O~~o~~ur simulations only capture ~~the~~an initial decline in runoff and soil moisture linked with the higher evapotranspiration and we note that the impact of revegetation on the long-time trend (25 - 50 years) would be valuable. Second, we used current boundary conditions (1996-2015) for WRF to predict the impact of further revegetation on the hydrology, which means the boundary conditions do not change in the future in response to climate change. This suggests that we might underestimate the impact of further revegetation in the future if future climate of the Loess Plateau suffers from large changes in response to global warming. Third, uncertainties exist in the current land surface model used to represent the response of vegetation to climate change in future. While using satellite observations to construct the land surface biogeophysical parameters helps overcome some land surface parameter limitations, this approach is obviously limited looking forward in terms of the status of future vegetation. Furthermore, ~~We~~ we note that our results are likely model depende~~a~~nt as we only used one model. Although we performed relatively high resolution (10 km for the nested domain), the cumulus convection scheme remains necessary which is a further potential source of uncertainty. These factors account for the discrepancy between our result and another model based study (Li et al., 2018). ~~which~~ Li et al (2018) found a positive rainfall feedbacks to greening and consequently ~~little~~small changes– in ~~side effects on~~ ~~r~~runoff and soil moisture over north China using a Global Climate Model. In contrast, we demonstrate the rainfall change is too small to compensate for the strongly enhanced evapotranspiration, causing a reduction of runoff and soil moisture in response to revegetation over the Loess Plateau. A large ensemble of models, each with a reasonable number of realisations, is needed to build a model independent assessment of the impact of revegetation but this is clearly beyond the scope of this study. Last, we investigated the impact of revegetation or greening, rather than GFGP, on the hydrology of the Loess Plateau. ~~It is still a great challenging to quantify the contribution of GFGP to observed changes in both land cover type and biophysical parameters as far as now.~~ Directly linking our results to the impact of GFGP on the hydrology of the Loess Plateau ~~Thus it~~ should be avoided ~~to regard our results equivalent to the impact of GFGP on the hydrology of the Loess Plateau~~.

Overall, our results highlight how ~~the GFGP led to a greening~~ revegetation of the Loess Plateau ~~, how this~~led to increased evapotranspiration and how as a consequence the runoff and soil moisture declined. This is consistent with the understanding of land-surface processes and how they respond to land cover change (Bonan, 2008). Critical in this impact of revegetation on the hydrology is what happens to rainfall. If the higher evapotranspiration increases rainfall, then revegetation has the potential to increase soil moisture and runoff. It is very likely this would be the consequences in some regions such as Amazonia (Lawrence and Vandecar, 2015; Perugini et al., 2017; Spracklen et al., 2018) and Sahel (Kemena et al., 2018; Xue and Shukla, 1996; Yosef et al., 2018). However, over the Loess Plateau we find no such result and thus the higher evapotranspiration simply leads to lower soil moisture and runoff. Additionally, Tobella et al. (2014) reported a positive impact of trees on soil hydraulic properties influencing groundwater recharging when termite mound is taken into account in Africa. While the termite mound is rare over the Loess Plateau suggesting this positive impact of trees is unlikely to occur. An implication of this result is that further revegetation, which requires water to be sustained, may not be viable. We also recognize that afforestation can help to sequester carbon, mitigate warming and alleviate soil erosion.

Therefore whether and how to implement further revegetation should be cautiously determined with the pros and cons of afforestation being carefully weighted for the Loess Plateau.

■ 5 Conclusions

We evaluated how the growing season hydrology of the Loess Plateau is impacted by revegetation since the launch of the “Grain for Green Program”, and by further revegetation in the future using the WRF model. We used satellite observations to describe key biophysical parameters including decreased albedo and increased leaf area index and fraction of photosynthetically active radiation. The observed greening trend increased evapotranspiration but because the impact on rainfall was negligible the underground runoff and soil moisture both decreased. Further future revegetation enhanced evapotranspiration, but still had little impact on rainfall. Overall therefore, revegetation over the Loess Plateau leads to higher evapotranspiration, and as a consequence lower water availability for agriculture or other human demands. Considering the negative impact of revegetation on runoff and soil moisture, and the lack of benefits on rainfall, we caution that further revegetation may threaten local water security over the Loess Plateau.

Code and data availability. The MODIS land cover type product (MCD12Q1) and LAI/FPAR products (MCD15A2H and MOD15A2H) are available on NASA’s Land Processes Distributed Active Archive Center (LP DAAC), https://lpdaac.usgs.gov/data/. The GLASS albedo product is available on Global land surface satellite (GLASS) products download and service, http://glass-product.bnu.edu.cn/. The ERA-Interim reanalysis data is available on the ECMWF Data Server, https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim. The gridded observation dataset is available on the National Meteorological Information Centre of the China Meteorological Administration, http://data.cma.cn/data/cdcindex.html. The code of Weather Research and Forecasting model is available on http://www2.mmm.ucar.edu/wrf/users/.

Author contributions. CF, JG and WG led the overall scientific questions and designed the research. JG, AJP and BZ analysed the data and wrote the manuscript. All authors contributed to the discussion of the results and to revising the manuscript.

Competing interest. The authors declare that they have no conflict of interest.

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Tables

Table 1. Descriptions of datasets used in this study

Variable	Dataset	Time span available	Temporal resolution	Spatial resolution
Land cover	MCD12Q1	2001-2017	Yearly	500 m
LAI/FPAR	MCD15A2H	4th July, 2002 to present	8-day	500 m
LAI/FPAR	MOD15A2H	8th Feburary, 2000 to present	8-day	500 m
Albedo	GLASS	1981 to present	8-day	0.05°
Initial and boundary conditions for WRF	ERA-Interim	1979 to present	6 hour	0.75°
Surface air temperature	National Meteorological Information Centre	1961 to present	Monthly	0.5°
Rainfall	National Meteorological Information Centre	1961 to present	Monthly	0.5°
Slope	SRTM	—	—	3 second (about 90 m)

Table 2. The International Geosphere-Biosphere Programme (IGBP) classification and class descriptions

Name	Value	Description
Evergreen Needleleaf Forests	1	Dominated by evergreen conifer trees (canopy >2m). Tree cover >60%.
Evergreen Broadleaf Forests	2	Dominated by evergreen broadleaf and palmate trees (canopy >2m). Tree cover >60%.
Deciduous Needleleaf Forests	3	Dominated by deciduous needleleaf (larch) trees (canopy >2m). Tree cover >60%.
Deciduous Broadleaf Forests	4	Dominated by deciduous broadleaf trees (canopy >2m). Tree cover >60%.
Mixed Forests	5	Dominated by neither deciduous nor evergreen (40-60% of each) tree type (canopy >2m). Tree cover >60%.
Closed Shrublands	6	Dominated by woody perennials (1-2m height) >60% cover.
Open Shrublands	7	Dominated by woody perennials (1-2m height) 10-60% cover.
Woody Savannas	8	Tree cover 30-60% (canopy >2m).
Savannas	9	Tree cover 10-30% (canopy >2m).
Grasslands	10	Dominated by herbaceous annuals (<2m).
Permanent Wetlands	11	Permanently inundated lands with 30-60% water cover and >10% vegetated cover.
Croplands	12	At least 60% of area is cultivated cropland.
Urban and Built-up Lands	13	At least 30% impervious surface area including building materials, asphalt, and vehicles.
Cropland/Natural Vegetation Mosaics	14	Mosaics of small-scale cultivation 40-60% with natural tree, shrub, or herbaceous vegetation.
Permanent Snow and Ice	15	At least 60% of area is covered by snow and ice for at least 10 months of the year.
Barren	16	At least 60% of area is non-vegetated barren (sand, rock, soil) areas with less than 10% vegetation.
Water Bodies	17	At least 60% of area is covered by permanent water bodies.

Table 3. Description of the experiment design

Experiment	Land cover	*VEGFRC*	*LAI*	α	Simulation period
LC$_{2001}$	2001	2001	2001	2001	1st May to 30th Sep. for years from 1996 to 2015
LC$_{2015}$	2015	2015	2015	2015	1st May to 30th Sep. for years from 1996 to 2015
LC$_{futr}$	Artifically constructed land cover and land surface biogeophysical parameters (see text)				1st May to 30th Sep. for years form 1996 to 2015
LCENS$_{2001}$	2001	2001	2001	2001	From varying initial time (from 21st April to 1st May) to 30th Sep. for the year 2001
LCENS$_{2015}$	2015	2015	2015	2015	From varying initial time (from 21st April to 1st May) to 30th Sep. for the year 2001

Figures

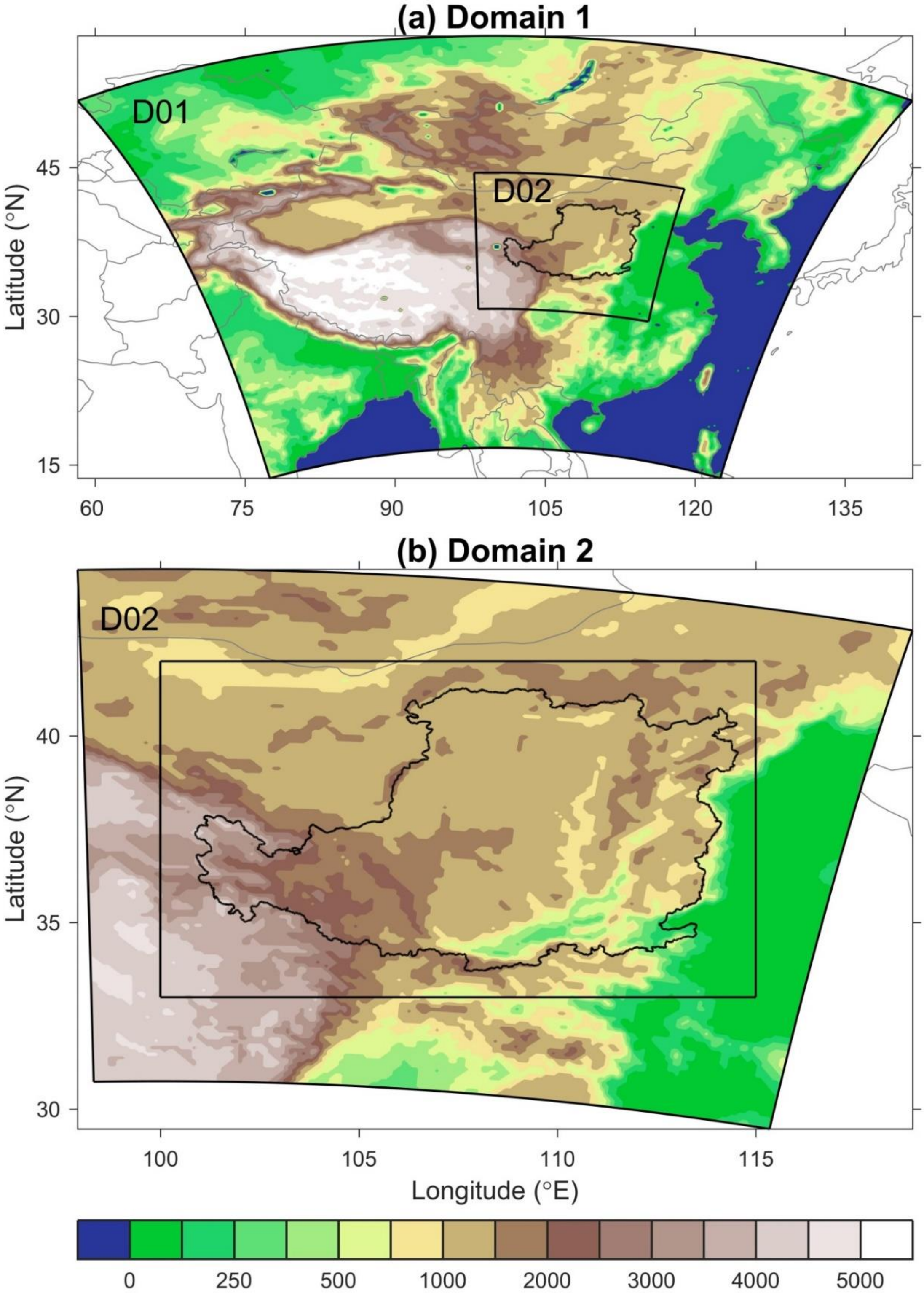


Figure 1. (a) The larger domain labelled D01 and (b) the inner nested domain labelled D02 configured for the WRF model. The topography (meters above sea level) is shown as colour shading. The Loess Plateau is enclosed by the black border. The black rectangle covers the region to be analysed in this study.

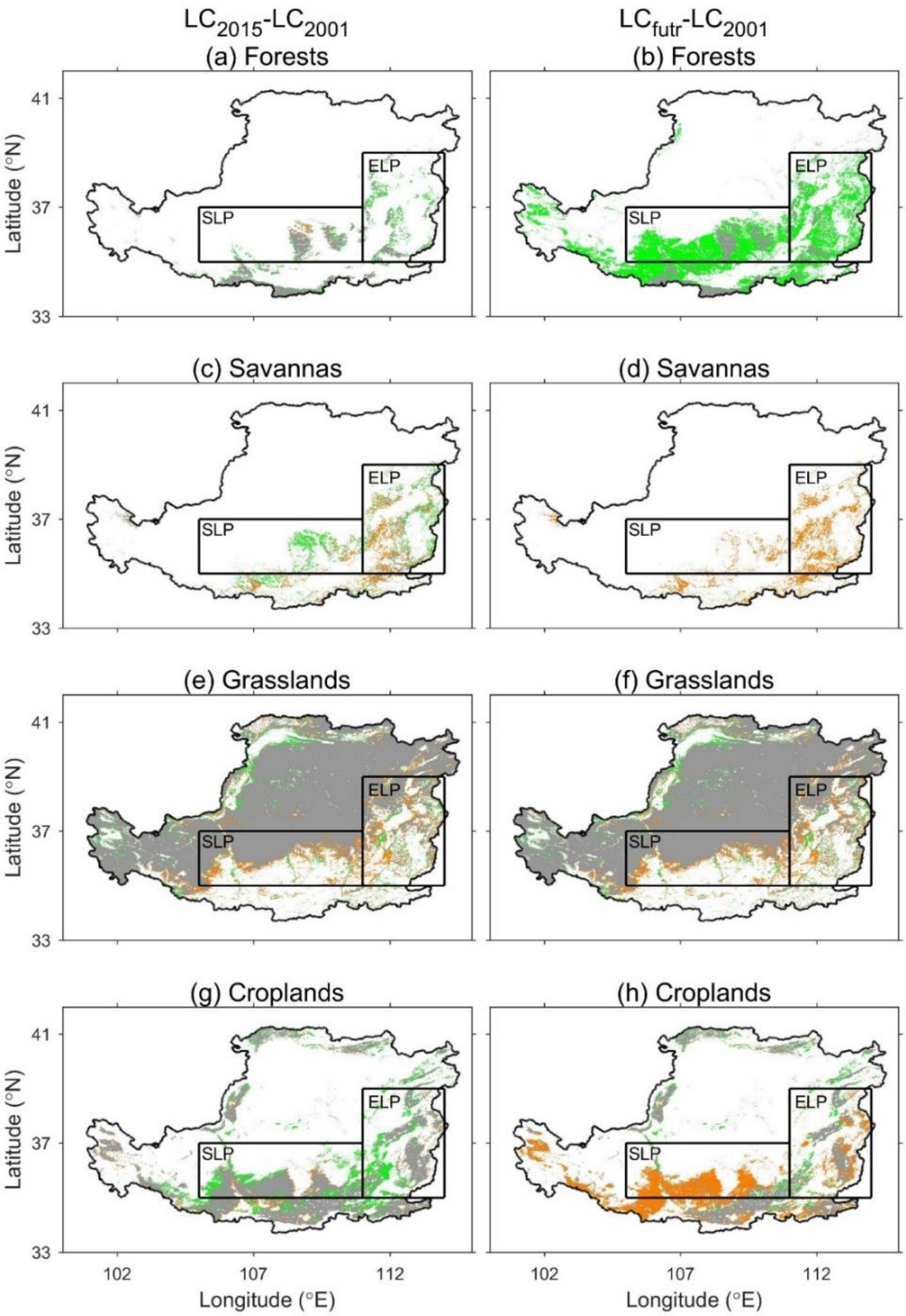
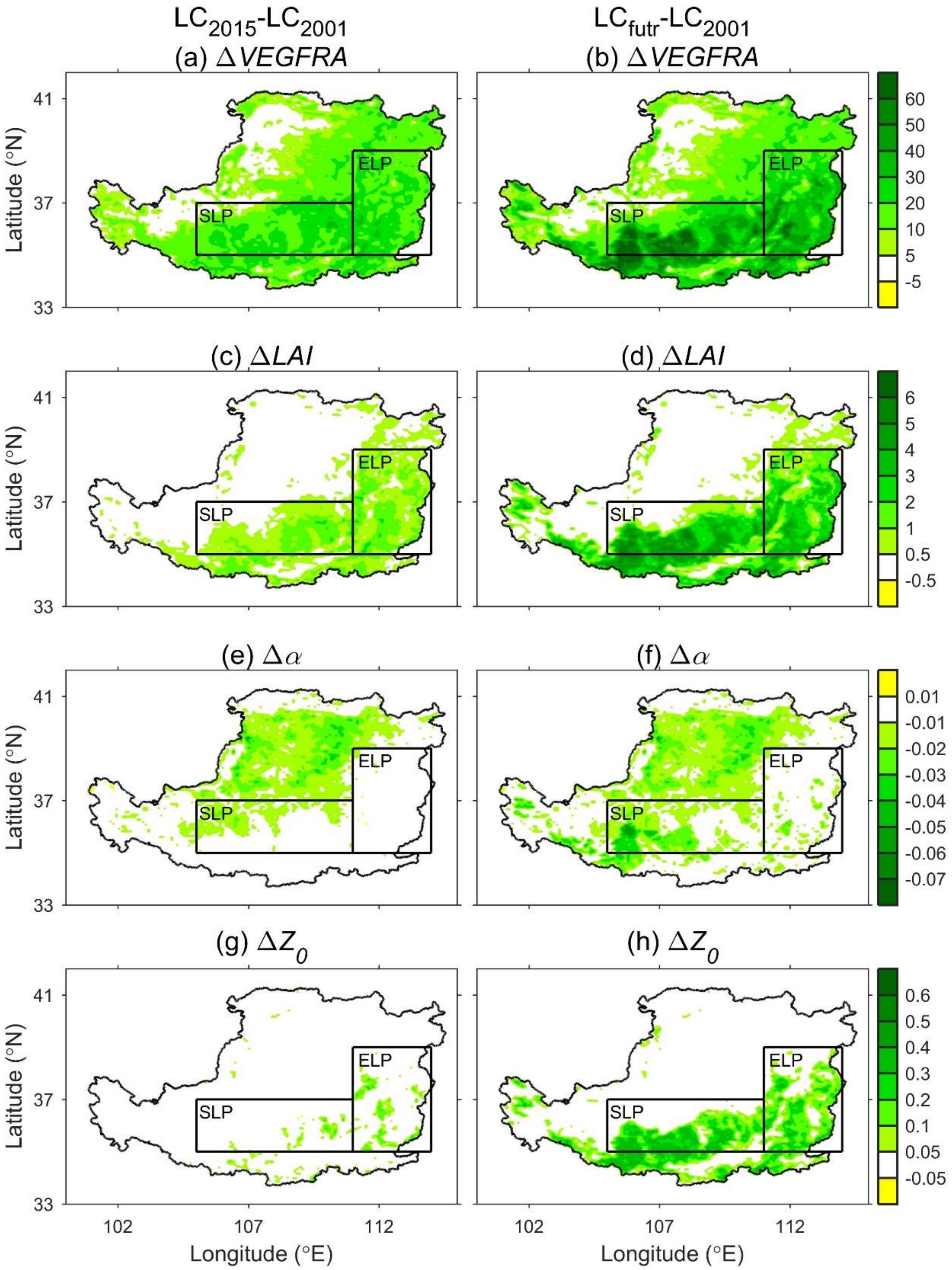


Figure 2. ~~(a, c, e and g)~~ Land cover type changes (a, c, e and g) between the LC$_{2001}$ and LC$_{2015}$ (LC$_{2015}$-LC$_{2001}$), and (b, d, f and h) between the LC$_{2001}$ and LC$_{futr}$ (LC$_{futr}$-LC$_{2001}$). The green, brown and grey colours denote the gained, lost and unchanged land cover type respectively in the LC$_{2015}$ (a, c, e and g) and LC$_{futr}$ (b, d, f and h) compared with the LC$_{2001}$. Forests include evergreen needleleaf, evergreen broadleaf, deciduous needleleaf, deciduous broadleaf and mixed forests (see Table 2). Savannas include woody savannas and savannas. Croplands include croplands and cropland/natural vegetation mosaics. The south (105-111°E, 35-37°N) and east (111-114°E, 35-39°N) Loess Plateau are enclosed by black rectangles and labelled SLP and ELP respectively.


LC2015-LC2001
LCfutr-LC2001
(a) ΔVEGFRA
(b) ΔVEGFRA
(c) ΔLAI
(d) ΔLAI
(e) Δα
(f) Δα
(g) ΔZ0
(h) ΔZ0
ELP
SLP
Latitude (°N)
Longitude (°E)
33
37
41
102
107
112
60
50
40
30
20
10
5
-5
6
5
4
3
2
1
0.5
-0.5
0.01
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
0.6
0.5
0.4
0.3
0.2
0.1
0.05
-0.05

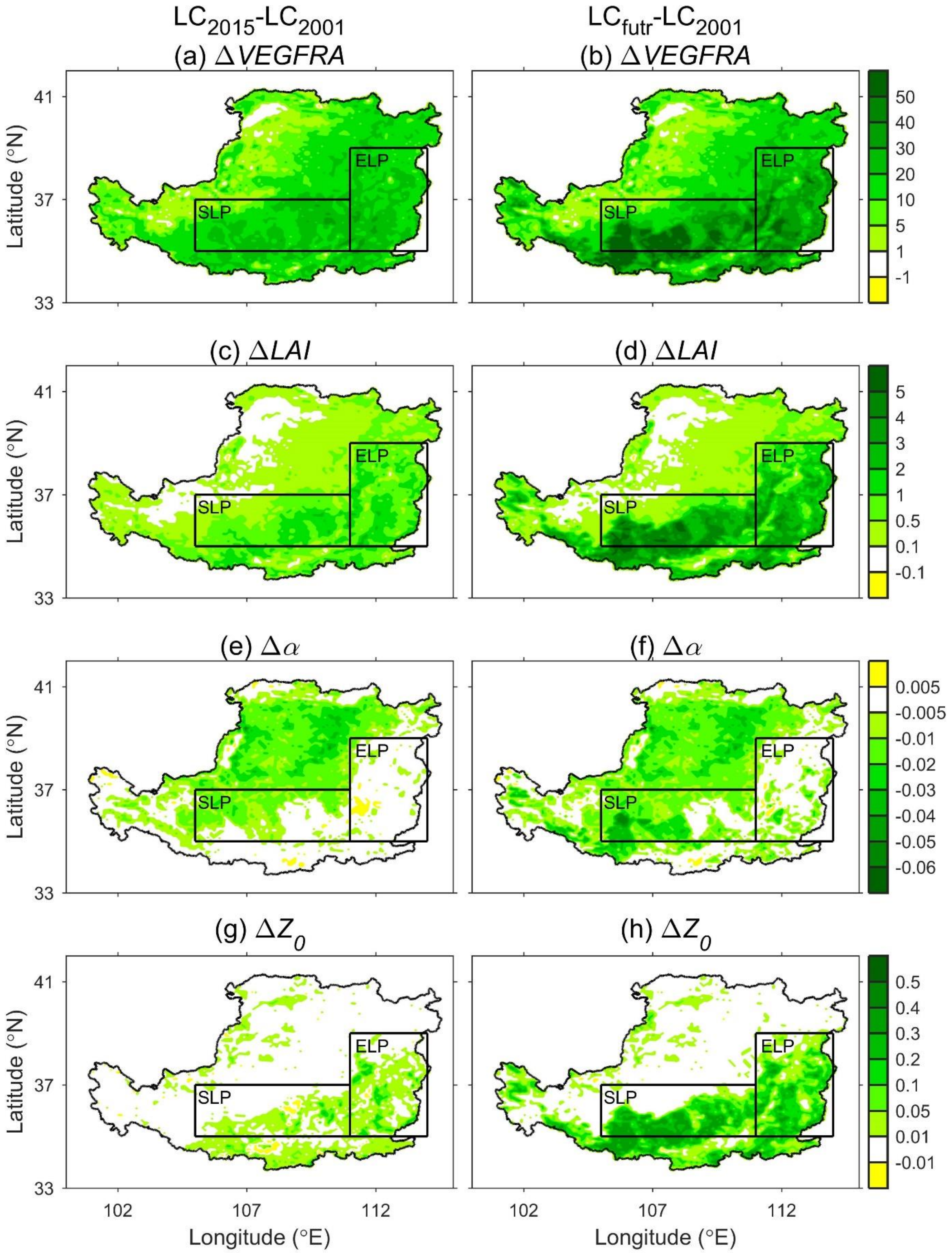


Figure 3. Changes in June-July-August-September mean (a and b) green vegetation fraction (%), (c and d) leaf area index (m^3·m^{-3}), (e and f) albedo and (g and h) roughness length (m) between the LC$_{2001}$ and LC$_{2015}$ (LC$_{2015}$-

LC_{2001}; a, c, e and g), and between the LC_{2001} and LC_{futr} (LC_{futr}-LC_{2001}; b, d, f and h). The south (SLP) and east (ELP) Loess Plateau regions are defined in Figure 2.

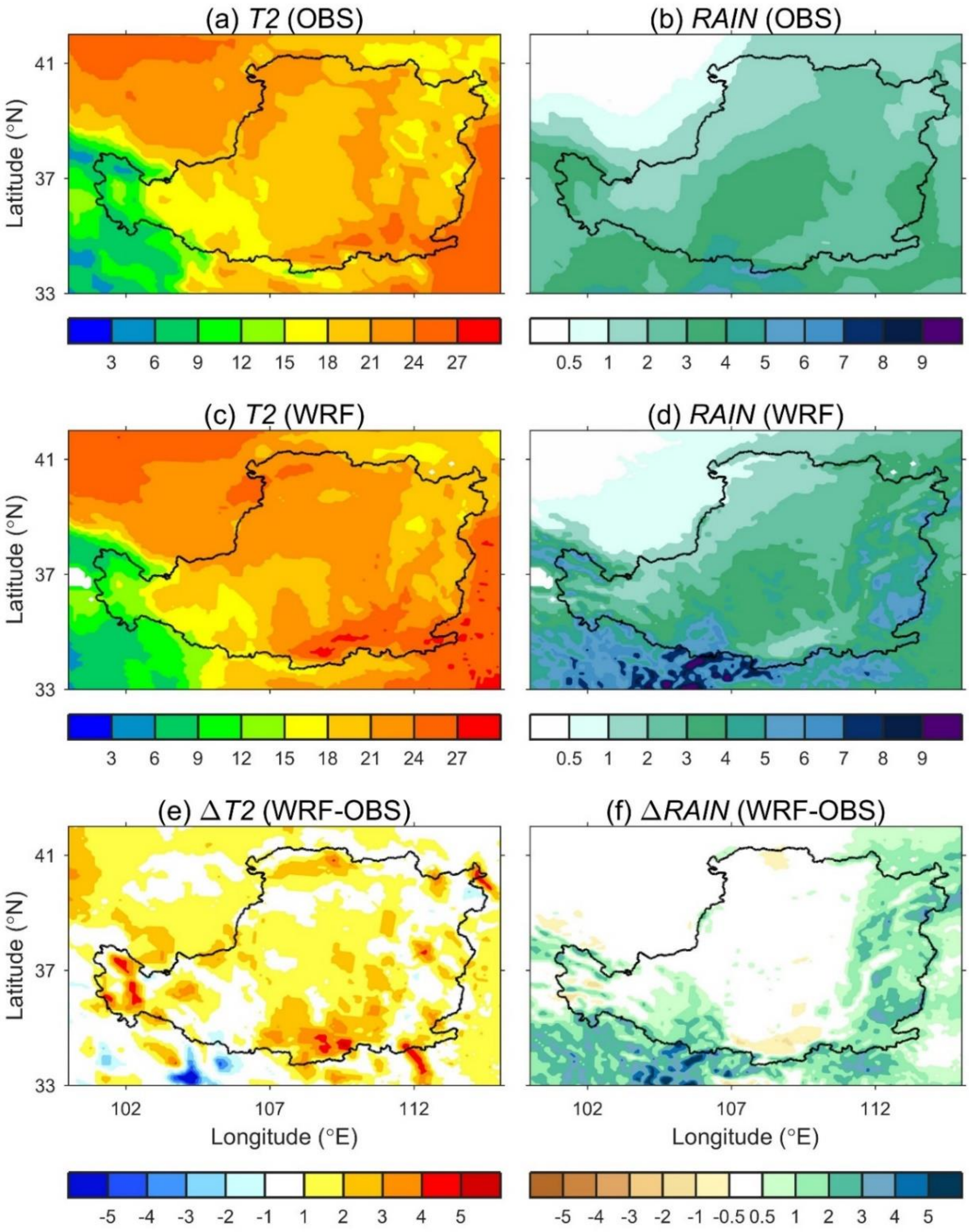


Figure 4. ~~The WRF simulated~~ June-July-August-September (JJAS) mean (a) observed surface air temperature (°C), (b) observed rainfall (mm·day^{-1}), (c) simulated surface air temperature (°C), (d) simulated rainfall (mm·day^{-1}), (e) the differences between observed and simulated surface air temperature (°C; simulation minus observation) and (f) the differences between observed and simulated rainfall (mm·day^{-1}; simulation minus observation) over the Loess Plateau in 2001. The observed surface air temperature and rainfall are ~~and (c) precipitation (mm·day^{-1}), and the observed JJAS mean (b) surface air temperature (°C) and (d) precipitation (mm·day^{-1})~~ from the gridded

observation dataset developed by the National Meteorological Information Centre of the China Meteorological Administration.~~,~~ The simulated surface air temperature and rainfall are obtained by averaging the 11 members (with different initial conditions) of LCENS$_{2001}$. ~~and the differences in JJAS mean (e) surface air temperature (°C) and (f) precipitation (mm·day^{-1}) between WRF simulations (WRF) and observations (OBS, WRF-OBS) over the Loess Plateau in 2001.~~

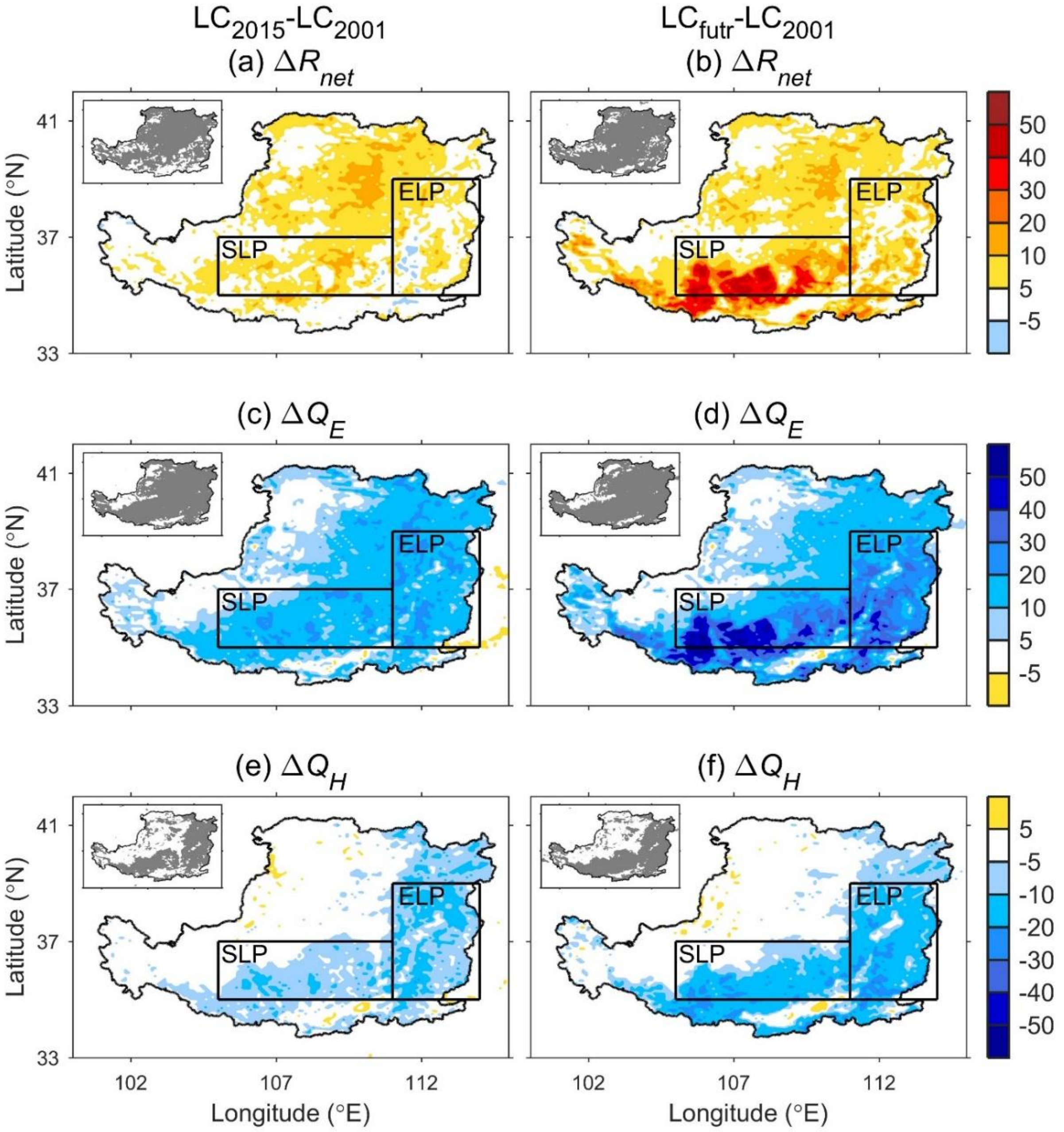


Figure 5. Changes in June-July-August-September mean (a and b) land surface net radiation (W·m^{-2}), (c and d) latent heat flux (W·m^{-2}) and (e and f) sensible heat flux (W·m^{-2}) between the LC$_{2001}$ and LC$_{2015}$ (LC$_{2015}$-LC$_{2001}$; a, c, and e), and between the LC$_{2001}$ and LC$_{futr}$ (LC$_{futr}$-LC$_{2001}$; b, d, and f) over the Loess Plateau from 1996 to 2015. The south (SLP) and east (ELP) Loess Plateau regions are defined in Figure 2. The map of statistical significance test is shown in the embedded figure on the upper left corner of each panel. The grey denotes the local change is statistically significant at 95% confidence level using a two-tailed Student's *t*-test.

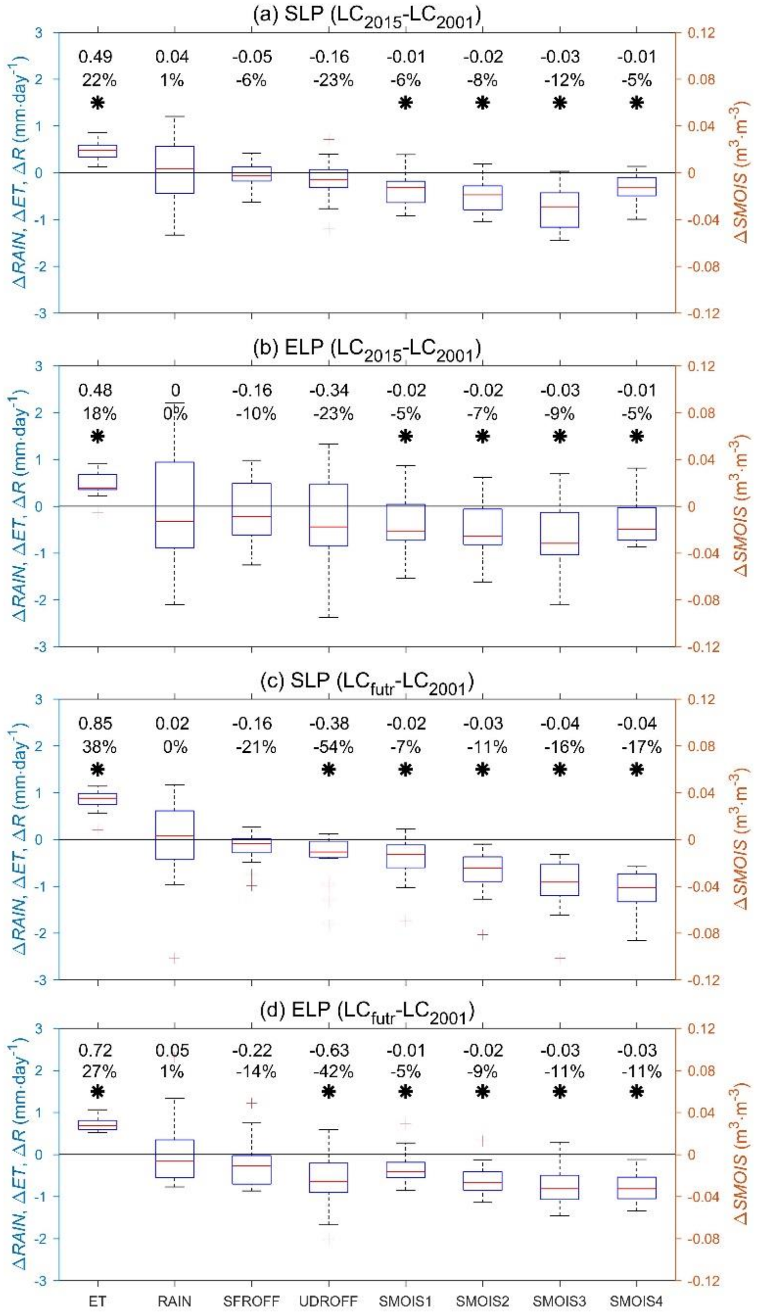


Figure 6. Box plot of changes in June-July-August-September mean evapotranspiration (*ET*, mm·day^{-1}), rainfall (RAIN, mm·day^{-1}), surface runoff (SFROFF, mm·day^{-1}), underground runoff (UDROFF, mm·day^{-1}) and soil moisture (m^3·m^{-3}) of 1st layer (*SMOIS1*, 0-10 cm), 2nd layer (*SMOIS2*, 10-40 cm), 3rd layer (*SMOIS3*, 40-100 cm) and 4th layer (*SMOIS4*, 100-200 cm) averaged over (a and c) south Loess Plateau and (b and d) east Loess Plateau between LC$_{2001}$ and LC$_{2015}$ (LC$_{2015}$-LC$_{2001}$; a and b), and between LC$_{2001}$ and LC$_{futr}$ (LC$_{futr}$-LC$_{2001}$; c and d) from 1996 to 2015. The south (SLP) and east (ELP) Loess Plateau regions are defined in Figure 2. The 1st and 2nd line members denote absolute and relative changes averaged by twenty members. The black asterisk denotes the change is statistically significant at 95% confidence level using a two-tailed Student's *t*-test.

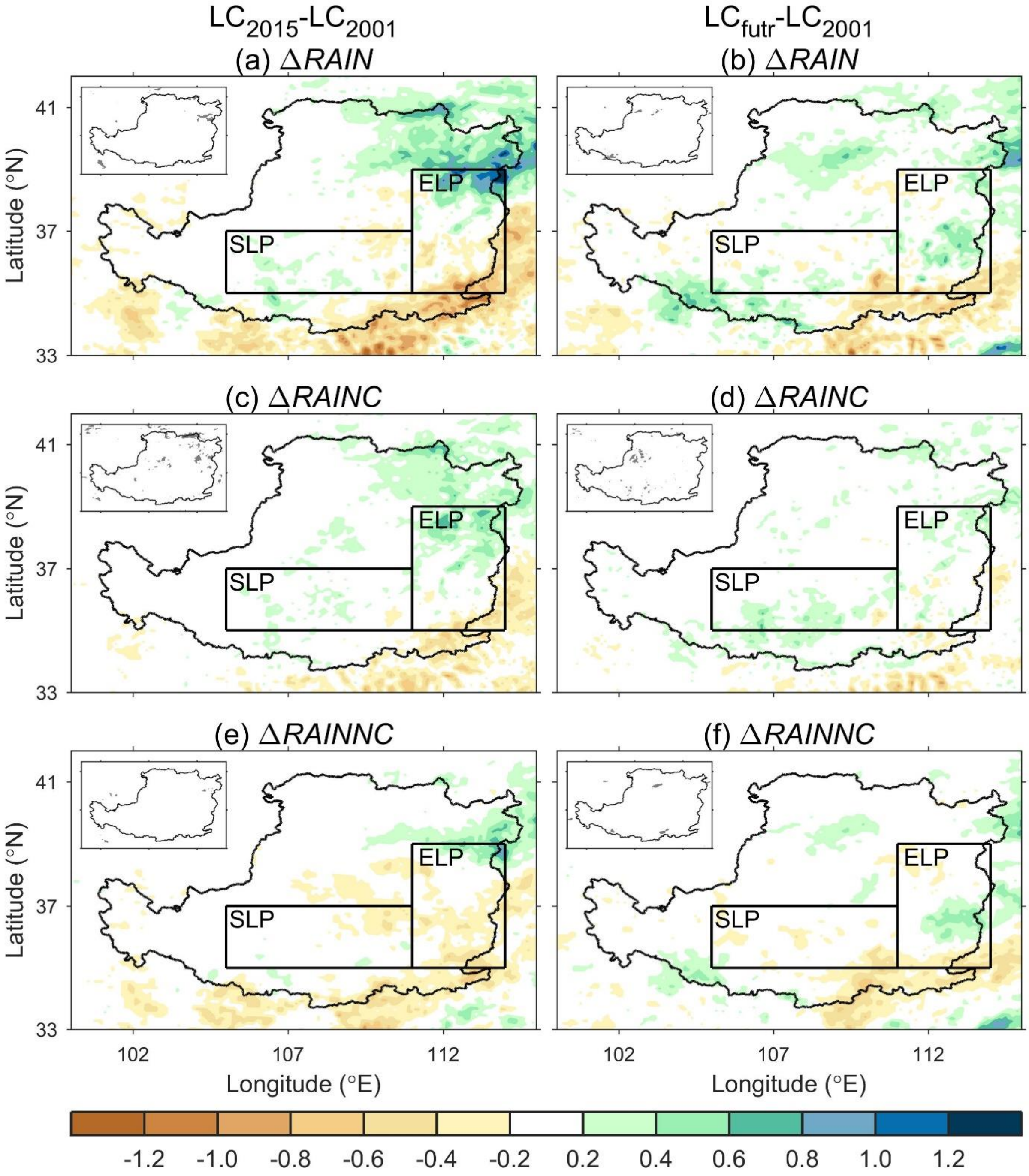
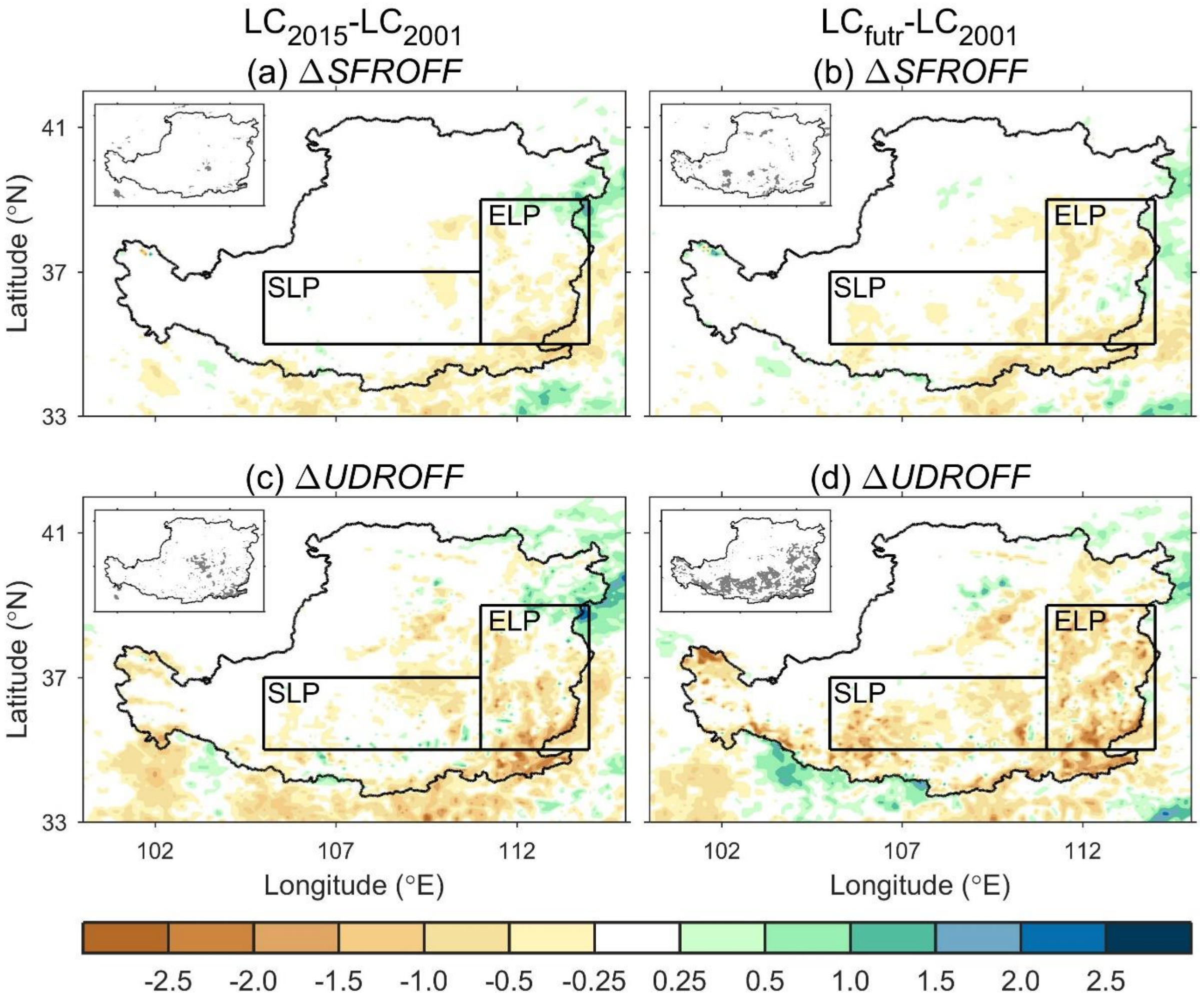


Figure 7. Same as Figure 5, but for (a and b) total rainfall (mm·day^{-1}), (c and d) convective rainfall (mm·day^{-1}) and (e and f) non-convective rainfall (mm·day^{-1}). The south (SLP) and east Loess Plateau (ELP) regions are defined in Figure 2.


LC_{2015}-LC_{2001}
(a) ΔSFROFF
LC_{futr}-LC_{2001}
(b) ΔSFROFF
(c) ΔUDROFF
(d) ΔUDROFF
ELP
SLP
Latitude (°N)
41
37
33
Longitude (°E)
102
107
112
-2.5
-2.0
-1.5
-1.0
-0.5
-0.25
0.25
0.5
1.0
1.5
2.0
2.5

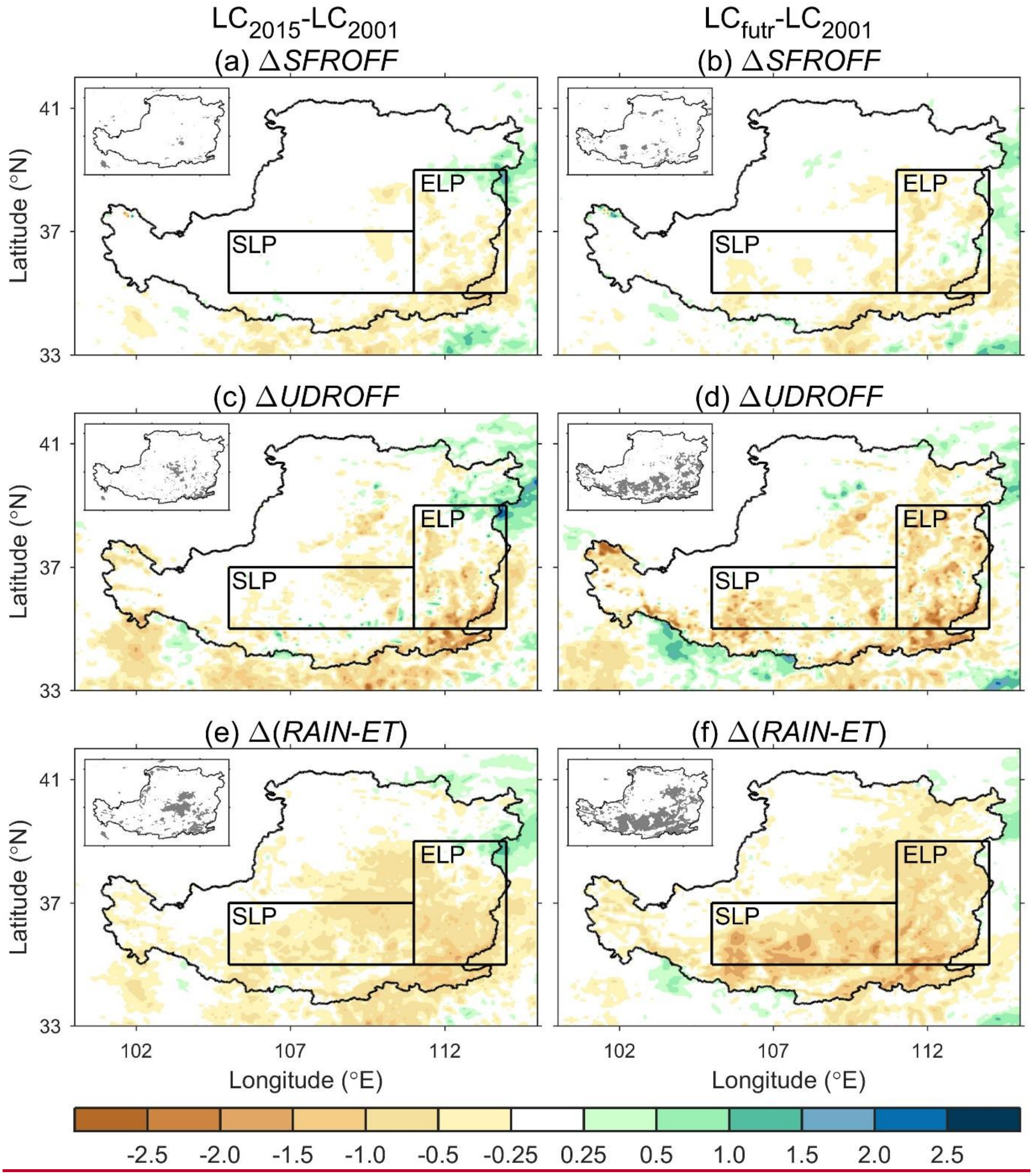


Figure 8. Same as Figure 5, but for (a and b) surface runoff (mm·day^{-1}), ~~and~~ (c and d) underground runoff (mm·day^{-1}) and (e and f) rainfall minus evapotranspiration (mm·day^{-1}). The south (SLP) and east Loess Plateau (ELP) regions are defined in Figure 2.

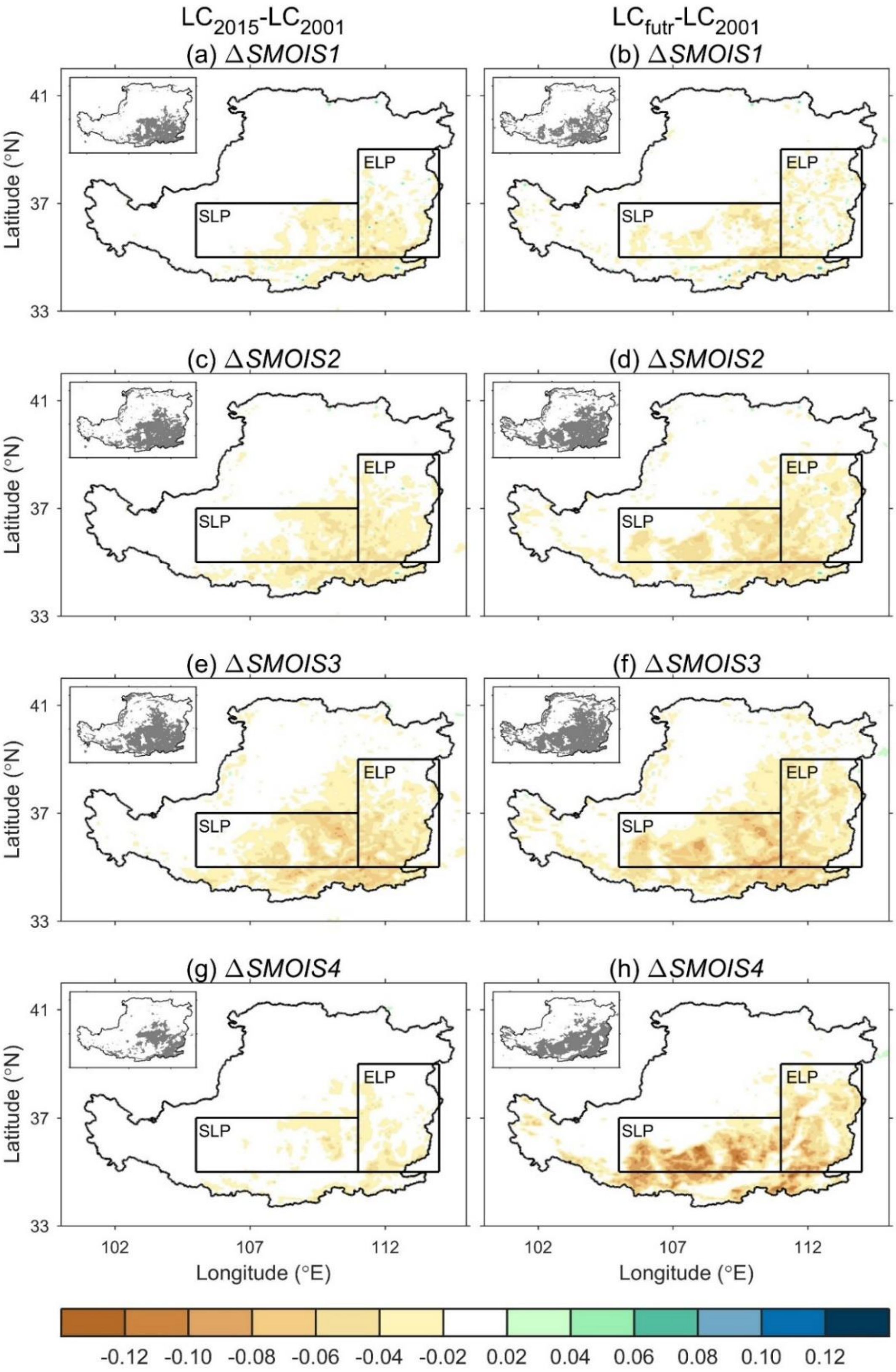


Figure 9. Same as Figure 5, but for the soil moisture change ($m^3 \cdot m^{-3}$) of (a and b) first layer (0-10 cm), (c and d) second layer (10-40 cm), (e and f) third layer (40-100 cm) and (g and h) forth layer (100-200 cm). The south (SLP) and east (ELP) Loess Plateau regions are defined in Figure 2.

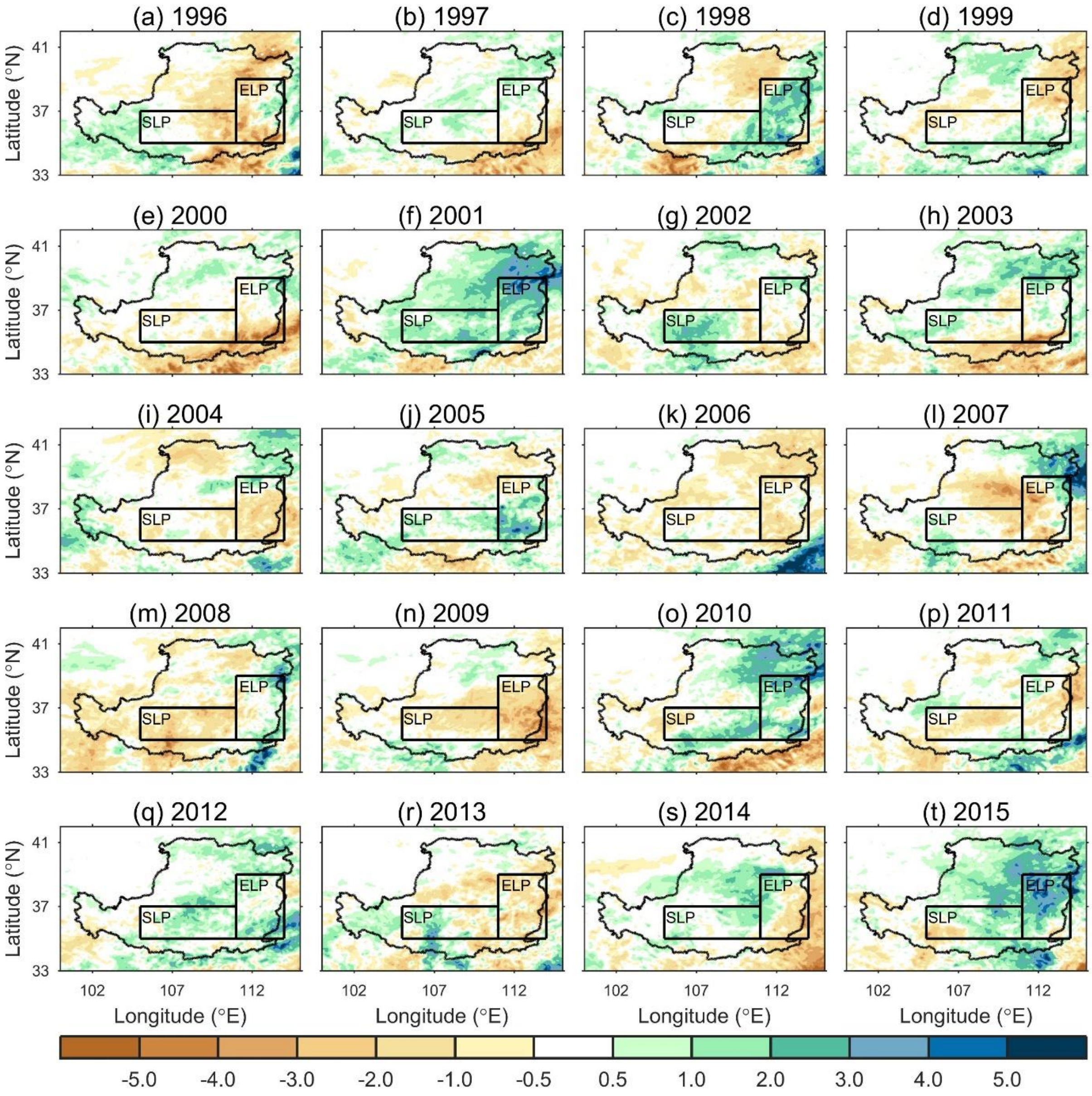


Figure 10. Changes in June-July-August-September mean rainfall (mm·day^{-1}) of each realisation members (years) between the LC$_{2001}$ and LC$_{2015}$ (LC$_{2015}$-LC$_{2001}$) over the Loess Plateau from 1996 to 2015. The south (SLP) and east Loess Plateau (ELP) regions are defined in Figure 2.

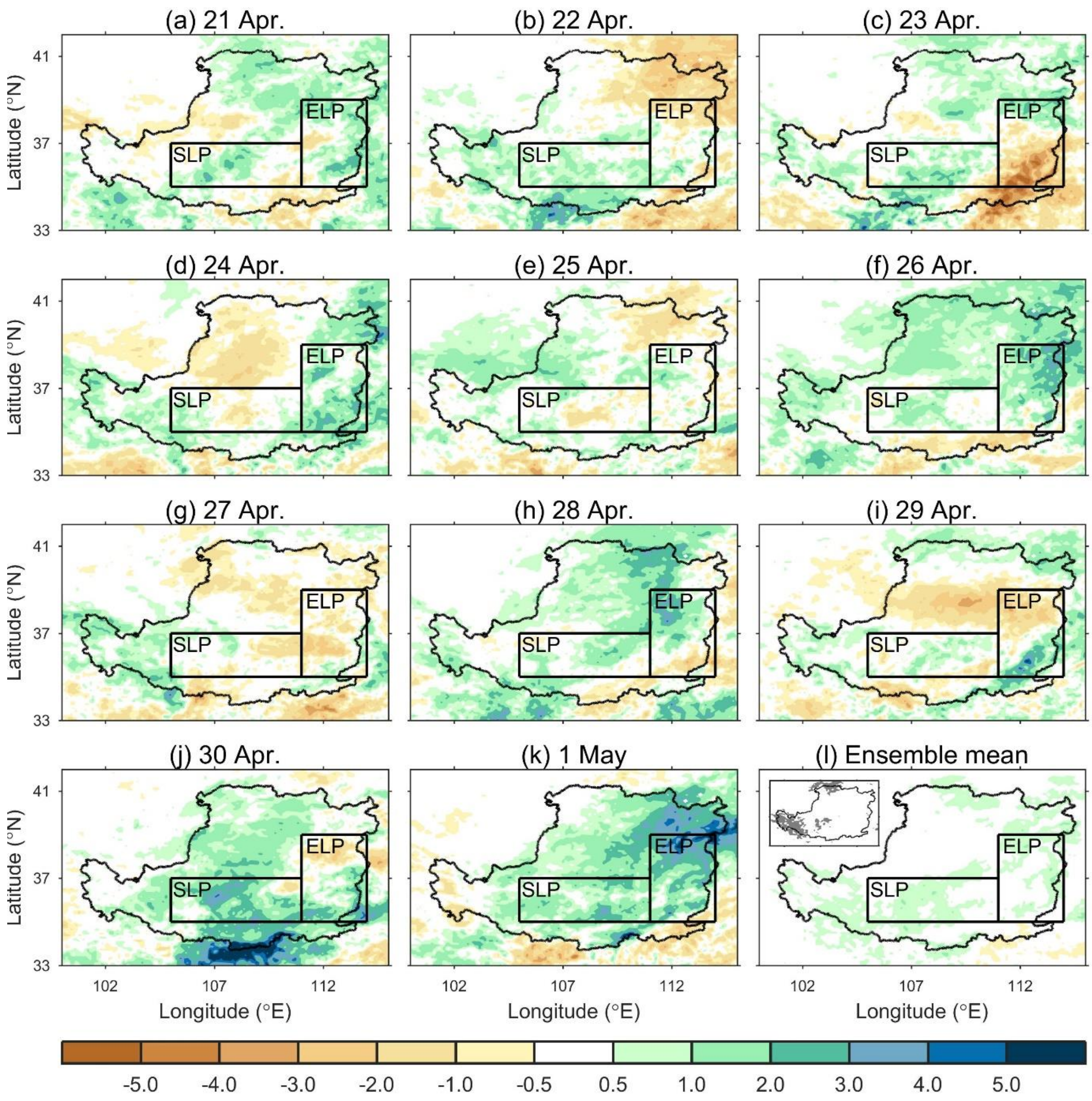


Figure 11. Changes in June-July-August-September mean rainfall (mm·day^{-1}) of each realisation member (a-k) and ensemble mean (l) between the LCENS$_{2001}$ and LCENS$_{2015}$ (LC$_{2015}$-LC$_{2001}$) over the Loess Plateau in 2001. The south (SLP) and east Loess Plateau (ELP) regions are defined in Figure 2. The map of statistical significance test is shown in the imbed figure on the upper left corner of panel l. The grey denotes the local change is statistically significant at 95% confidence level using a two-tailed Student's *t*-test.

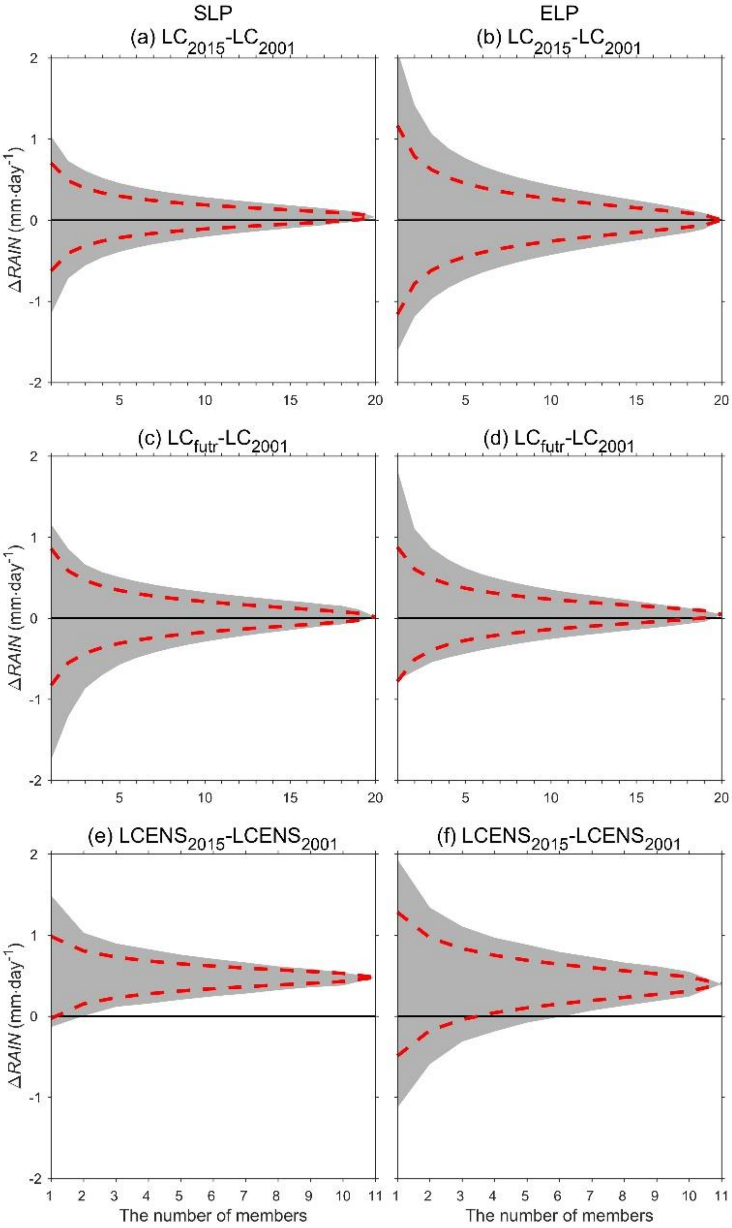


Figure 12. The relationship between the changes in June-July-August-September mean rainfall (mm·day^{-1}) and the number of members. The number of members ranges from 1 to 20 for (a and b) LC_{2015}-LC_{2001} and (c and d) LC_{futr}-LC_{2001}, and from 1 to 11 for (e and f) $LCENS_{2015}$-$LCENS_{2001}$. The mean rainfall change is averaged over (a, c and e) south Loess Plateau and (b, d and f) east Loess Plateau respectively. The south (SLP) and east (ELP) Loess Plateau regions are defined in Figure 2. For a given number of realisations, the rainfall is averaged over these members. The grey area denotes the range of rainfall changes from all possible combinations of a given number of members. The red dashed line denotes the 5th and 95th percentile of the rainfall changes from all possible combination of a given number of members.