How transpiration by forests and other vegetation determines alternate moisture regimes

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Abstract. The terrestrial water cycle links the soil and atmosphere moisture reservoirs through four fluxes: precipitation, evaporation, runoff and atmospheric moisture convergence. Each of these fluxes is essential for human and ecosystem well-being. However, predicting how the water cycle responds to changes in vegetation cover, remains a challenge (Lawrence and Vandecar, 2015; Ellison et al., 2017; te Wierik et al., 2021). Recently, rainfall was shown to decrease disproportionally with reduced forest transpiration following deforestation (Baudena et al., 2021). Here, combining these findings with the law of matter conservation, we show that in a sufficiently wet atmosphere forest transpiration can control atmospheric moisture convergence such that increased transpiration enhances atmospheric moisture import. Conversely, in a drier atmosphere increased transpiration reduces atmospheric moisture convergence and runoff. This previously unrecognized dichotomy can explain the seemingly random observations of runoff and soil moisture sometimes increasing and sometimes reducing in response to re-greening (e.g., Zheng et al., 2021). Evaluating the transition between the two regimes is crucial both for characterizing the risk posed by deforestation as well as for motivating and guiding global ecosystem restoration.

1 Precipitation, column moisture and mass conservation

Forests play an important role for atmospheric moisture generation and transport through transpiration and atmospheric moisture convergence. Deforestation and reforestation can therefore strongly alter the hydrological cycle depending on the prevailing climate regime in the region. Based on data for a tropical island, Holloway and Neelin (2010) showed that the rainfall probability rises sharply with increasing column water vapor W (see also Yano and Manzato, 2022). Using the radiosonde data for several meteostations in Brazil (Fig. 1), Makarieva et al. (2014) concluded that, in the Amazon forest, a small relative in-
crement of $W$ should lead to a larger relative increment in rainfall probability. Baudena et al. (2021) found that in the relatively flat part of the Amazon including the Amazon-Cerrado transition zone ($0 - 18^\circ$S and $65 - 50^\circ$W), the mean hourly precipitation $P$ (ERA5 data for 2002-2013, binned for each 1 mm of $W$) depends non-linearly on $W$ (Fig. 1a).

$$\frac{dP}{P} = k_P(W) \frac{dW}{W},$$  \hfill (1)

where $k_P \gg 1$ for $W > 30$ mm, while $k_P \simeq 0$ for $10$ mm < $W < 20$ mm (Fig. 1b). (We excluded observations at $W \leq 8$ mm and $W \geq 67$ mm from our consideration (all bins with less than 20,000 data points, or about 0.1% of all observations, see inset in Fig. 1b), since $k_P$ displayed an erratic behavior apparently due to the relatively small number of rainfall events at these extreme $W$ values.)

Interestingly, relationship (1) established for local hourly rainfall for a specific study area in the Amazon region (Baudena et al., 2021) encompasses characteristic precipitation rates over a broad range of spatial and temporal scales, from annual precipitation in deserts, temperate and tropical forests, to hurricane and flood-causing rainfall (Fig. 1a, data from Makarieva et al., 2013, 2017; Smirnova et al., 2017; Beudert et al., 2018; Almazroui, 2020; Kreienkamp et al., 2021).

Evapotranspiration $E$ adds moisture to the atmosphere, so we expect that $W$ grows with $E$. We can write such a dependence as follows:

$$\frac{dE}{P} = k_E(W) \frac{dW}{W},$$  \hfill (2)

where $k_E > 0$. In the Amazon basin, with mean transpiration $T = 45$ mm month$^{-1}$ (Staal et al. 2018) and mean annual rainfall of $P = 2200$ mm year$^{-1}$ (Marengo 2006), a loss of evapotranspiration due to the loss of transpiration from the entire basin is equal to $\Delta E/P = -T/P = -0.25$, i.e., a decrease of 25% (in proportion to precipitation). According to Baudena et al. (2021), zeroing transpiration in a region reduces $W$ in a given location by the fraction of water vapor originating from transpiration in the considered region. In the Amazon basin, the fraction of water vapor originating from the Amazon transpiration is equal to 0.32 (Staal et al. 2018). With $\Delta W/W = -0.32$ and $\Delta E/P = -T/P = -0.25$, we have $k_E = 0.8$.

For a steady-state atmospheric column, the vertically integrated continuity equation representing the water vapor convergence over the whole atmospheric column as equal to the difference of precipitation and evaporation fluxes (see scheme in Fig. 1c), reads:

$$C \equiv - \int_{0}^{\infty} \text{div}(\rho_v \mathbf{u}) dz = - \int_{0}^{\infty} \dot{\rho}_v dz \equiv P - E,$$  \hfill (3)

where $\mathbf{u}$ is the air velocity vector, $\rho_v$ is water vapor density, $\dot{\rho}_v$ is the mass source/sink and $C$ is water vapor convergence (net flux of water vapor through the column surface). The mass balance (3) can be applied both locally and on a regional scale. It is valid when the rate of change in moisture content is small compared to precipitation ($dW/dt \ll P$), i.e., on a time scale $\tau \lesssim \tau_a$, where $\tau_a \equiv W/P$ (a few days) is the time scale of atmospheric moisture turnover via precipitation. In a system of units where liquid water density $\rho_l = 10^3$ kg m$^{-3}$ is set to unity, column water vapor $W = \int_{0}^{\infty} \rho_v dz$ has the units of length (mm), while $C$, $P$ and $E$ are measured in units of length per unit of time (for example, mm day$^{-1}$).
Figure 1. Atmospheric moisture budget terms $P$, $E$ and $C$ as related to column water vapor content $W$. Hourly precipitation data (from Baudena et al., 2021, re-averaged arithmetically) give the blue curve in (a), which we then integrate according to Eq. (2) to obtain $E$ (black curves in (a)) and $k_P(W)$ (the black curve in (b)). The inset in (b) shows the number of data points $N(W)$ for each 1 mm bin (Baudena et al., 2021). Constrained by the mass balance Eq. (3) illustrated in (c), we derive moisture convergence $C$ (d) from $P(W)$ and $E(W)$. Circles in (a) represent daily averaged $P$ and $W$ for several meteostations in Brazil (Makarieva et al., 2014, Table 2, columns 4 and 11); arrows indicate characteristic precipitation rates in different locations in the world (see text). In (c), the steady-state water balance is shown for a forest location that receives moisture solely from the ocean (thin blue arrows indicate moisture inflow $C_+$ and outflow $C_-$, cf. Eltahir and Bras, 1994, their Fig. 12). A certain part of the recycled transpired moisture (red dashed lines) flows to the forest further inland, the rest precipitates locally. Thick yellowish arrows indicate the ascending and descending air motions that generate precipitation and are responsible for local moisture convergence $C > 0$ (and steady-state runoff $R = C$). In (a) and (d), red squares indicate the point where the moisture convergence (and runoff) are minimal, but begin to grow with increasing $E$ at larger $W$. 
2 Ecosystem’s two moisture regimes

Using the dependence $P(W)$, Eq. (1) we can integrate Eq. (2) assuming $E(W_{\text{min}}) = 0$ for minimal water vapor content $W_{\text{min}} = 9$ mm. Then we can find $C(W)$ combining Eqs. (1) and (2)

$$dC = dP - dE = (k_P - k_E)dE.$$  

(4)

This reveals two regimes, for high and low $W$. In the drier regime with $k_P < k_E$, moisture convergence declines with increasing evapotranspiration and moisture content, while precipitation remains relatively constant. In the wetter regime with $k_P > k_E$, moisture convergence increases together with evapotranspiration, moisture content and precipitation (Fig. 1d). (If the soil moisture content is steady, runoff $R$ is equal to moisture convergence $C$ and thus behaves similarly.)

The quantitative details of the $P(W)$, $E(W)$ and $C(W)$ dependencies will be specific to each region, season and ecosystem type and depend on the spatial and temporal scale of observations (Fig. 1h, see also Peters and Neelin 2006). However, the established pattern is qualitatively robust with respect to different values of $E(W_{\text{min}})$ (not shown) and $k_E$ (Fig. 1h). At higher $k_E$ (i.e., a slower accumulation of atmospheric moisture with growing $E$), there appears an interval of $W$ with negative moisture convergence. This corresponds to dry conditions when the ecosystem transpires at the expense of previously accumulated soil moisture or at the expense of irrigation.

Equations (1)–(3) make it clear that both regimes exist irrespective of specific $k_E$ and $k_P$ values, provided that $k_P < k_E$ at lower $W$ and $k_P > k_E$ at higher $W$. The robustness of the pattern has a profound physical meaning related to the saturated state of the atmosphere. Since precipitation requires saturation, at low $W$ far from the saturation, $k_P$ is low, i.e., an increase in local $W$ does not markedly increase the probability precipitation that may then be determined by non-local weather systems (Makarieva et al. 2014). Evaporation, on the contrary, is significant at high water vapor deficits and enriches the atmosphere with water vapor, so if $E$ grows, so will $W$. This dry regime can be characterized as “abiotic”, because the ecosystem exploits the geophysical moisture flows and, at $C < 0$, the previously accumulated water stores (Fig. 1d).

As the air column approaches saturation at high $W$, precipitation begins to increase markedly with $W$. Evaporation, on the other hand, depends on the moisture deficit near the surface atmosphere, which is largely decoupled from total water vapor content $W$ (Holloway and Neelin 2009, their Fig. 3e,f). (Indeed, evapotranspiration and moisture convergence have distinct physics. Moisture convergence occurs when the air rises and water vapor condenses. In contrast, evapotranspiration is not explicitly linked to directional air motions; it adds water vapor directly to the atmospheric column facilitated by turbulent diffusion.) Under nearly saturated conditions, evaporation can only proceed if precipitation depletes moisture from the atmosphere creating a water vapor deficit (Murakami 2006, 2021; Jiménez-Rodríguez et al. 2021). Therefore, at high $W$ precipitation $P$ and evapotranspiration $E$ should grow approximately proportionally to each other. The recycling ratio $E/P$ and the runoff-to-precipitation ratio $R/P = C/P = 1 - E/P$ stabilize at high values of $W$ and then remain approximately constant (Fig. 1h). In this wet regime all the components of the water cycle should be under biotic control.

The wetter the atmosphere, the stronger the water cycle control and the more resilient the forest: by slightly changing evapotranspiration, it can compensate for unfavorable disturbances of the water cycle (Makarieva et al. 2014). Conversely, in a drier atmosphere with less rainfall, the forest is more vulnerable to external perturbations. This elucidates why the Amazon
forest appears to be losing resilience mostly in the regions where the rainfall is relatively low (rather than where rainfall is decreasing) (Boulton et al., 2022).

3 Conclusions

Our findings, that forest transpiration can control and switch atmospheric moisture convergence, corroborate the biotic pump concept (Makarieva and Gorshkov, 2007; Makarieva et al., 2014). Independent studies have shown that the Amazon forest transpiration during the late dry season moistens the atmosphere and triggers the wet season and associated ocean-to-land moisture inflow (Wright et al., 2017). This dry-season transpiration has a phenological and, hence, evolutionary component that encodes the Amazon dry-season greening (Saleska et al., 2016). Enhanced forest transpiration preceding the wet season was also observed in Northeast India and Congo basin (Pradhan et al., 2019; Worden et al., 2021). Regulation of moisture convergence could explain how forests buffer precipitation extremes across continents (O'Connor et al., 2021; Silva de Oliveira et al., 2021). While over a broad range of $30 \text{ mm} \lesssim W \lesssim 60 \text{ mm}$ the value of $k_P$ is relatively constant (pink area in Fig. 1b), it increases sharply at larger $W$. The interval of $W > 60 \text{ mm}$ harbors very high precipitation rates observed under extreme weather conditions (Fig. 1a). It remains to be investigated whether/how forest disturbances influence the probability of such extremes. If natural forest ecosystems have evolved to stabilize and sustain the continental water cycle, their destruction contributes to destabilization and impoverishment of regional water cycles. This contribution is underestimated (Sheil et al., 2019). Future studies of vegetation cover impacts on atmospheric moisture flows must emphasize the role of natural forests (Zemp et al., 2017; Makarieva et al., 2020; Leite-Filho et al., 2021; Hua et al., 2022).

The existence of the two regimes with a possibly non-steady transition between them have important implications for large-scale afforestation efforts e.g., in China where increasing atmospheric moisture content with progressive re-greening can be in drier areas associated with a decline of runoff and soil moisture content (e.g., Jiang and Liang, 2013; Zhang et al., 2021). This decline has been interpreted as limiting further ecosystem restoration (Feng et al., 2016). However, Fig. 1d suggests that if re-greening is continued, the ecosystem can pass a tipping point and enter a wetter state when further re-greening will enhance both rainfall, moisture convergence and runoff. Indeed, in the wetter areas in China re-greening did cause an increase in runoff (e.g., Wang et al., 2018). On the Loess Plateau, soil moisture content decreased in the drier, but increased in the wetter, parts of the region (Zheng et al., 2021, Fig. 10a). Establishing key parameters of the two regimes and assessing the potential transition from the drier to the wetter state (during which the recovering ecosystem might require extra water inputs) can inform and guide afforestation and reforestation strategies, including possible recovery of ecosystem productivity in the driest regions.

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References

Almazroui, M.: Rainfall trends and extremes in Saudi Arabia in recent decades, Atmosphere, 11, 964, https://doi.org/10.3390/atmos11090964 2020.

Baudena, M., Tuinenburg, O. A., Ferdinand, P. A., and Staal, A.: Effects of land-use change in the Amazon on precipitation are likely underestimated, Global Change Biology, 27, 5580–5587, https://doi.org/10.1111/gcb.15810 2021.

Beudert, B., Bernsteinová, J., Premier, J., and Bässler, C.: Natural disturbance by bark beetle offsets climate change effects on streamflow in headwater catchments of the Bohemian Forest, Silva Gabreta, 24, 21–45, 2018.

Boulton, C. A., Lenton, T. M., and Boers, N.: Pronounced loss of Amazon rainforest resilience since the early 2000s, Nature Climate Change, 12, 271–278, https://doi.org/10.1038/s41558-022-01287-8 2022.

Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., van Noordwijk, M., Creed, I. F., Pokorny, J., Gaveau, D., Spracklen, D. V., Tobella, A. B., Ilstedt, U., Teuling, A. J., Gebrehiwot, S. G., Sands, D. C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., and Sullivan, C. A.: Trees, forests and water: Cool insights for a hot world, Global Environmental Change, 43, 51–61, https://doi.org/10.1016/j.gloenvcha.2017.01.002 2017.

Eltahir, E. A. B. and Bras, R. L.: Precipitation recycling in the Amazon basin, Quarterly Journal of the Royal Meteorological Society, 120, 861–880, https://doi.org/10.1002/qj.49712051806 1994.

Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lü, Y., Zeng, Y., Li, Y., Jiang, X., and Wu, B.: Revegetation in China’s Loess Plateau is approaching sustainable water resource limits, Nature Climate Change, 6, 1019–1022, https://doi.org/10.1038/nclimate3092 2016.

Holloway, C. E. and Neelin, J. D.: Moisture Vertical Structure, Column Water Vapor, and Tropical Deep Convection, Journal of the Atmospheric Sciences, 66, 1665–1683, 2009.

Holloway, C. E. and Neelin, J. D.: Temporal relations of column water vapor and tropical precipitation, Journal of the Atmospheric Sciences, 67, 1091–1105, https://doi.org/10.1175/2009JAS3284.1 2010.

Hua, F., Bruijnzeel, L. A., Meli, P., Martin, P. A., Zhang, J., Nakagawa, S., Miao, X., Wang, W., McEvoy, C., Peña-Arancibia, J. L., Brancalion, P. H. S., Smith, P., Edwards, D. P., and Balmford, A.: The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches, Science, 0, eabl4649, https://doi.org/10.1126/science.abl4649 2022.

Jiang, B. and Liang, S.: Improved vegetation greenness increases summer atmospheric water vapor over Northern China, Journal of Geophysical Research: Atmospheres, 118, 8129–8139, https://doi.org/10.1002/2012JD019502 2013.

Jiménez-Rodríguez, C. D., Coenders-Gerrits, M., Schilperoort, B., González-Angarita, A. P., and Savenije, H.: Vapor plumes in a tropical wet forest: Spotting the invisible evaporation, Hydrology and Earth System Sciences, 25, 619–635, https://doi.org/10.5194/hess-25-619-2021 2021.

Kreienkamp, F., Philip, S. Y., Tradowsky, J. S., Kew, S. F., Lorenz, P., Arrighi, J., Belleflamme, A., Bettmann, T., Caluwaerts, S., Chan, S. C., Ciavarella, A., De Cruz, L., de Vries, H., Demuth, N., Ferrone, A., Fischer, E. M., Fowler, H. J., Goergen, K., Heinrich, D., Henrichs, Y., Lenderink, G., Kaspar, F., Nilson, E., Otto, F. E. L., Ragone, F., Seneviratne, S. I., Singh, R. K., Skålevåg, A., Termonia, P., Thalheimer, L., van Aalst, M., Van den Bergh, J., Van de Vyver, H., Vannitsem, S., van Oldenborgh, G. J., Van Schaeybroeck, B., Vautard, R., Vonk, D., and Wanders, N.: Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021, Report, http://hdl.handle.net/1854/LU-8732135 2021.

Lawrence, D. and Vandecar, K.: Effects of tropical deforestation on climate and agriculture., Nature Climate Change, 5, 27–36, https://doi.org/10.1038/nclimate2430 2015.
Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M., and Börner, J.: Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon, Nature Communications, 12, 2591, https://doi.org/10.1038/s41467-021-22840-7 2021.

Makarieva, A. M. and Gorshkov, V. G.: Biotic pump of atmospheric moisture as driver of the hydrological cycle on land, Hydrology and Earth System Sciences, 11, 1013–1033, https://doi.org/10.5194/hess-11-1013-2007 2007.

Makarieva, A. M., Gorshkov, V. G., and Li, B.-L.: Revisiting forest impact on atmospheric water vapor transport and precipitation, Theoretical and Applied Climatology, 111, 79–96, https://doi.org/10.1007/s00704-012-0643-9 2013.

Makarieva, A. M., Gorshkov, V. G., Sheil, D., Nobre, A. D., Bunyard, P., and Li, B.-L.: Why does air passage over forest yield more rain? Examining the coupling between rainfall, pressure, and atmospheric moisture content, Journal of Hydrometeorology, 15, 411–426, https://doi.org/10.1175/JHM-D-12-0190.1 2014.

Makarieva, A. M., Gorshkov, V. G., Nefiodov, A. V., Chikunov, A. V., Sheil, D., Nobre, A. D., and Li, B.-L.: Fuel for cyclones: The water vapor budget of a hurricane as dependent on its movement, Atmospheric Research, 193, 216–230, https://doi.org/10.1016/j.atmosres.2017.04.006 2017.

Makarieva, A. M., Nefiodov, A. V., Morozov, V. E., Aleynikov, A. A., and Vasilov, R. G.: Science in the vanguard of rethinking the role of forests in the third millennium: Comments on the draft concept of the federal law “Forest code of the Russian Federation”, Forest Science Issues, 3, https://doi.org/10.31509/2658-607x-2020-3-3-1-25 2020.

Marengo, J. A.: On the hydrological cycle of the Amazon basin: A historical review and current state-of-the-art, Rev. Bras. Meteor., 21, 1–19, 2006.

Murakami, S.: A proposal for a new forest canopy interception mechanism: Splash droplet evaporation, Journal of Hydrology, 319, 72–82, https://doi.org/10.1016/j.jhydrol.2005.07.002 2006.

Murakami, S.: Water and energy balance of canopy interception as evidence of splash droplet evaporation hypothesis, Hydrological Sciences Journal, 66, 1248–1264, https://doi.org/10.1080/02626667.2021.1924378 2021.

O’Connor, J. C., Dekker, S. C., Staal, A., Tuinenburg, O. A., Rebel, K. T., and Santos, M. J.: Forests buffer against variations in precipitation, Global Change Biology, 27, 4686–4696, https://doi.org/10.1111/gcb.15763 2021.

Peters, O. and Neelin, J.: Critical phenomena in atmospheric precipitation, Nature Phys., 2, 393–396, https://doi.org/10.1038/nphys314 2006.

Pradhan, R., Singh, N., and Singh, R. P.: Onset of summer monsoon in Northeast India is preceded by enhanced transpiration, Scientific Reports, 9, https://doi.org/10.1038/s41598-019-55186-8 2019.

Saleska, S. R., Wu, J., Guan, K., Araujo, A. C., Huete, A., Nobre, A. D., and Restrepo-Coupe, N.: Dry-season greening of Amazon forests, Nature, 531, E4–E5, https://doi.org/10.1038/nature16457 2016.

Sheil, D., Bargués-Tobella, A., Ilistedt, U., Ibisch, P. L., Makarieva, A., McAlpine, C., Morris, C. E., Murdiyarso, D., Nobre, A. D., Poveda, G., Spracklen, D. V., Sullivan, C. A., Tuinenburg, O. A., and van der Ent, R. J.: Forest restoration: Transformative trees, Science, 366, 316–317, https://doi.org/10.1126/science.aay7309 2019.

Silva de Oliveira, A., Sande Silva, J., Gaspar, J., Nunes Guiomar, N. R. G., and Fernandes, P. M.: Is native forest an alternative to prevent wildfires in the WUI in Central Portugal?, vol. 2, pp. 67–77, RISCOS – Associação Portuguesa de Riscos, Prevenção e Segurança, Simões & Linhares, Lda., https://doi.org/10.34037/978-989-9053-06-9_1.2_05 2021.

Smirnova, O. V., Bobrovsky, M. V., Khanina, L. G., Zaugolnova, L. B., Korotkov, V. N., Aleynikov, A. A., Evstigneev, O. I., Smirnov, V. E., Smirnov, N. S., and Zaprudina, M. V.: Boreal Forests, in: European Russian Forests., pp. 59–203, Springer, Dordrecht, https://doi.org/10.1007/978-94-024-1172-0_3 2017.
Staal, A., Tuinenburg, O. A., Bosmans, J. H. C., Holmgren, M., van Nes, E. H., Scheffer, M., Zemp, D. C., and Dekker, S. C.: Forest-rainfall cascades buffer against drought across the Amazon, Nature Climate Change, 8, 539–543, https://doi.org/10.1038/s41558-018-0177-y, 2018.

te Wierik, S. A., Cammeraat, E. L. H., Gupta, J., and Artzy-Randrup, Y. A.: Reviewing the impact of land use and land-use change on moisture recycling and precipitation patterns, Water Resources Research, 57, https://doi.org/10.1029/2020WR029234, 2021.

Wang, Y., Liu, Y., and Jin, J.: Contrast effects of vegetation cover change on evapotranspiration during a revegetation period in the Poyang Lake Basin, China, Forests, 9, https://doi.org/10.3390/f9040217, 2018.

Worden, S., Fu, R., Chakraborty, S., Liu, J., and Worden, J.: Where does moisture come from over the Congo Basin?, Journal of Geophysical Research: Biogeosciences, 126, https://doi.org/10.1029/2020JG006024, 2021.

Wright, J. S., Fu, R., Worden, J. R., Chakraborty, S., Clinton, N. E., Risi, C., Sun, Y., and Yin, L.: Rainforest-initiated wet season onset over the Southern Amazon, Proceedings of the National Academy of Sciences of the United States of America, 114, 8481–8486, https://doi.org/10.1073/pnas.1621516114, 2017.

Yano, J.-I. and Manzato, A.: Does more moisture in the atmosphere lead to more intense rains?, Journal of the Atmospheric Sciences, 79, 663–681, https://doi.org/10.1175/JAS-D-21-0117.1, 2022.

Zemp, D. C., Schleussner, C.-F., Barbosa, H. M. J., Hirota, M., Montade, V., Sampaio, G., Staal, A., Wang Erlandsson, L., and Rammig, A.: Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks, Nature Communications, 8, https://doi.org/10.1038/ncomms14681, 2017.

Zhang, J., Zhang, Y., Sun, G., Song, C., Dannenberg, M. P., Li, J., Liu, N., Zhang, K., Zhang, Q., and Hao, L.: Vegetation greening weakened the capacity of water supply to China’s South-to-North Water Diversion Project, Hydrology and Earth System Sciences, 25, 5623–5640, https://doi.org/10.5194/hess-25-5623-2021, 2021.

Zheng, H., Miao, C., Zhang, G., Li, X., Wang, S., Wu, J., and Gou, J.: Is the runoff coefficient increasing or decreasing after ecological restoration on China’s Loess Plateau?, International Soil and Water Conservation Researchs, 9, 333–343, https://doi.org/10.1016/j.iswcr.2021.04.009, 2021.