Responses of terrestrial water cycle components to afforestation within and around the Yellow River basin

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ABSTRACT
Reforestation has attracted worldwide attention because of its multiple environmental benefits, but its impact on water resources is complicated and still controversial. In this study, the authors conducted numerical experiments within and around the Yellow River basin under the Grain-for-Green project using the Weather Research and Forecasting model. The results showed that the terrestrial water cycle process was sensitive to land use/cover change in the study region. Under the increase of mixed forests within and below the basin, the basin-averaged precipitation and evaporation increased by 223.17 and 223.88 mm respectively, but the surface runoff decreased by 2.22 mm from 2006 to 2010. In other words, the forest-induced increase in evaporation exceeded that of precipitation along with decreased surface runoff. Importantly, the afforestation effects on water resources seemed to enhance with time, and the effects of the same vegetation change were different in dry and wet years with different precipitation amounts (i.e. different atmospheric circulation background). It should be noted that it is difficult to obtain one product that can explicitly reflect the spatial distribution of actual land cover change promoted by the Grain-for-Green project in the Yellow River basin, which is an important obstacle to clearly identify the reforestation impacts. A land cover dataset derived from advantages of multiple sets of data therefore needs to be proposed.

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1. Introduction
Land use/cover change has a large impact on water resources. However, there is still debate about the effect of vegetation (particularly forest) on water availability (Jiang and Liang 2013; Wang et al. 2017), e.g. demand-side and supply-side debates (Ellison, Futter, and Bishop 2012). Also, it has been reported that tree planting can have both negative and positive effects on water resources in drylands and the net effect is the result of a balance between them, in which tree density plays an important role (Tobella et al. 2014). Moreover, it has been argued that the impact of vegetation on annual streamflow depends on the sizes of river basins (Huang et al. 2009).

The Grain-for-Green project is a large afforestation program aimed at returning cultivated land across China to forest or perennial grassland (Yuan et al. 2014). The total conversion area had reached 29.9 million ha by 2014 (Li 2015). The project has been widely implemented on the Loess Plateau within the Yellow River basin to control soil and water loss (Chen et al. 2015). The water scarcity is severe in this basin, with ~50% of streamflow withdrawn by humans without flowing into the Bohai Sea, according to the Bulletin of Water Resources of the Yellow River (http://www.yellowriver.gov.cn/). That is why the South-to-North Diversion Project has been implemented in China. Under the Grain-for-Green project, the vegetation has been largely improved in the basin (Chen et al. 2015; Zhou, Shao, and Cao 2016; Li, Peng, and Li 2017), but runoff and soil water storage have in many studies...
been found to have decreased (McVicar et al. 2007; Feng et al. 2016; Li et al. 2016; Jia et al. 2017; Zhang et al. 2018b). However, Wang et al. (2017) found that streamflow consistently increased with agricultural land converted into forest over the Wei River basin on the Loess Plateau. Pan, Wu, and Liu (2015) indicated that land-use change played a negative role in water supply from 2000–05, but a positive role from 2005–08, in the Yellow River source region. Nevertheless, in their study, the forested land areas were reported to be 7030, 7412, and 7585 km² in 2000, 2005, and 2008, respectively. Therefore, the effect of vegetation change on water resources requires further study to provide guidance for further revegetation, which Zhang et al. (2018a) argued should be applied with caution on the Loess Plateau.

The primary objective of this study was to investigate the effects of afforestation on the regional water cycle within and around the Yellow River basin. The considered variables included precipitation, evaporation, runoff, soil moisture, atmospheric water vapor content, and the average wind field.

2. Model and experimental design

Version 3.7.1 of the Weather Research and Forecasting (WRF) model was employed in this study, which has been widely used since its first release in 2000 (Meng, Evans, and McCabe 2014). In our simulation, two nested domains (domain 1: 30 × 30 km, with 178 × 145 grids; domain 2: 10 × 10 km, with 244 × 145 grids) were used. The parameterization schemes employed are detailed in Table 1. The simulation period was from December 2005 to December 2010, with data from NCEP-FNL (spatial resolution: 1°; temporal resolution: 6 h) used as the forcing. The first month (i.e. December 2005) was used for spin-up and excluded from the analysis to eliminate the impact of the initial conditions. Time-varying sea surface temperature was applied, and the initial condition files were generated for domains 1 and 2.

In our study, the land cover boundary conditions in 2001 and 2010 derived from Moderate Resolution Imaging Spectroradiometer (MODIS) measurements were used to investigate the impact of vegetation change on the regional water cycle. Based on MODIS products, it was found that cropland increased within the Yellow River basin from 2001 to 2010, which is contrary to fact. As a result, the MODIS-based 2001 land cover that already existed in the WRF model and the land cover from MODIS products in 2010 were used in our experiments. Note that the MODIS-based land cover that already existed in the WRF model also took into account land cover information from other datasets. The differences in these two land cover conditions in the study region are shown in Figure 1, which shows that decreased cropland was largely replaced by mixed forest from 2001 to 2010. The area of urban and built-up land hardly changed, and decreased open shrubland was mainly replaced by grassland. Furthermore, 13 of 17 parameters changed slightly, ranging from 0 to 23.3% between grassland and open shrubland in the WRF model. Therefore, the conversion from cropland to mixed forest was the most significant change in land cover.

It should be noted that there is almost no product that can explicitly reflect the spatial distribution of actual land-cover change promoted by the Grain-for-Green project in the Yellow River basin. In recent years, the GlobeLand30 dataset has become available, which is the world’s first global land-cover dataset at a resolution of 30 m, released by the National Geomatics Center of China (http://www.ngcc.cn/). This dataset shows that the forest area increased and cropland decreased from 2000 to 2010 in the Yellow River basin, but the spatial distribution of these changes differed markedly from the reality. The lack of accurate land-cover-change data is an important reason for the fact that afforestation effects still have not been clearly identified in the basin.

3. Results and discussion

3.1. Variations of basin-averaged water cycle components

For simplicity, the simulations under the 2001 and 2010 land cover conditions are denoted as A₁ and A₂, respectively. The differences between A₂ and A₁ (i.e. A₂ minus A₁) are used to discuss the vegetation impact on the terrestrial water cycle. As shown in Figure 2(a), the simulated precipitation matched well overall with two sets of observed results from the China Meteorological Administration (CMA). The first observational dataset included daily precipitation at 824 meteorological stations across China (CMA-gauge), and the second dataset was a 0.5° monthly gridded product derived from 2472 stations (CMA-0.5°). Figure 2 shows that both

Table 1. Parameterization schemes employed in the simulation.

| Scheme type          | Scheme used                           |
|----------------------|---------------------------------------|
| Land surface model   | Unified Noah land-surface model       |
| Microphysics         | WSM 6-class graupel scheme            |
| Longwave radiation   | RRTM scheme                           |
| Shortwave radiation  | Dudhia scheme                         |
| Cumulus parameterization | Kain–Fritsch (newEta) scheme         |
| Planetary boundary layer | YSU scheme                           |
precipitation and evaporation increased, but especially evaporation, along with the increase in mixed forest. However, the net surface runoff change was negative for the entire period of 2006–10, with both negative and positive change values in individual months. As previously mentioned, vegetation can have both negative and positive effects on water resources, and the impacts of vegetation on streamflow are complicated (Tobella et al. 2014; Wang et al. 2017). The surface runoff was analyzed because the runoff generation in arid areas is dominated by infiltration excess (Horton) runoff. The increase in basin-averaged precipitation and evaporation during 2006–10 was 223.17 and 223.88 mm respectively, while the decrease in runoff was 2.22 mm. Similarly, some studies have reported that artificial vegetation can induce an increase in air humidity and precipitation (Xu et al. 2010; Ma 2011; Chen et al. 2016) as well as evaporation (Feng et al. 2016; Jin et al. 2017). Jiang and Liang (2013) found that increased vegetation greenness caused strengthened evapotranspiration in summer over northern China, and was a major contribution to increased total atmospheric precipitable water. Qiu et al. (2010) used numerical modeling to reveal that revegetation resulted in flood reduction in the Yellow River basin.

In our study, the effects of revegetation in different years were not always the same, suggesting a complexity to the impacts of revegetation. Pan, Wu, and Liu (2015) found that, in the headwater region, land-use change played a negative (positive) role in water supply in 2000–05 (2005–08), despite the land-cover changes having been similar in these two periods: an increase in forest and high/middle-coverage grassland, and a decrease in low-coverage grassland. Therefore, it is necessary to examine typical years, which were selected according to the precipitation amount using both 1987–2000 and

Figure 1. Differences in land cover in 2010 relative to 2001 within and around the Yellow River basin, where green (red) coloring indicates an increase (decrease).
1956–2000 as reference periods. The precipitation amounts in these two reference periods were obtained from the Bulletin of Water Resources of the Yellow River (available at http://www.yellowriver.gov.cn/). The precipitation amount in 2006 was 4.6% and 8.9% less than that in the two reference periods, respectively, whereas that in 2007 was 13.5% and 8.3% more. The precipitation changes in the other three years were relatively small. As a result, the spatial variations of water cycle terms in 2006 and 2007 were investigated, as reported below.

### 3.2. Spatial variations of water cycle components in typical years under afforestation

In the relatively dry year of 2006, the summertime precipitation, surface runoff, evaporation, soil moisture of 0–2 m, total atmospheric water vapor content, and average wind field at 700 hPa were investigated. Summer was selected because the difference in vegetation coverage is obvious and precipitation mainly occurs in this season. As shown in Figure 3, precipitation increased in the region (31°–34°N, 105°–112°E), where the land use changed from cropland into mixed forest. The increased precipitation near the headwater region corresponded to the conversion from open shrubland and barren/sparsely vegetated land to grassland. The decreased precipitation in the Toudaoguai–Longmen region corresponded to land conversion from open shrubland to grassland. Furthermore, the spatial variations of surface runoff, evaporation and soil moisture were generally consistent with that of precipitation. Notably, afforestation-

![Figure 2](image_url)

**Figure 2.** (a) Comparison of precipitation between simulated and observed values. (b–d) Differences in simulated (b) precipitation (P), (c) evaporation (E), and (d) surface runoff (R) between the 2001 and 2010 land-cover conditions.
induced soil desiccation has been reported to appear below ~2 m on average in the Loess Plateau (Wang, Shao, and Liu 2010; An et al. 2017). The soil moisture extended to 2 m in the Noah land surface model used in our study, and the spatial variations in average soil moisture were similar between the depths of 0–1 m and 1–2 m (not shown). As a result, the variations in soil moisture above 2 m were mainly controlled by precipitation.

Furthermore, the atmospheric water vapor content and average wind field at 700 hPa were examined to discuss the reason for the precipitation changes (Figure 3(e, f)). The results show that the change in atmospheric water vapor matched well with that of precipitation. A cyclonic circulation anomaly existed in the east of the study region, with a southerly wind anomaly in the southeast corner, which corresponded to increases in atmospheric water vapor and precipitation. On the contrary, a northerly wind anomaly corresponded to decreases in atmospheric water vapor and precipitation on the Loess Plateau. The change in the average wind field at 850 hPa was similar to that at 700 hPa, but the influence of terrain was more obvious at 850 hPa (not shown). The direction of anomalous wind changed to easterly at 500 hPa in most regions of the Loess Plateau without a southerly wind anomaly. On the other hand, it has been reported that increased vegetation can cause an increase in precipitation and a decrease in wind (Xu et al. 2010; Ma 2011; Ma et al. 2013; Yosef et al. 2018). Generally, increased vegetation height and leaf area index can induce higher surface roughness and decreased wind speed (Ma et al. 2013). In response to afforestation, precipitation has been found to significantly increase annually by 0.20 mm d⁻¹ in the East China monsoon region (Ma et al. 2013). In our study, it is likely that the increase in mixed

Figure 3. Differences in (a) total precipitation, (b) surface runoff, (c) evaporation, (d) average 2-m soil moisture, (e) total water vapor content in the atmosphere, and (f) the average wind field at 700 hPa, in the summer of 2006.
forest blocked the summer southerly wind from moving north via increased surface roughness; hence, precipitation increased in the south and decreased in the north of the study region in 2006. Ma (2011) indicated that the correspondence was not very clear between precipitation variation and land use/cover change, which suggests a complexity to the impacts of vegetation.

In the relatively wet year of 2007, precipitation increased overall within the Yellow River basin (Figure 4(a)), which was in accordance with the variation in atmospheric water vapor (Figure 4(e)). Meanwhile, a southeasterly wind anomaly existed in the basin, which was conducive to water vapor increasing (Figure 4(f)). An anticyclonic anomaly appeared near Bohai Bay, which was not conducive to the formation of rainfall and corresponded to decreased water vapor and precipitation. A southerly wind anomaly also existed at 850 hPa and 500 hPa in the river basin (not shown). It has been reported that the land, atmosphere, and ocean are strongly coupled in the Asian Monsoon system (Yasunari 2007), and the oceans play an important role in modulating the interactions between vegetation and climate in the East China monsoon region (Ma et al. 2013). Similarly, in our study, the changes in surface runoff, evaporation, and soil moisture were largely consistent with that of precipitation.

In summary, the patterns of variation in precipitation differed in 2006 and 2007. However, there was a common feature in the atmospheric water vapor in that it increased near the Yellow River headwater region and the area where croplands were replaced by mixed forest. The difference in the summer monsoon between 2006 and 2007 may have played an important role in the discrepancy of precipitation variations on the Loess Plateau.

Figure 4. Differences in (a) total precipitation, (b) surface runoff, (c) evaporation, (d) average 2-m soil moisture, (e) total water vapor content in the atmosphere, and (f) the average wind field at 700 hPa, in the summer of 2007.
4. Conclusion

The impact of vegetation on water resources remains a controversial topic in the scientific community. Here, the effect of the Grain-for-Green afforestation project was investigated within and around the Yellow River basin using the land cover boundary conditions in 2001 and 2010 based on the WRF model.

The results showed that, under the increase in mixed forest within and below the basin, the basin-averaged precipitation and evaporation increased by 223.17 and 223.88 mm respectively, but surface runoff decreased by 2.22 mm from 2006 to 2010. That is, the increase in forest induced an increase in both precipitation and evaporation, but the increase in evaporation was relatively larger. Importantly, the afforestation-induced effects on terrestrial water cycle terms seemed to enhance with time. For instance, runoff reductions were more obvious in the last three years in the simulation. Furthermore, the effects of the same vegetation change were different in dry and wet years with different precipitation amounts. Anticyclonic and cyclonic anomalies appeared in different years, which was mainly associated with the large-scale circulation background. According to the surface runoff change, afforestation played a negative role overall in alleviating the water shortage of the Yellow River basin. However, more evidence needs to be collected through long-term modeling with consideration of deep soil moisture and groundwater. Also, it should be noted that almost no product can currently reflect the actual spatial distribution of land-cover change induced by the Grain-for-Green project in the Yellow River basin. Modeling studies are mainly based on sensitivity experiments, and simulations with continuously changing vegetation boundary conditions are rare. A land-cover dataset derived from the advantages of multiple sets of data is therefore necessary.

This study can provide some guidance for water resources management during revegetation efforts in the Yellow River basin. However, the impact of vegetation on the terrestrial water cycle needs to be further studied in the future using coupled regional climate and hydrological models under changing vegetation boundary conditions.

Disclosure statement

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References

An, W., Z. Li, S. Wang, X. Wu, Y. Lu, G. Liu, and B. Fu. 2017. “Exploring the Effects of the “Grain for Green” Program on the Differences in Soil Water in the Semi-Arid Loess Plateau of China.” Ecological Engineering 107: 144–151. doi:10.1016/j.ecoleng.2017.07.017.
Chen, L., Z. Ma, R. Mahmood, T. Zhao, Z. Li, and Y. Li. 2016. “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. doi:10.1007/s00703-016-0478-5.
Chen, Y., K. Wang, Y. Lin, W. Shi, Y. Song, and X. He. 2015. “Balancing Green and Grain Trade.” Nature Geoscience 8 (10): 739–741. doi:10.1038/ngeo2544.
Ellison, D., M. N. Futter, and K. Bishop. 2012. “On the Forest Cover-Water Yield Debate: From Demand- to Supply-Side Thinking.” Global Change Biology 18 (3): 806–820. doi:10.1111/j.1365-2486.2011.02589.x.
Feng, X., B. Fu, S. Piao, S. Wang, P. Ciais, Z. Zeng, Y. Lü, et al. 2016. “Revegetation in China’s Loess Plateau Is Approaching Sustainable Water Resource Limits.” Nature Climate Change 6 (11): 1019–1022. doi:10.1038/nclimate3092.
Huang, Z., Z. Ouyang, F. Li, H. Zheng, and X. Wang. 2009. “Progress in the Effects of Forest Ecosystem on Runoff Based on Forest Catchments.” World Forestry Research 22 (3): 36–41. doi:10.1007/978-1-4020-9623-5_5.
Jia, X., Y. Wang, M. Shao, Y. Luo, and C. Zhang. 2017. “Estimating Regional Losses of Soil Water Due to the Conversion of Agricultural Land to Forest in China’s Loess Plateau.” Ecohydrology 10 (6): e1851. doi:10.1002/eco.1851.
Jiang, B., and S. Liang. 2013. “Improved Vegetation Greenness Increases Summer Atmospheric Water Vapor over Northern China.” Journal of Geophysical Research: Atmospheres 118 (15): 8129–8139. doi:10.1002/jgrd.50602.
Jin, Z., W. Liang, Y. Yang, W. Zhang, J. Yan, X. Chen, S. Li, and X. Mo. 2017. “Separating Vegetation Greening and Climate Change Controls on Evapotranspiration Trend over the Loess Plateau.” Scientific Reports 7 (1): 8191. doi:10.1038/s41598-017-08477-x.
Li, J., S. Peng, and Z. Li. 2017. “Detecting and Attributing Vegetation Changes on China’s Loess Plateau.” Agricultural and Forest Meteorology 247: 260–270. doi:10.1016/j.agrformet.2017.08.005.
Li, P. 2015. “The Nation Has Invested a Total of More than 4000 Billion Yuan for the First Round of the Grain for Green Project.” Xinhuanet.com. Accessed November 2018. http://www.xinhuanet.com/politics/2015-08/07/c_1116185623.htm.
Li, S., W. Liang, B. Fu, Y. Lu, S. Fu, S. Wang, and H. Su. 2016. “Vegetation Changes in Recent Large-Scale Ecological Restoration Projects and Subsequent Impact on Water Resources in China’s Loess Plateau.” Science of the Total Environment 569–570: 1032–1039. doi:10.1016/j.scitotenv.2016.06.141.
Ma, D., M. Notaro, Z. Liu, G. Chen, and Y. Liu. 2013. "Simulated Impacts of Afforestation in East China Monsoon Region as Modulated by Oceanic Variability." Climate Dynamics 41: 2439–2450. doi:10.1007/s00382-012-1592-9.

Ma, Y. 2011. "Climatic and Agricultural Effect of Converting Farmland into Forest or Grass Land in ShanGanNing Region in China." PhD diss., Chinese Academy of Meteorological Sciences and Nanjing University of Information Science & Technology (in Chinese).

McVicar, T. R., L. Li, T. G. Van Niel, L. Zhang, R. Li, Q. Yang, X. Zhang, et al. 2007. "Developing a Decision Support Tool for China’s Re-Vegetation Program: Simulating Regional Impacts of Afforestation on Average Annual Streamflow in the Loess Plateau." Forest Ecology and Management 251 (1–2): 65–81. doi:10.1016/j.foreco.2007.06.025.

Meng, X. H., J. P. Evans, and M. F. McCabe. 2014. "The Impact of Observed Vegetation Changes on Land-Atmosphere Feedbacks during Drought." Journal of Hydrometeorology 15 (2): 759–776. doi:10.1175/jhm-d-13-0130.1.

Pan, T., S. Wu, and Y. Liu. 2015. "Relative Contributions of Land Use and Climate Change to Water Supply Variations over Yellow River Source Area in Tibetan Plateau During the Past Three Decades." PLoS One 10 (4): e0123793. doi:10.1371/journal.pone.0123793.

Qiu, Y. Q., Y. W. Jia, J. C. Zhao, X. H. Wang, J. Bennett, and Z. H. Zhou. 2010. "Valuation of Flood Reductions in the Yellow River Basin under Land Use Change." Journal of Water Resources Planning and Management 136 (1): 3581–3585. doi:10.1061/(ASCE)0733-9496(2010)136:1(1106).

Tobella, A. B., H. Reese, A. Almaw, J. Bayala, A. Malmer, H. Laudon, and U. Ilstedt. 2014. "The Effect of Trees on Preferential Flow and Soil Infiltrability in an Agroforestry Parkland in Semiarid Burkina Faso." Water Resources Research 50 (4): 3342–3354. doi:10.1002/2013WR015197.

Wang, H., F. Sun, J. Xia, and W. Liu. 2017. "Impact of LUCC on Streamflow Based on the SWAT Model over the Wei River Basin on the Loess Plateau in China." Hydrology and Earth System Sciences 21: 1–17. doi:10.5194/hess-21-1-2017.

Wang, Y., M. Shao, and Z. Liu. 2010. "Large-Scale Spatial Variability of Dried Soil Layers and Related Factors across the Entire Loess Plateau of China." Geoderma 159: 99–108. doi:10.1016/j.geoderma.2010.07.001.

Xu, L., G. Yang, Y. Feng, Y. Du, and X. Han. 2010. "A Study on Microclimate Impacts of Artificial Vegetation on the Loess Plateau." Research of Soil and Water Conservation 17 (4): 170–179. (in Chinese).

Yasunari, T. 2007. "Role of Land-Atmosphere Interaction on Asian Monsoon Climate." Journal of the Meteorological Society of Japan 85: 55–75. doi:10.2151/jmsj.85B.55.

Yosef, G., R. Walko, R. Avisar, F. Tatarinov, E. Rotenberg, and D. Yakir. 2018. "Large-Scale Semi-Arid Afforestation Can Enhance Precipitation and Carbon Sequestration Potential." Scientific Reports 8 (1): 996. doi:10.1038/s41598-018-19265-6.

Yuan, W., X. Li, S. Liang, X. Cui, W. Dong, S. Liu, J. Xia, Y. Chen, D. Liu, and W. Zhu. 2014. "Characterization of Locations and Extents of Afforestation from the Grain for Green Project in China." Remote Sensing Letters 5: 221–229. doi:10.1080/2150704X.2014.894655.

Zhang, S., D. Yang, Y. Yang, S. Piao, H. Yang, H. Lei, and B. Fu. 2018a. "Excessive Afforestation and Soil Drying on China’s Loess Plateau." Journal of Geophysical Research: Biogeosciences 123 (3): 923–935. doi:10.1002/2017jg004038.

Zhang, S., Y. Yang, T. R. McVicar, and D. Yang. 2018b. "An Analytical Solution for the Impact of Vegetation Changes on Hydrological Partitioning within the Budyko Framework." Water Resources Research 54 (1): 519–537. doi:10.1002/2017wr022028.

Zhou, S., Q. Shao, and W. Cao. 2016. "Characteristics of Land Use and Land Cover Change in the Loess Plateau over the past 20 Years." Journal of Geo-Information Science 18 (2): 190–199. doi:10.3724/SP.J.1047.2016.00190. (in Chinese).